A CROSS-LINGUISTIC STUDY OF LINGUAL COARTICULATION IN KANNADA, MALAYALAM AND HINDI LANGUAGES USING ULTRASOUND IMAGING PROCEDURE

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ABSTRACT

Sound segments are affected by the influence of neighbouring segments, which is explained as the result of coarticulation. Coarticulation is studied using various methods including perceptual, acoustic and physiological. However, there is a lack of crosslinguistic physiological studies of coarticulation in Indian languages. Phonology and phonetic structure of Indian languages are distinct from other most studied languages. Hence, the present investigation aimed to examine the extent of coarticulation, direction of coarticulation and coarticulation resistance within the languages i.e. Kannada, Malayalam (Dravidian languages) and Hindi (Indo-Aryan) and across these three languages.

Ninety adult native speakers, 30 each in Kannada, Malayalam and Hindi groups comprising equal number of males and females in the age range of 20-30 years served as participants in the study. The stimuli consisted of V_1CV_2 sequences with C corresponding to voiced/ unvoiced counterparts of dental (/t̪/, /d̪/) or retroflex (/ʈ/, /ɖ/) or velar stops (/k/, /g/), in the context of vowels /a, i, u/. Tongue contours and the distance between tongue contours of each vowel and consonant (V_1 to C and V_2 to C) were obtained using Mindray 6600 Ultrasound module and was calculated using the software Articulated Assistance Advanced (AAA) based on Root Mean Square (RMS) method. The study considered five major parameters of coarticulation which included the extent of coarticulation, direction of coarticulation, coarticulation resistance of the consonant, coarticulation resistance of the preceding and the following vowels.

Findings showed different patterns of extent of coarticulation (EC) in each language, both in the preceding and following vowel contexts. In general, dentals had lowest EC or maximum coarticulation in vowel /a/ context, velars in /i/ and retroflexes in /u/ contexts. Retroflexes were

found to have significantly higher coarticulation resistance compared to dentals and velars for all the vowel pair contexts. Among vowels, highest coarticulation resistance was for vowel /i/ and lowest for /a/ in all the three languages across three places of articulation in both preceding and following contexts. Anticipatory coarticulation was predominant for almost all tokens across languages, places of articulation and vowels. Based on the findings, there was no major voicing and gender effect on coarticulation.

Direction of coarticulation was found to be significantly anticipatory in all the three languages. Coarticulation resistance of consonants and vowels were different across language families especially for retroflex, and proves that both the Dravidian languages exhibited higher coarticulation resistance of consonants than Hindi.

The implications of the study are that it augments our understanding on the articulatory gestures of three places of articulation i.e. dentals, retroflexes and velars in the context of the three primary vowels /a/, /i/ and /u/. The results provide an insight into the pattern of coarticulation resistance and extent of coarticulation across three key languages of India. Study explains typical speech production in an improved way, and has applications in the area of linguistics as it focuses on the coarticulation patterns. The study also adds information to the existing theories and models of coarticulation.

CHAPTER I- INTRODUCTION

"A fundamental characteristic of spoken language is that the movements of different articulators for the production of successive phonetic segments overlap in time and interact with one another. As a consequence, the vocal tract configuration at any point in time is influenced by more than one segment" and this effect is termed as coarticulation (Farnetani & Recasens, 2010). It is defined in a broad manner that a phonological segment is not realized identically in all environments, but often apparently varies to become more like an adjacent or nearby segment (Kuhnert & Nolan, 1999).

Lingual coarticulation is important since the tongue is a complex, mobile articulator which plays a major role in the production of all vowels and majority of the consonants. As for lingual coarticulation, the different areas of the tongue are modelled as being quasi-independent of each other (Ohman, 1965). Precisely tongue tip/ blade and tongue body can act quasi independently as two distinct articulators so that their activity in the production of adjacent segments may overlay in time (Farnetani & Recasens, 2010). Coarticulation sensitivity for a given lingual region depends not only on place and manner of articulation requirement but also on the mechanical restrictions such as flexibility and coupling with other lingual regions (Recasens, 1989). The term coarticulation resistance refers to the degree to which a given segment resists potential interference of neighbouring segments. It is inversely proportional to linguo-palatal contact associated with lingual consonants and also to a segment's degree of sonority (Lindblom, 1963). Sounds having relatively higher coarticulation resistance exert a stronger influence on their neighbouring vowels; they exhibit the lowest contextual variation and induce the greatest.

The influences of lingual coarticulation often extend well beyond the boundaries of a particular segment and appear to be the influence of both spatial and temporal linking of articulatory gestures. It arises for different reasons, some having to do with the phonology of a particular language, some with the basic mechanical or physiological constraints of the speech apparatus. Some coarticulatory patterns are learnt and others are the inevitable consequences of muscles, ligaments and bones of the speech apparatus that are linked together and unable to move with infinite speed (Kent, 1983). Hence, it is possible to consider language universal or articulatory position related and language specific coarticulation as components of coarticulation. The universal properties stem from the fact that all humans have similar constraints on vocal tract anatomy and neuromotor processing, including the speed and agility with which the speech articulators can be moved. This explains the effect of articulatory posture on coarticulation. Such effects are thought to largely reflect inertial or mechano-elastic properties of the articulatory system. Language specific coarticulation discusses the phonological system of particular language (Manuel & Krakow, 1984).

I. Effect of articulatory gestures on coarticulation

Production of a phonetic segment may demand one or more articulatory gestures of a single articulator. For example, in the production of syllable /ki/ the constriction is at the level of tongue root for velar /k/ and tongue tip for high front vowel /i/. Hence, there should be sort of biomechanical or articulatory gestures which help to couple between the articulatory gestures (Recasens, Pallares & Fontdevila, 1997). This can be varied from phoneme to phoneme based on the articulatory gestures composed for the motor goal (Browman & Goldstein, 1988). Coarticulation occurs if these articulatory gestures are compatible enough to each other. Also speech production system, specifically tongue in case of lingual coarticulation is flexible enough to constitute variation based on the phonetic segment i.e. Vowel to Consonant (V-C) and Consonant to Vowel (C-V). Hence, nature of consonant and vowel and inter articulatory coordination determine the compatibility of articulatory gestures and coarticulation.

1. Effect of places of articulation and vowels

The magnitude and extent of coarticulatory effects in VCV sequences are related to the tongue dorsum position based on the adjacent phonetic segments (Recasens, 1985). The onset of vowel-dependent coarticulation appears to vary inversely with the degree of tongue dorsum constraint for the immediate consonant. Researchers invoking a C-to-V mode of coarticulation have reported a longer delay in onset of vowel-related tongue dorsum activity with the degree of tongue dorsum involvement for the preceding consonant (for /k/ > /t/ > /p/) (Recasens, 1999). Similar pattern was reported where velars had greater coarticulation and labials showed lowest coarticulation (Krull, 1988; Lindblom, 1963; Sussman et al. 1997). Gibson and Ohde (2007) agreed with greater coarticulation of velars, but reported of higher coarticulation for bilabials than dentals.

Concerning dentoalveolar consonants, laminar fricatives (/s/, /z/) appear to be more resistant than apicals (/t/, /d/, /n/, /l/) in British English (Bladon & Nolan 1977). In German, the degree of coarticulation variability usually decreases in the progression /n/ > /l/ > /d/ > /t/ > /s/ (Hoole, Gfroerer & Tillmann, 1990). Electropalatographic data stated lesser vowel coarticulation at the place of articulation for lingual fricatives than for /n/ and /l/ in Catalan. The apicoalveolar tap /ɾ/ is also highly sensitive to coarticulatory effects in different vowel context (Catalan: Recasens 1999; Japanese: Sudo, Kiritani & Yoshioka, 1982). Articulatory gestures of voiceless fricative labiodental consonant /f/ varied based on the vowel neighboured, especially variation at the level of tongue body and tongue root. Tongue body raised when /f/ occurred with vowel /u/ and tongue root moved forward in /i/ context (Carney & Moll, 1971).

As seen in literature, front vowel /i/ shows maximum resistance to coarticulation since the tongue body becomes highly constrained when fronted and raised simultaneously (Hillenbrand, Clark & Houde, 2000; Recasens, 1985; Zharkova, 2007; Zharkova & Hewlett, 2008). This has been reported in many languages such as American English (Stevens & House, 1963), Dutch (Pols, 1977) and Catalan (Recasens, 1985). The vowel shows decreased palatal contact especially when it is adjacent to velarized consonants (Russian: Kuznetsov & Ott, 1987) and pharyngealized consonants (Arabic: Yeou, 1995).

The tongue body indicates considerable context-dependent variability for back vowel (Perkell & Nelson, 1985; Recasens & Espinosa, 2009; Zharkova, 2007). Concerning back vowel /a/, dento-avleolar and alveolo-palatal consonants cause some raising and stretching of the tongue dorsum and blade (Recasens, 1999); velars cause considerable tongue post-dorsum raising (MacNelage & DeClerk, 1969). Back vowels /u/ and /o/ influence dental, alveolar, alveopalatal and palatal consonants causing tongue dorsum stretching, raising of the tongue tip and blade (Recasens, 1991).

2. Direction of coarticulation

Literature showed two distinct stances regarding the directionality of influence, across places of articulation. Predominance of vowel-dependent carryover effects in some of the consonants such as bilabials (Manuel & Krakow, 1984), dentoalveolar stops (Bell-Berti & Harris, 1982), alveolar taps and flaps and non-velarized /l/ (Recasens, 1991; Farnetani 1990). Other studies, however, indicate that the vowel-dependent anticipatory component may prevail upon the vowel-dependent carryover component (Swedish, American, and Russia- Ohman, 1965; French- Ushijima & Hirose, 1974; German- Butcher & Weiher, 1976; Ndebele and Shona- Manuel, 1990; Scottish English - Zharkova, Hewlett & Hardcastle, 2008; Zharkova & Hewlett, 2008; Chinese- Wang & Huang, 2013; Kannada- Kochetov, Sreedevi, Kasim, & Manjula, 2014; French and Mandarian- Ma, Perrier & Dang, 2006). Consistently with this view, Hoole, Gfroerer and Tillmann (1990) have shown that anticipatory effects may be larger than carryover effects and influence happened more at a flexible articulator such as the tongue front; moreover, a decrease in tongue dorsum involvement may cause an increase in vowel-dependent anticipatory coarticulation (for labials > dentoalveolars > velars), and larger anticipatory than carryover effects (labials in German: Hoole et al, 1990; labials and dentoalveolars in English: Magen, 1997). Parush, Ostry and Munhall (1983) reported of spatial variations for anticipatory coarticulation, conversely, temporal constraint for carryover coarticulation.

3. Coarticulation resistance (CR) of consonants and vowels

The term "Coarticulation Resistance (CR)" was introduced by Bladon and Al-Bamerni (1976) to express the resistance of influence of phoneme from neighbouring phonemes quantitatively. It can be varied from phoneme to phoneme based on the articulatory constriction. Degree of Articulatory Constraint model explains that CR varies based on the "the degree of involvement of the speech articulators in the formation of a closure or constriction" (Recasens et al, 1997). There are studies exploring the same across phonemes and in different languages. Based on Pastatter and Pouplier (2015) greater resistant consonants were /s, ʃ/, less resistant consonants were /m, p, k/ and /n, l/ showed intermediate resistance in English. In Catalan the pattern was /ʃ, ɲ, k/ > /s/ > /p, n, l/ since the tongue body height is greater for the lamino-dorsal and dorsal consonants / ʃ, J, k/ than for /s/, and lowest for the bilabial /p/ and the non-fricative alveolars /n, l/ (Recasens & Espinosa, 2009). Similar to this, Recasens and Rodríguez (2016) reported that coarticulation resistance vary in the progression /ʎ, ɲ, ʃ > /s, r/> /t, n, ɾ, l/ > /d/ for consonants and /i, e/ > /a/ > /o, u/ for vowels. Three Australian languages including Burarra, Gupapuyngu and Warlpiri also followed same trend (Graetzer, 2007).

II. Effect of language on coarticulation

There are two existing theoretical stances that might account for language differences in coarticulation. Manuel (1990) proposed that the degree of coarticulation is predictable from the phonological inventory of a given language and a perceptual constraint applying across all languages whereby speakers constrain variability in order to maintain perceptual distinctiveness among phonemes. He provided evidence in support of this stance showing that languages with smaller phonemic inventories, in which there is less possibility of confusing phonetic contrasts, allow more coarticulatory variation than languages with a larger number of phonemes, where maximal coarticulation may confuse the distinctive properties of sounds (Beddor, Harnsberger & Lindemann, 2002; Choi & Keating, 1991; Cohn, 1988; Flemming, 1997; Lubker & Gay, 1982; Magen, 1984; Manuel & Krakow, 1984). However, coarticulatory variability is not determined solely by the perceptual distinctiveness constraint as applied to a given language. As discussed in Manuel (1990), there appear to be differences in vowel-to-vowel coarticulation even between two languages with the same number of vowels. He suggested that there are universal constraints on the minimum distinctiveness of different phonemes, but coarticulation resistance varies from phoneme to phoneme.

The second stance, proposed by Keating (1985, 1990), is that coarticulation and other phonetic details are language-specific. Since the language-specific phonetic facts of each language are specified in its grammar, it predicts that a language learner must learn all the phonetic details, including coarticulation, that are specific to a target language as well as its phonological grammar. According to this theory, language learners do not necessarily exploit any predictable relationship between inventory size and amount of coarticulation.

Keating (1985, 1990) and Manuel (1990) are suggesting language specific coarticulation rather than mechano-inertial properties of articulators. Manuel (1990) predicts that coarticulation is more to do with the phonetic inventory of each language and it is similar in languages having parallel phonemic constraints. Though Keating (1985, 1990) agreed that coarticulation is language specific, his notion of coarticulation was more related to grammatical.

There were a few attempts to investigate the language universality and language specificity of coarticulation using perceptual, acoustical and physiological method. Most of the perceptual studies of coarticulation show the fact that coarticulation depends on language constraints. Crosslinguistic studies opine that the coarticulatory variation across languages support language specific coarticulation (Beddor & Krakowb, 1999; Lubker, Lindgren & Gibson, 1982). That is, crosslinguistic studies have also proved that the coarticulatory phenomenon can also arise due to the effects of the ambient language. However, this finding cannot be established solely by qualitative studies, but requires quantitative data too.

Need for the study

Coarticulation can be studied perceptually, acoustically and physiologically. Perceptual analysis of coarticulation provides more of qualitative information and is more feasible and requires less time. Though acoustic mode of analysis is relatively easy, the environmental noise can hinder the analysis procedure. Physiological studies including imaging techniques provide more of spatial and temporal information of coarticulation. Electromagnetic articulometry (EMA) is one of the articulatory imaging techniques for recording the movement of the speech articulator which analyses the articulation. However, there can be many sources of potential errors with the placement of electrodes which influence the trajectory movement. Electropalatography (EPG) records details of the tongue contact with a hard palate and each individual requires custom made pseudo-palate to assess the same.

Ultrasound imaging technique comes with the advantage of providing an explicit image of tongue configuration in real time. It depicts the surface of the tongue from a midsagittal or coronal view which enables the extraction of the tongue contour from one or several frames, visualisation of tongue movements, comparing tongue positions and measuring the amount of tongue movement between frames, duration analysis, and 2D reconstruction. It is a safe, non-invasive, and cost-effective method of analysing articulatory gestures. The process of ultrasound data acquisition is relatively comfortable for the subject and possible to acquire extensive amounts of tongue movement data. It helps in providing stabilisation techniques for imaging of speech articulation, tongue shape, place and amount of constriction and provides information about both phonetic and phonological hypotheses.

As evident from the literature, the number of subjects is limited in all the reported physiological studies because of the tedious data collection and analysis procedure. There are limited reported cross linguistic studies based on physiological methods. Ma, Perrier and Dang (2006) studied French and Mandarin languages where they collected EMA and acoustic data from 3 speakers of each language. And reported that anticipatory coarticulation was there in whole V_1CV_2 sequence in French, while it is strictly limited to CV_2 for Mandarin speakers. There was no comparison of coarticulation across places of articulation and vowels.

India is a multilingual country which has a number of diverse languages spoken across the country. Some of these languages are accepted nationally, while others are accepted as dialects of particular regions. All of these languages belong to major language families, such as Indo-Aryan, Dravidian languages, Austro-Asiatic languages and Tibeto-Burman linguistic languages. There are a few reported studies in the Indian context on coarticulation patterns using acoustical analysis especially in Kannada and Malayalam (Dravidian languages). Both these languages are syllabic in nature. But Kannada has restricted occurrence of closed syllable structures in spoken language where as Malayalam and Hindi (Indo-Aryan) have both open and closed syllable structures (Kumari, 1972; Upadhyaya, 1972). Hence, these languages have similarities and differences in language structure across them.

These languages have shown differences in voicing contrast of consonants as there are X- ray reports of variations in tongue gestures in voiced and unvoiced counterparts (Dixit, 1990; Ladefoged, 1993) specifically for retroflex. Using ultrasound imaging, Sindusha, Irfana and Sreedevi (2014) reported that unvoiced retroflex dominantly showed apical pattern of retroflection, whereas sub-apical pattern was seen predominantly in voiced retroflex in Kannada. They also reported that female subjects had higher degree of angle of retroflection compared to male speakers.

Though there are a number of acoustic analysis based coarticulation studies, there is only one physiological study reported in Kannada. Kochetov and Sreedevi (2013) investigated effects of vowel context on the articulation of geminate retroflex, dental and labial stops based on ultrasound tongue imaging data from Kannada speakers. The magnitude of the coarticulatory effects was much greater for the labial than for the two lingual articulations, and somewhat greater for the retroflex than for the dental. This was reported in other studies also (Kochetov, Sreedevi, Kasim & Manjula, 2014; Kochetov & Sreedevi, 2015). There was no gender effect on coarticulation in Kannada (Kochetov & Sreedevi, 2013). Scobbie, Punnoose and Khattab (2013) reported that in Malayalam, /i/ had greater coarticulation even in the context of liquid.

Studies of coarticulation in many languages have revealed a set of properties that distinguish various places of articulation across vowel contexts. The studies also indicate a wide variation in coarticulation across and within languages. Most studied non-Indian languages are American English, Catalan, Spanish, Dutch, Russian, French, Swedish, Polish, Thai, German and British English, where most of them have a 2 way voicing contrast (Voiced unaspirated and unvoiced unaspirated). Indian languages also differ in terms of voicing contrast and other language specific features. It has been well established that Hindi, Kannada and Malayalam have several differences and similarities across them.

First of all Kannada and Hindi have a 4-way voicing contrast (Voiced unaspirated, voiced aspirated, unvoiced unaspirated and unvoiced aspirated) whereas, Malayalam has a 3-way voicing contrast for stop consonants (Voiced unaspirated, unvoiced unaspirated and unvoiced aspirated) (Savithri, Sreedevi & Santhosh, 2002). Also in Malayalam, the occurrence of an unvoiced unaspirated consonant is restricted to geminate or non-geminate cluster in the medial position and has five stop places of articulation (Velar, retroflex, alveolar, dental and bilabial), whereas Hindi and Kannada have only four stop places of articulation (Velar, retroflex, dental and bilabial) (Ramaswami, 1999). Preliminary ultrasound studies have revealed that retroflection is more apical in Kannada whereas it is predominantly sub apical in Malayalam (Sindusha et al. 2014). Also, it was found that female subjects had higher degree of angle of retroflection compared to male speakers (Kochetov et al. 2015). With reference to syllable structures, Hindi and Malayalam permit the occurrence of open and closed syllabic structures but Kannada permits only open syllables (Upadhyaya, 1972).

These above cited differences across languages become the motivational factor for the present study. Kannada and Malayalam are considered as they have been researched to some extent for the tongue contours using Ultrasound imaging in the recent past. Hence, it would be interesting to further explore the coarticulation characteristics in these two languages. Hindi is included as it falls in a different language family and is our national language.

Stop consonants are studied extensively especially using acoustical method in several languages of the world as they have very special acoustic properties compared to other consonants. In the current study, stop consonants excluding bilabials are considered as their tongue contours are easily identifiable in ultrasound imaging due to the complete articulatory closure. Other class of consonants such as fricatives, nasals and glides create artefacts due to partial contact with the palate which obscure the tongue images.

With respect to place of articulation, velar, retroflex and dental stops are studied since they are common in all the three languages and it will help to investigate the mechano-inertial properties of the articulatory apparatus. Bilabials are excluded considering the difficulty in tracing the lip movements in ultrasound imaging.

Three different vowel contexts i.e. /a/- low central vowel, /i/- high front vowel, /u/- high back vowel considered as these are the cardinal vowels produced with the tongue in extreme positions, front or back, high or low. Also these are the vowels common across the world's languages and hence serve for comparative studies.

The extent and systematicity of coarticulation has been difficult to gauge, given the relatively small group of participant or subject profiling of most previous studies. Similarly, methodological limitations have constrained the scope of previous research, which focused mainly on static characteristics of consonant and vowel production, with its spatial gesture aspects remaining poorly understood. Phonology and phonetic structure of Indian languages are distinct from other most studied languages. Coarticulation patterns are different across languages though they are from same language families (Choi & Keating, 1990; Embarki et al, 2007). Retroflex place of articulation is not present in other studied languages such as American English, Catalan, Spanish, Dutch, Russian, French, Swedish, Polish, Thai, German and British English. Also vowels /a/ and /u/ are tongue back vowels in these languages, whereas /a/ is a low central vowel in Indian languages. The only reported study of coarticulation in Indian language using ultrasound explained greater coarticulation for vowel /i/ than /u/ in Kannada (Kochetov & Sreedevi, 2013). However, there was no comparison with low central vowel /a/ and velar place of articulation was not included in their study. Also the speculation of coarticulation extracted directly from the tongue contour, not considered any quantification methods. Therefore, the present study intends to address the outstanding features discussed above by documenting the articulatory production in two language families i.e Dravidian (Kannada and Malayalam) and Indo-Aryan (Hindi) languages to understand some parameters of coarticulation within and across these languages.

Aim of the study

The study aimed to investigate the extent and direction of coarticulation and coarticulation resistance within the three languages i.e. Kannada and Malayalam (Dravidian languages) and Hindi (Indo-Aryan) and across the languages.

Objectives of the study

1. To investigate the effect of language on coarticulation across Kannada and Malayalam (Dravidian languages) and Hindi (Indo-Aryan)
2. To investigate the effect of spatial measures on coarticulation including:
    - Places of articulation (dental, retroflex and velar stop consonants)
    - Vowel contexts (/a/- low central vowel, /i/- high front vowel, /u/- high back vowel)
    - Voicing of consonants
3. To investigate the effect of gender on coarticulation

Hypothesis

1. There is no significant effect of language (Kannada, Malayalam and Hindi) on coarticulation
2. There is no significant effect of places of articulation on coarticulation
3. There is no significant effect of vowel contexts on coarticulation
4. There is no significant effect of voicing of consonants on coarticulation
5. There is no significant effect of gender on coarticulation

CHAPTER II- REVIEW OF LITERATURE

Speech rarely involves production of one sound in isolation, but rather is a continuous, dynamic sequencing of vocal tract movements produced in rapid succession. Though it might be convenient to consider phonemes as independent, invariant units that are simply linked together to produce speech, this simplistic approach does not really fit the facts. When phonemes are put together to form syllables, words, phrases and sentences, they interact in complex ways and sometimes appear to lose their separate identity. This influence that sounds exert on one another is called coarticulation, which means that the articulation of one sound is influenced by a preceding or following sound.

The term coarticulation dates back to 1930's, proposed by Menzerath and De Lacerda (1933) as koarticulation (synkinese), which explained that the articulators are prepared for the following sound during the production of preceding sound segment itself. The degree of coarticulation varies from phoneme to phoneme depending on the language spoken and/or articulatory characteristics. Researchers are exploring this area since 60's using different methods across different languages. Initially perceptual methods were employed followed by acoustic analysis in the later years. By 90's physiological methods were applied in the field of speech production. Majority of the studies have been carried out on non Indian languages: Mandarin, American English, Catalan, Spanish, Dutch, Russian, French, Swedish, Polish, Thai, German and British English; and Indian languages: Kannada, Malayalam, Hindi and Tamil. Though there were variations across methods of studies within and across languages, researchers tried to conclude coarticulation as language universal and/or language specific. Language universality explains that speech is a motor act; hence the articulators and articulatory gestures decide the amount of coarticulation. However language specificity needs to be addressed and speech cannot be isolated from language as speech is the verbal expression of language.

Language universality

Language universality explains the coarticulation properties of consonants across places of articulation. Researchers supporting this had articulatory dynamics or the physiological perspective as the basis. Chomsky and Halle (1968) explained that coarticulation occurs when two articulators are moving at the same time for different phonemes. Borden and Harris (1980) are of the same view and explained that it is more of a physiological consequence rather than the speech segment feature. Sharf and Ohde (1981) provided more detailed description by stating that, acoustically, coarticulation occurs due to modifications by certain contextual features on the spectral and temporal characteristics; and physiologically, the integration of neural commands to the speech musculature, timing and movement pattern of articulators and aerodynamic forces which results in spreading of features from one sound to another. Ladefoged (1993) reported that coarticulation happens because of the relative changes in the articulatory gestures, consequently leading to the acoustic target values of speech sounds. Kuhnert and Nolan (1999) defined coarticulation in a broad manner as the fact that a phonological segment is not realized identically in all environments, but often apparently varies to become more like an adjacent or nearby segment. It refers to the events in speech in which the vocal tract shows immediate changes which is appropriate for the production of different sounds at a given time.

Coarticulation is explained based on different parameters. The degree of influence of phonemes is discussed as extent of coarticulation. Many studies have reported that extent of coarticulation varied across consonants based on the articulatory properties (Fort, Martin & Peperkamp, 2015;

Lindblom, 1963; Repp & Mann, 1981; West, 1992). Using acoustic method, Sussman, Bessel, Dalston and Majors (1997) explained that the slope values were different across bilabial, alveolar, and velars, both in the preceding and following vowel contexts. Krull (1988) explored the locus equation slopes and *y* intercepts in a single Swedish speaker and reported a clear pattern of decreased y-intercept values from velar > dental > labial in VC context. Gibson and Ohde (2007) found the same pattern of coarticulation, i.e. /g/>/b/>/d/, even in young children below 2 years of age. Slope values of locus equation for velar and bilabial places of articulation were higher than coronal consonants in Yindjibarndi and Yanyuwa (Tabain & Butcher, 1999). Repp and Mann (1981) reported that velars had higher coarticulation than alveolar consonant in the context of /u/ with higher F_4 onset. On the other hand, greater coarticulation was reported for velars even in the context of vowel /i/ (Fowler & Brancazio, 2000; Fletcher, 2004). Sussman, Hoemke and Ahmed (1993) reported based on F_2 locus equation data that dentoalveolar had higher coarticulation than retroflex consonants in Urdu.

Similar to the extent of coarticulation, coarticulation resistance also is subjected to variation. In Standard Chinese, velars had weak coarticulation resistance. Dental and retroflex consonants strongly resisted the influence of neighbouring vowels not only in monosyllables but even in symmetrical $V_1\#C_2/\#C_2V_2$ and $V_1\#C_2V_2$ sequences (Li et al., 2012). Fowler and Brancazio (2000) also reported similarly with velars having low resistance in English. Zharkova (2007) reported that the tongue position changes for velar /k/ across the two vowel environments /a/ and /i/.

Two Australian languages followed the same trend with alveolar consonant displaying higher coarticulation than labials and dentals (Graetzer, 2007). Also, variation of coarticulation resistance (CR) for palatal and velar consonant was explained based on the fact that the production of palatal and velar consonants require the use of the tongue body in conflict with the production of vowels, thereby restricting coarticulation by adjacent vowels. This was observed in children even at 3 years, 5 years, and adult speakers of English (Karen et al. 1985). Lin et al (2013) explained that dentals have weak coarticulation with low tongue height and displacement than palatals in ‘Kaytetype’, another Australian language.

Coarticulatory variation across consonants have also been explained based on surrounding vowels (Blumstein & Stevens, 1979; Fowler & Brancazio, 2000; Gibson & Ohde, 2007; Haris, 1984; Hawkins & Slater, 1994; Hillenbrand & Clark, 2000; Magen, 1996; Ohala, 1993; Ohman, 1965; Recasens, 1984, 1985, 1986, 2012; Recasens et al, 1997; Rossato, Badin & Bouaouni, 2003; Sereno & Lieberman, 1987; Zharkova, 2007, 2008; Zharkova & Hewlett, 2009; Zharkova et al, 2011, 2012). Zharkova (2007) reported variation in the articulatory posture for the production of alveolar consonant /t/ in the context of vowels /a/ and /i/. The tongue root was more retracted in the /a/ context than in the /i/ context. The dorsum was lower in the /a/ context than in the /i/ context. The only portion in the two /t/ contours that overlapped was the front region of the tongue.

In majority of the studies, greater coarticulation resistance has been reported for vowel /i/ (Fowler & Brancazio, 2000; Hillenbrand, 2008; Iskarous, Fowler & Whalen, 2010; Ohman, 1965; Scobbie et al, 2014; Recasens, 1986; Zharkova, 2007; Zharkova & Hewlett, 2009). The same finding has been reported in English (Stevens & House, 1963), Dutch (Pols, 1977), Catalan (Recasens, 1986, Recasens & Rodriguez, 2016) and Scottish English (Zharkova, 2007). However, Yun (2005) explained that vowels /a/ and /u/ had higher coarticulation resistance than front vowel /i/ in Korean language. Similarly, Recasens and Rodriguez (2016) reported that CR was high for /a/ than /u/ in Catalan language.

Effect of voicing on coarticulation showed inconsistent findings. Voiced velar consonants are reported to have a higher peak velocity and larger amplitude (Lofquist & Gracco, 1994). In Swedish language, researchers attributed this to tongue trough variation (Engstrand, 1989; McAllister & Engstrand 1991; McAllister & Engstrand 1992; Modarresi et al. 2004) whereas in English, the reason attributed to magnitude of tongue displacement difference (Svirsky et al. 1997) both across /p/ and /b/. Australian English also showed similar trend of voicing effect based on the locus equation data, conversely no effect was reported in EPG data (Tabain, 2002).

Inconsistent reports are also available in the literature on the gender effect of coarticulation (Oh, 2010). Hazan and Simpson, (2000) reported that both males and females showed similar pattern of articulatory gestures for most of the tokens; discrepancy between gender can be because of the different degrees of stiffness of the articulators.

Language specificity

Language specificity is based on phonological or phonetic constraints of language. Researchers explain this phenomenon through studies across languages. As Manuel (1990) discussed, knowledge of all the characteristics of a language compose easiness of understanding of coarticulation of that language. Keating (1985) and Manuel (1990) discussed coarticulation as a segmental feature of language instead of articulatory dynamics. Keating (1990) proposed that coarticulation and other phonetic details are language specific and a language learner must learn all the phonetic details including coarticulation that are specific to a target language as well as to its phonological grammar. Manuel (1990) agreed with Keating's ideology and explained that phonetic contrast of a particular language can be the base for coarticulation.

Theories of coarticulation

There are two existing theoretical stances that might account for language differences in coarticulation. Manuel (1990) proposed that the degree of coarticulation is predictable from the phonological inventory of a given language. Perceptual constraint is applicable across all languages whereby speakers constrain variability in order to maintain perceptual distinctiveness among phonemes. Also provided evidence in support of this stance showing that languages with smaller phonemic inventories, in which there is less possibility of confusing phonetic contrasts, allow more coarticulatory variation than languages with a larger number of phonemes, where maximal coarticulation may confuse the distinctive properties of sounds (Beddor, Harnsberger & Lindemann, 2002; Choi & Keating, 1991; Cohn, 1988; Flemming, 1997; Lubker & Gay, 1982; Magen, 1984; Manuel & Krakow, 1984). However, coarticulatory variability is not determined solely by the perceptual distinctiveness constraint as applied to a given language. Manuel (1990) reported the presence of differences in vowel-to-vowel coarticulation even between two languages with the same number of vowels. He suggested that there are universal constraints on the minimum distinctiveness of different phonemes, but coarticulation resistance varies from phoneme to phoneme.

The second stance, proposed by Keating (1985, 1990), described coarticulation as language-specific. Since the language-specific phonetic facts of each language are specified in its grammar, it predicts that a language learner must learn all the phonetic details, including coarticulation, that are specific to a target language as well as its phonological grammar. According to this theory, language learners do not necessarily exploit any predictable relationship between inventory size and amount of coarticulation.

Keating (1985, 1990) and Manuel (1990) suggested that coarticulation is language specific rather than mechanic- inertial properties of articulators. Manuel (1990) predicts that coarticulation is more to do with the phonetic inventory of each language and it is similar in languages where parallel phonemic constraints are present. Though Keating (1985, 1990) agreed that coarticulation is language specific, but as more of phonotactics related.

Models of coarticulation

Models of coarticulation discussed in literature try to bridge the invariant units of representation in articulation and acoustics. In this section, models based on language rules and models concerning the articulatory dynamics related to the current study are discussed.

The 'window' model of coarticulation, elaborated by Keating (1985, 1990) accounts for both continuous changes in space and time observed in speech, and for intersegment and inter-language differences in coarticulation. For each articulatory or acoustic dimension, the feature value of each phoneme is associated with a range of values, called a window. Windows have their own duration and a width representing all possible physical values that a target can take, i.e. the range of variability within a target. The window width mainly depends on the output of the phonological component: if features are specified, the associated window will be narrow and allow little contextual variation; if features are left unspecified, their corresponding windows will be wide and allow large contextual variation. The exact width of a window is derived for each language from information on the maximum amount of contextual variability observed in speech. By allowing windows to vary continuously in width, the model can represent the phonologically unspecified segments that offer some resistance to coarticulation, i.e. they are associated with articulatory targets.

Manuel (1990) formulated a similar model based on the concept of constraints of language which can potentially value in understanding particular instances of coarticulatory behaviour.

According to this model, the movement from target to other sound is affected by the narrowness of the target spaces themselves. Extremely narrow targets do not allow variability in the movement from one target to the next to a greater extent, where as large targets allow various trajectories through a given space. Figure 1, depicts the narrowness of the target sound in a connected speech. The task is to start in circle A, move through circle B, and end up in circle C or D. When circle B is quite small, the trajectory from A to B is rather insensitive to the following target C or D. In contrast, when circle B is large, the trajectory from A to B is highly affected by the location of the following target, that is, C or D.

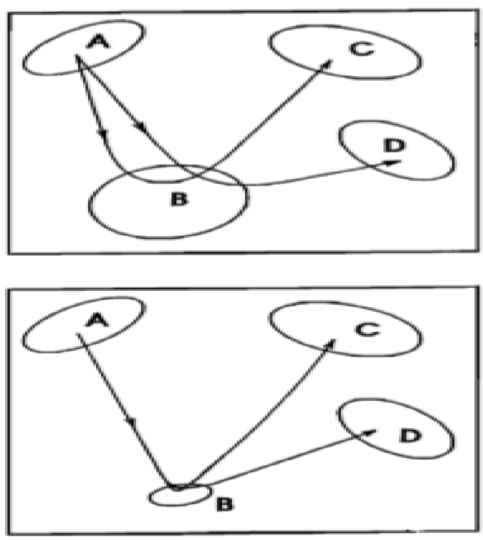


Figure 1. When the target B is large (Upper panel), the trajectory from A to B is affected by the location of the next target (C vs D). In contrast, when target B is small (lower panel), the trajectory from A to B is more restricted and it minimally influenced by the location of the next target (Manuel, 1990).

Kozhevnikov and Chistovich (1965) assumed that the range of forward coarticulation mirrors in direct fashion to the size of the programming unit of articulation. From recordings of speech movements in Russian subjects, they observed that gestures of lip protrusion for consonant clusters preceding rounded vowels began simultaneously with the first consonant in the sequence. Thus, using the schematic conventions introduced above, the forward coarticulation of lip protrusion assumed the following patterns, where C is a consonant and V is a rounded vowel. Kozhevnikov and Chistovich concluded that articulatory movements are organized in the form of syllables CV, CCV, CCCV, etc., that is, a syllable comprising any number of consonants followed by a vowel. The basic hypothesis generated by the Kozhevnikov-Chistovich theory is that the motor programming of speech is discontinuous at certain intervals, namely, following the production of any given vowel. That is, anticipatory adjustments are bounded by vowel segments, because consonants are programmed with the following vowel. After a vowel is encountered, a new programming unit begins.

On the other hand, Ohman (1966) considered VCV segments of coarticulation instead of CV and found that speech production in input V_1CV_2 utterances involve slow, steady movement of the tongue from vowel V_1 to vowel V_2 with superimposed articulatory gestures for the consonants. These consonant gestures coarticulated with vowels, depending on the degree of tongue involvement in their production.

Van der Merwe (1997) explained speech production in various stages. Linguistic-symbolic planning is the first stage where selection and sequencing of consonants and vowels are considered based on the phonotactics of a particular language. Second stage is motor planning, during which each utterance is specified as motor goal and each phoneme in an utterance is considered in terms of spatial and temporal features. This includes coarticulation, synchronization between articulators. Each motor plan is articulatory gesture specific and is vital for speech production. Third stage is motor programming with selection and sequencing of articulatory gestures for each motor plan. During this stage, muscle specific information "in terms of spatial-temporal and force dimensions such as muscle tone, rate, direction and range of movements" will be varied (Van der Merwe, 1997). Execution is the final stage where output of earlier stages is utilized as speech production at acoustical level.

Execution level of coarticulation is explained in other models also. Recasens, Palleres and Fontdevila (1997) proposed Degree of Articulatory Constraint (DAC) model to explain this property. The biomechanics of the lingual articulators may cause some displacement on other tongue regions. Thus the strength of the coupling effects between the tongue tip or the tongue blade and the tongue dorsum should increase with an increase in the retraction and the extent of the apicolaminal closure or constriction, for alveolopalatals versus alveolars and for laminoalveolars versus apicoalveolars. The formulation of the DAC is based on assumptions about the degree of involvement of the speech articulators in the formation of a closure or constriction based on information obtained from experimental production data, e.g., data on articulatory displacement and linguopalatal contact. The consonants and vowels are assigned with different DAC values depending on the degree of tongue dorsum constraint during their production. The DAC scale proceeds from a DAC minimum of 1 to a DAC maximum of 3. Based on this, assigned DAC scale, ranks are as follows /p, ə/ = 1; /n, a/= 2 and / i, k, s, l/= 3.

Further, Recasens research group explained this model in Catalan language based on different studies. Based on three speakers' recordings of Electromagnetic midsagittal articulometry, Recasens (2002) reported that there is greater tongue dorsum activation than tongue tip during the production of fricatives and liguopalatals which leads to greater coarticulation. Recasens (2012) explained that coarticulation varies across consonants and vowels in Catalan language and is inversely proportional to the differences in jaw height. Also, reported that "fricatives and high vowels are most resistant, and /n, l, k/ and the low vowel are least resistant". Recasens and

Rodriguez (2016) supported this model using ultrasound imaging technique, and explained that high front vowel /i/ had greater coarticulation resistance than other vowels /a/ and /u/.

Types of coarticulation

Coarticulation is majorly divided into two types based on the direction of coarticulatory effect: anticipatory (Right to left) and carryover (Left to right). Based on the component of articulatory system, coarticulation is classified as lingual, laryngeal, velopharyngeal and labial coarticulation.

a. Anticipatory coarticulation and carryover coarticulation

Coarticulation is majorly divided into two types based on the direction of coarticulatory effect: anticipatory (Right to left) and carryover (Left to right). Anticipatory coarticulation refers to the influence of a given sound segment on a preceding sound (Daniloff & Moll, 1968; Sereno & Lieberman, 1987). Physiologically, it is an adjustment of the vocal tract posture in anticipation of the next phoneme. It envisaged as cognitively controlled, intentional and large scale and is often viewed as reflecting pre-programming strategies. It is a small scale effect of mechanical and inertial force acting on the articulators. For example in the words “snoozed” and “sneezed” the contrast shows that the /sn/ cluster acquires lip rounding only if it is followed by a rounded vowel /u/ and is unrounded when followed by unrounded vowel /i/. This is the result of anticipatory coarticulation where the following vowel influences the preceding phonemes. In contrast, in carryover coarticulation, the feature of the preceding phoneme will spread to the following sound. For example in the word “me” vowel /i/ becomes nasalized because of the preceding nasal sound /m/.

Most studies on direction of coarticulation report of anticipatory coarticulation is more frequent than carryover coarticulation (German- Butcher & Weiher, 1976; French and Mandarian- Ma et al. 2016; Ndebele and Shona- Manuel, 1990; Swedish, American, and Russia- Ohman, 1966; Kannada- Kochetov et al. 2014; French- Ushijima & Hirose, 1974; Chinese- Wang & Huang, 2013; Scottish English - Zharkova & Hewlett, 2009). Similarly anticipatory coarticulation was observed in long term coarticulation (Kochetov & Neufeld, 2013; Recasens, 2002). However, there are reports which disagree with this directionality of coarticulation, and explain that carryover coarticulation is greater than anticipatory coarticulation (Bell-Berti & Harris, 1976; Fowler, 1981; Flege, 1988; Gay, 1977; Recasens, 1985; Rossato, Badin & Bouaouni, 2003). This discrepancy can be related to language effect as stated by Sharf and Ohde (1981) by reviewing 31 studies with 14 reporting anticipatory effects, 8 carryover coarticulation and 9 symmetrical effects.

b. Lingual coarticulation

Lingual coarticulation is important assince the tongue is a complex, mobile organ and plays a major role in the production of all vowel sounds and the majority of the consonants. The vowel and lingual consonant production involves activity of extrinsic and intrinsic tongue musculature to position and shape the tongue mass. The larger, slower extrinsic tongue musculature controls tongue positions for vowels. The joint behaviour of the extrinsic muscles and the faster, more complex and precise intrinsic muscle control of the tongue, help to produce consonants having different places and manner of production (Perkel, 1969). In lingual coarticulation the different areas of the tongue is modelled as being quasi independent of each other. Precisely tongue tip/ blade and tongue body can act quasi independently as two distinct articulators, so that their activity in the production of adjacent segments may overlay in time (Farnetani & Recasens, 2010). Coarticulatory sensitivity for a given lingual region depends not only on place and manner of articulation requirement but also on the mechanical restrictions such as flexibility and coupling with other lingual region (Recasens, 1989). The term coarticulatory resistance refers to the degree to which a given segment resists potential interference of neighbouring segments. It is inversely proportional to linguopalatal contact associated with lingual consonants and also to segments' degree of sonority (Lindblom, 1963). Lingual gestures can undergo both spatial and temporal variability during coarticulation.

Literature review reveals that front vowel /i/ shows maximum resistance of coarticulation since the tongue body becomes highly constrained when fronted and raised simultaneously. This has been reported in many languages such as American English (Stevens & House, 1963), Dutch (Pols, 1977) and Catalan (Recasens, 1985). Also, vowel /i/ shows decreased palatal contact especially when it is adjacent to velarized consonants (Russian: Kuznetsov & Ott, 1987) and pharyngealized consonants (Arabic: Yeou, 1995).

In the context of back vowel, the tongue body indicated considerable context-depended variability. Dentoavleolar and alveolopalatal consonants cause some raising and stretching of the tongue dorsum and blade (Recasens, 1991); velars cause considerable tongue postdorsum raising (MacNelage & DeClerk, 1969) in the context of back vowel /a/. Back vowels /u/ and /o/ influenced dental, alveolar, alveopalatal and palatal consonants due to tongue dorsum stretching, raising of the tongue tip and blade (Recasens, 1991).

Coarticulatory effects on the activity of primary articulators depend on articulatory flexibility, interarticulatory coordination, coupling and antagonism. Concerning dentoalveolar consonants, laminal fricatives (/s, z/) appear to be more resistant than apicals (/t, d, n, l/) (British English:

Bladon & Nolan 1977). In German, the degree of variability usually decreases in progression [n] > [l] > [d] > [t] > [s] (Hoole, Gfroerer & Tillmann 1990). Catalan Electropalatographic data reveal indeed lesser vowel coarticulation at the place of articulation for lingual fricatives than for [n] and [l]. The apicoalveolar tap [ɾ] is also highly sensitive to coarticulatory effects at the place of articulation (Japanese: Sudo, Kiritani & Yoshioka, 1982; Catalan: Recasens 1991).

Coarticulatory trends at the place of dentoalveolar articulation are often conditioned by tongue dorsum positioning. Closure location for English alveolar [t] may be fairly front when the tongue dorsum is lowered with adjacent [a] and more laminal and retracted when the tongue dorsum is raised with adjacent [i]; on the other hand, Italian apicodental [t] is highly resistant to such vowel-dependent coarticulatory effects, presumably because it is articulated further away from the tongue dorsum (Farnetani, Hardcastle & Marchal, 1989). Hindi retroflex stop /ʈ/ is produced at the alveolar zone in the context of back vowels and at the dentoalveolar zone in the context of [i], presumably because the curling back of the tongue front for the execution of the consonant is hard to reconcile with the simultaneous raising of the tongue dorsum (Dixit & Flege, 1991). Velar consonants are realized at the medio-postpalatal zone before [i] and other front vowels (Swedish: Ohman 1966; American English: Kent & Moll, 1972). In Catalan, the dorsal closure for [k] is more fronted when the consonant is adjacent to [i] than to [a] and [u]. According to data on Japanese VCV sequences (Wada et al. 1970), velars present as many places of articulation as constriction locations for the adjacent vowel. EMA data for German VCV sequences (Mooshammer & Hoole, 1993) reveal tongue dorsum movement towards the medio-postpalatal zone during the velar stop closure period even when [i] is absent.

The magnitude and extent of the vowel-dependent effects in VCV sequences is related to the tongue body demands for the production of the adjacent and distant phonetic segments. The onset of vowel-dependent coarticulation appears to vary inversely with the degree of tongue dorsum constraint for the immediately preceding consonant. Researchers invoking a C-to-V mode of coarticulation have reported a longer delay in the onset of vowel-related tongue dorsum activity with the degree of tongue dorsum involvement for the preceding consonant (for [k] > [t] > [p]) (Recasens, 1999).

With respect to directionality in ligual coarticulation, literature shows two distinct stances across places of articulation. Predominance of vowel-dependent carryover effects in some of the consonants such as bilabials (Manuel & Krakow, 1984), dentoalveolar stops (Bell-Berti & Harris, 1976), alveolar taps and flaps and non velarized [l] (Recasens, 1991; Farnetani 1990). Other studies indicate that the vowel-dependent anticipatory component may prevail upon the vowel-dependent carryover component. Consistently with this view, Hoole, Gfroerer and Tillmann (1990) have shown that anticipatory effects may be larger than carryover effects at a more flexible point of articulator such as tongue front; moreover, a decrease in tongue dorsum involvement may cause an increase in vowel-dependent anticipatory coarticulation (for labials > dentoalveolars > velars), and larger anticipatory than carryover effects (labials in German: Hoole, Gfoerer & Tillmann 1990; labials and dentoalveolars in English: Magen, 1997).

Methods to analyse coarticulation

There are attempts to investigate the language universality and language specificity of coarticulation. Perceptual, acoustical and physiological methods are used to study coarticulation. Physiological studies are conducted to measure the coarticulatory pattern of different articulators. It provides more direct information of articulatory segmental overlap.

Carney and Moll (1971) analysed cinefluorographic films which indicated the position of the articulators during the production of the voiceless labiodental fricative consonant /f/. There is essentially no variation in the tongue-tip position; however the positions of tongue-body and tongue-root tend to shift towards articulatory positions appropriate for the particular vowel followed to be. That is, the tongue body is higher in the high vowel and the tongue-root is more anterior in the high front vowel environment /i/.

Parush, Ostry and Munhall (1983) assessed intra-articulator anticipatory and carryover coarticulation in both temporal and spatial terms. Three subjects produced VCV sequences with velar stop consonants and back vowels. Pulsed ultrasound was used to examine the vertical displacement, duration, and maximum velocity of the tongue dorsum raising (VC transition) and lowering (CV transition) gestures. Anticipatory coarticulation was primarily temporal for two subjects, with decreases in the duration of the VC transition accompanying increases in displacement for the CV transition. Carryover coarticulation was primarily spatial for all three subjects, with decrease in CV displacement and maximum velocity accompanying increase in VC displacement. It is suggested that these intra-articulator patterns can be accounted in terms of an interaction between the raising gesture and a vowel specific onset time of the lowering gesture towards the vowel.

Parush and Ostry (1993) identified that the final vowel in VCV sequences affected the kinematic characteristics of the initial VC transition. Both amplitude and duration of the movement between the initial vowel and the consonant were greater when the final vowel was /u/ rather than /a/. Similarly, the initial vowel affected the kinematic characteristics of the final CV transition.

Zharkova is a pioneer researcher in the field of coarticulation, who conducted several significant researches especially using ultrasound imaging technique. Zharkova (2007) reported significant vowel influence on all intervocalic consonants including lingual and non-lingual consonants. The vocalic influence on the consonants was significantly greater than the consonantal influence on the vowels. Non-lingual consonants exhibited varying coarticulatory patterns. Zharkova, Hewlett and Hardcastle (2009) compared children and adults coarticulation patterns of alveolar /t/ in three different vowel context in Standard Scottish English. The ultrasound data showed significantly greater amount of anticipatory lingual coarticulation in children than in adults. Within speaker variability was also significantly greater in children than in adults.

Zharkova (2008) compared techniques, ultrasound and EPG for analysing vowel-consonant coarticulatory effects. Four speakers of Scottish English produced /VC/ sequences with the consonants /p, f, t, s, l, r, k/ and the vowels /a, i/. The difference between each consonant in the two vowel contexts was computed using an EPG measure and an ultrasound measure. A significant positive correlation was observed between the two measures, with labial consonants, followed by /r/, having the highest values. The two techniques also provided complementary data on lingual coarticulation. The velar stop was more coarticulated on the EPG measure than on the ultrasound measure, because EPG registered a shift in closure location across vowel contexts, while ultrasound captured the close proximity of the tongue root across the vowel contexts. The sibilant was more coarticulated on the ultrasound measure than on the EPG measure, because ultrasound, unlike EPG, registered vowel-dependent difference in the tongue root. Combined EPG and ultrasound data would be useful in future studies of coarticulation. The positive correlation between temporal and spatial measures of lingual coarticulation suggests that the motion of the tongue region responsible for creating a constriction/closure towards the consonant target tends to start earlier in the consonants which are less affected by the preceding vowel.

Zharkova and Hewlett (2009) measured the lingual coarticulation from midsagittal tongue contour for two English phoneme /t/ and /a/. The tongue surface outline for /t/ in /ata/ was compared with /t/ in /iti/ and for /a/ in /aka/ was compared with those in /ata/. The results showed that the tongue contour during /t/ adapts to the influence of neighbouring vowels approximately three times more than the tongue contour for /a/ adapting to the influence of neighbouring consonants. Thus, the phoneme /t/ is more susceptible for coarticulation than /a/. This study also measured the coarticulatory effect of consonant on the first and second vowels. Results claimed that coarticulation within a CV syllable is stronger than coarticulation within VC sequence whose segments are separated by a syllable boundary. Davidson (2007) examined Russian stop-stop #CC, C#C, and #CəC using ultrasound imaging. The tongue shape trajectories suggested that, C#C and #CC coarticulation timing are not interchangeable. In some cases, native Russian #CC articulation is more similar to #CəC than to C#C, suggesting that learning timing and coarticulation of these sequences may be a challenge for L_2 acquisition.

Similarly, Yun (2008) conducted a study to explore vowel-to-vowel coarticulation patterns involving the environment of vowel assimilation in Korean language. Results showed that anticipatory coarticulatory effects occur and vowel assimilation is truly phonological and the degree of coarticulation is stronger in assimilated words than in non-assimilated words. These results imply that phonological rules might directly influence coarticulation in a phonology-phonetics unified grammar.

Combined of different methods to study coarticulation

a) Acoustical vs Physiological studies

Tabain (2002) investigated coarticulation of stop consonants /t, k/ and fricatives /θ, s, E/. The slope value of locus equation, indicating degree of coarticulation in the CV syllable, was compared with EPG data on coarticulation. It was observed that, overall; there was a very poor correlation between locus equation and EPG data as regards with coarticulation. It was also shown that more accurate locus equation results in terms of their correlation with EPG data were obtained for stop consonants when F_2 onset was sampled at stop release, rather than at the onset of voicing for the vowel. While comparing the voiceless consonants with their homorganic voiced counterparts, results revealed no significant difference between voiced and voiceless consonants in the EPG data, but there was a significant difference in the locus equation data. These results suggest that locus equations cannot provide invariant cues for stop and fricative place of articulation across the voiced-voiceless distinction.

Noiray, Menard and Iskarous (2013) focused on differences in lingual coarticulation between French children and adults. The specific question pursued was whether 4–5 year old children have already acquired a synergy observed in adults in which the tongue back helps the tip in forming alveolar consonants. Locus equations, estimated from acoustic and ultrasound imaging data were used to compare degree of coarticulation between adults and children and further investigate differences in motor synergy between front and back region of the tongue. Results show similar slope and intercept patterns for adults and children in both acoustic and articulatory domains, with an effect of place of articulation in both groups between alveolar and non-alveolar consonants.

b) Perceptual, Acoustical versus Physiological studies

Katz, Kripke and Tallal (1991) investigated anticipatory lingual and labial coarticulation in [sV] productions of children and adults. Acoustic, perceptual and video data were used to trace the development of intra syllabic coarticulation in speech of adults and children. Children show greater variability in their articulatory patterns than adults. The acoustic and video data suggested that young children and adults produce similar patterns of anticipatory coarticulation, and the perceptual data indicated that coarticulatory cues in the speech of 3-year-old children are less perceptible than those of other age groups.

Indian studies on coarticulation

In the Indian context studies on coarticulation patterns using acoustical and physiological procedure have been carried out. Perumal (1993) analysed the developmental trends of coarticulation in Kannada speaking children and reported no specific developmental pattern for any of the parameters like transition duration, terminal frequency, and extent of transition and speed of transition. Jayaradha (2001) study on coarticulation in Kannada speaking hearing impaired children and reported that hearing impaired speakers have difficulty in producing vowel /i/, as it is difficult to visualize the movement of articulators. Labial coarticulation in Malayalam speaking adults and results showed that anticipatory coarticulation was stronger than carryover coarticulation (Mili, 2003).

Banumathy and Manjula (2005) studied coarticulation in propositional and non-propositional speech. Propositional speech involves more of semantic processing and non-propositional speech involves a phonological processing. Results showed that both significantly differed in terms of coarticulatory features of preceding vowel duration, closure duration and preceding vowel transition duration. They concluded that articulatory movements from one sound to another is greater for propositional speech as it requires a voluntary and conscious thought process in comparison to a less voluntary effort in non-propositional speech.

Sreedevi, Smitha, Irfana and Nimisha (2012) studied coarticulation in hearing impaired population using F_2 locus equation which showed variation across hearing aid users, cochlear implantees and normal controls among places of articulation. Velars showed higher degree of coarticulation, whereas bilabials and dentals showed weaker coarticulation effect. Control group participants articulated more effectively and were highly positively correlated with the F_2 locus equation measures. Among children with hearing impairment, as expected, the hearing aid users showed comparatively poorer performance than cochlear implantees particularly for velar coarticulation.

Sreedevi, Irfana and Alphonsa (2013) used locus equation as a metric to describe coarticulation patterns in voiced stop CV productions of children aged 12-24 months. Results indicated that velars had maximum coarticulation followed by bilabial and dental places of articulation. Vowel in CV syllables moderately influenced velar /g/ and bilabial /b/ and with a minimal vowel influence for dental /d/. Also, voiced velar stop revealed moderate goodness of fit around the regression line followed by voiced bilabial and dental stops. Dutta and Redmon (2013) explained that alveolars have stronger coarticulation resistance than retroflex followed by dental consonant in Malayalam. Another study using locus equation in Kannada reported that coarticulation varied across places of articulation but not as a function of age on comparison across different age groups of children within six years and others (Sreedevi, Vasanthalakshmi & Sushma, 2014).

Based on the findings, low central vowel /a/ had maximum extent of coarticulation than vowel /i/ and retroflex /ḍ/ had greater coarticulation resistance than velar /g/.

Kochetov and Sreedevi (2014) investigated effects of vowel context on the articulation of geminate retroflex, dental and labial stops based on ultrasound tongue imaging data from Kannada speakers. The results revealed consistent fronting/backing of the tongue in the high front /i-i/ and high back /u-u/ context respectively. The magnitude of the coarticulatory effect was much greater for the labial followed by retroflex and dental places of articulation.

In summary, studies of coarticulation in a number of languages have revealed a set of properties that distinguish various places of articulation across vowel contexts. The studies also showed a wide variation in the degree of coarticulation across and within languages. It is difficult to conclude the amount and systematicity of this variation, because of the differences in methodological procedures and subject profiling of most previous studies. Extensive cross language studies similar to the present investigation, using a physiological method considering different places of articulation in different vowel contexts are not exist in literature. Therefore the current study is intended to address the objective outlined above by exploring the speech production of two Dravidian languages (Kannada and Malayalam) and Hindi an Indo Aryan language.

CHAPTER III- METHOD

The study was conducted with the aim to investigate the extent and direction of coarticulation and coarticulation resistance within the languages i.e. Kannada and Malayalam (Dravidian languages) and Hindi (Indo-Aryan) and across these three languages.

Participants: A total of 90 adults in the age range of 20-30 years served as participants in the study. These included native speakers of Kannada, Malayalam and Hindi and each language group included 30 participants comprising of equal number of males and females. It was ensured that the subjects have a normal oro-motor mechanism and was free of any speech, language, hearing, neurological and cognitive impediments. A check list for sensory motor examination of tongue was adapted from Johnson- Root (2015) to rule out any sensory motor deficits of the tongue in participants (Appendix I). The study was approved by All India Institute of Speech and Hearing Ethical Committee based on the ethical guidelines for bio-behavioural research involving human subjects.

Material: The test material consisted of VCV sequences with C corresponding to geminate forms of voiced and unvoiced counterparts of dental (/t̪/, /d̪/), retroflex (/ʈ/, /ɖ/) and velar stops (/k/, /g/). Likewise, the vowels in the VCV stimulus form were in symmetrical environment (both vowels same), high front vowel /i/, low central vowel /a/ or high back vowel /u/. Table 2.1 shows the test items. The stimulus prepared were non-words and was used commonly for the three languages considered to control variability as they were intended to test the coarticulation effects. It was highly improbable to decide on common words meaningful in all the three languages.

Consonants in three different places of articulation were incorporated to quantify the coarticulation effects across places of articulation. The material included both voiced and unvoiced stop consonants to investigate the effect of voicing on coarticulation. The three corner vowels /a/, /i/, /u/ allowed for testing diverging tongue positions. The test VCV sequences were embedded in a short carrier phrase in the respective language (Now I will say “VCV”).

Table 2.1.

Stimuli list of V_1CV_2 sequences with consonant in 3 places of articulation in the context of vowel V_1 and V_2 (/a, i, u/)

Vowels	Places of articulation					
	Dental		Retroflex		Velar	
	Voiced	**Unvoiced**	**Voiced**	**Unvoiced**	**Voiced**	**Unvoiced**
Low	/ad̪d̪a/	/at̪t̪a/	/aɖɖa/	/aʈʈa/	/agga/	/akka/
High front	/id̪d̪i/	/it̪t̪i/	/iɖɖi/	/iʈʈi/	/iggi/	/ikki/
High back	/ud̪d̪u/	/ut̪t̪u/	/uɖɖu/	/uʈʈu/	/uggu/	/ukku/

Principle and instrumentation: An ultrasound instrument works on the reflective principle of sound waves. When a pulse of acoustic energy is directed at an object with suitable conductivity, it puts the object into oscillation and elicits echoes. In ultrasound tongue imaging technique, when the sound wave travels upward from the probe through the tongue body, it is reflected downward from the upper tongue surface. The upper tongue surface interface is typically with the palate bone and airway, both of which have very different densities from the tongue and cause a strong echo. When the signal passes through air or bone, the sound wave is lost and no echo is passed back to the transducer because the conductivity for the sound is either too low (bone) or too high (air) (Bressmann, Ackloo, Heng & Irish, 2007). This resultant absence of echo leads to the formation of ultrasound tongue image.

In the present study, the instrument Mindray Ultrasound 6600 was used to obtain the ultrasound tongue images and the software Articulate Assistant Advanced (AAA) ultrasound module

Version 2.14 (Articulate Instrument, 2012) was used for the analysis with 60 frames per second. The instrument was synchronized to the audio input with a sample rate of 22,050 Hz. Hardware pulse generated a tone frequency of 1000 Hz with a beep length of 50 ms for an accurate synchronisation. Some of the parameters of Mindray Ultrasound 6600 were set as shown below:

i) Edge enhancement was set for 3

ii) Noise restriction of zero

iii) Smooth and soften of image functions was set as 2

These default settings helped to suppress the tongue image noise. The transducer, a long-handled microconvex probe, operating at 6.5 MHz, was placed beneath the chin of the participant with the support of stabilization headset (Articulate instrument, 2010). Each ultrasound frame was stored by AAA system as a set of raw echo-pulse with a depth of 7 mm, facilitating a standard two dimensional image. The instrument setup used is shown in Figure 2.1.

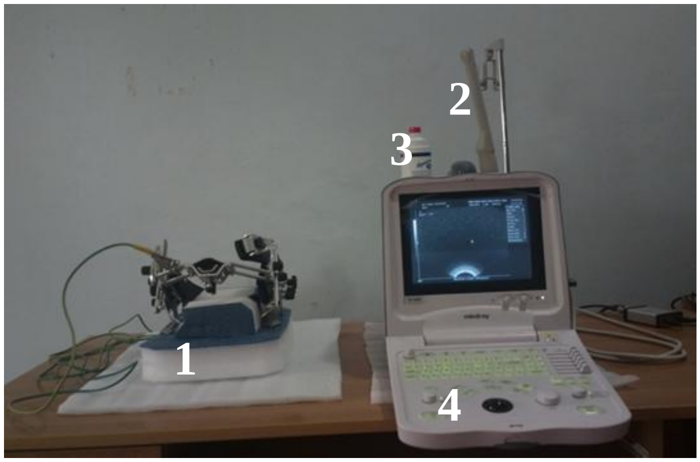
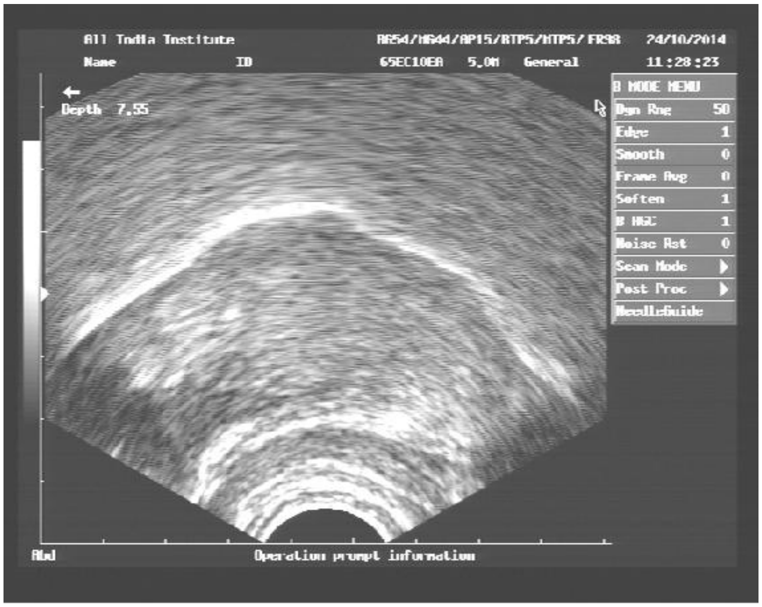


Figure 2.1: Shows instrument setup: 1. Stabilization headset, 2. Transducer probe, 3. Conduction gel, and 4. Ultrasound instrument (Note. Instrument in the Phonology Lab, Department of Speech Language Sciences, All India Institute of Speech and Hearing, Mysore).

The ultrasound imaging system provides three modes of recording including Amplitude (A-Mode), Motion (M-Mode) and brightness (B-Mode). Present study considered B-Mode since it has wide gray scale which helps to visualize even very small differences in echogenicity in the borders between different structures including cartilage, bone and layers of tongue tissue. Grey scale depicts the density of the tissue where the solid areas are depicted in 'white' and the fluid areas in 'black'. The interface between the tongue and the air is visible as a bright white band. Figure 2.2 depicts the midsagittal 2D ultrasound image of vowel /a/. The midsagittal plane is preferentially used in ultrasound imaging as the image is most intuitive and can be compared across different speakers.



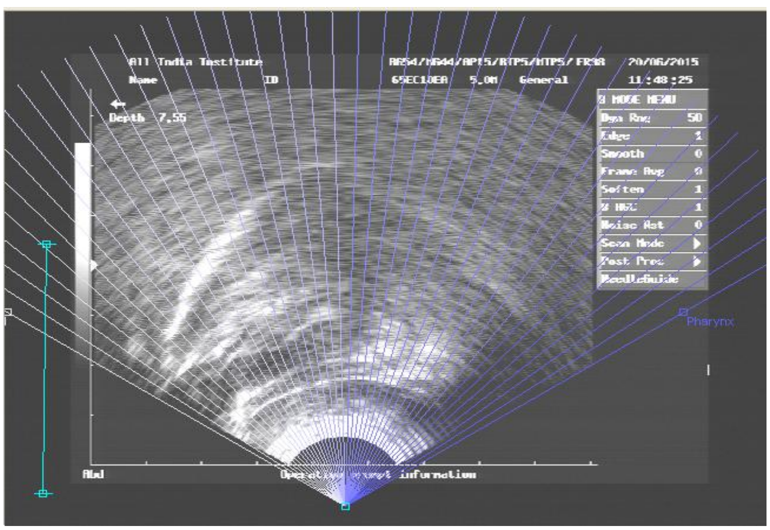
X axis – Tongue advancement, Y axis – Tongue height

Figure 2.2. Midsagittal 2D image of vowel /a/. The anterior tongue is towards the right side. (Note: Tongue image in Articulate Assistant Advanced, Phonology Lab, Department of Speech Language Sciences, All India Institute of Speech and Hearing, Mysore).

Data collection: Individual participants were made to sit comfortably on a high back chair. They were briefed on the test procedure before the recording and were asked to sip water before the recording to moisturize the oral cavity for better ultrasound images. The transducer probe placed beneath the chin was smeared with ultrasound transmission gel (*Aquasonic 100*) for superior tongue imaging. The probe was fastened by stabilization headset (*Articulate Assistant Advanced*) to reduce the artefacts caused by head movements. For recording the speech sample, a multimedia microphone (*iball i 333)* was used. Stimulus list was presented visually on the computer screen to one participant at a time and 10 repetitions of each prompt were recorded. Tokens were selected only after perceptual confirmation for further analysis. A total of 180 utterances were recorded for each participant that included ten repetitions of 18 target samples (3 vowel contexts (V_1CV_2) x 6 consonants including voiced and unvoiced counterparts of 3 places of articulation = 18 x 10 repetitions = 180). A total of 5400 utterances (30 participants x 180 =

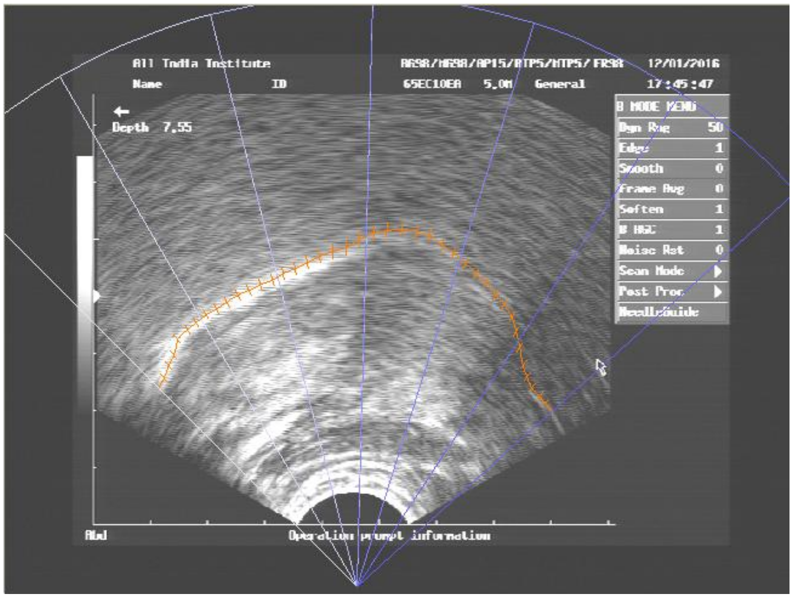
5400) were recorded for each language group. A grand total of 16, 200 utterances (30 x 3 = 90 participants x 180 = 16200) were analysed for the study.

Data Analysis: For analysis, the software AAA was used with a technique 'fan spline' which had 42 axes or points. Figure 2.3 depicts 42 fan splines embedded on a tongue contour image of vowel /a/. Splines are curves defined by a mathematical function that are constrained to pass through specified points. Fan spline setups were decided for each place of articulation and used respectively. For dental and retroflex sounds, the fan spline had to be set more anteriorly, and for velars, more towards the posterior region. Semiautomatic contour plotting of midsagittal view was used in this study.



X axis – Tongue advancement, Y axis – Tongue height

Figure 2.3. 42 fan splines (white) embedded on a tongue contour image. The anterior tongue is towards the right side.



X axis – Tongue advancement, Y axis – Tongue height

Figure 2.4. Tongue contour based on the 42 fan splines. The anterior tongue is towards the right side.

Plotted contours were exported to the workspace to measure the following parameters considered in the study:

2.1. Extent of coarticulation (EC) and direction of coarticulation

2.2. Coarticulation resistance (CR)

  2.2.1. Coarticulation resistance of consonants (CRC)

  2.2.2. Coarticulation resistance of preceding vowel (CRPV)

  2.2.3. Coarticulation resistance of following vowel (CRFV)

2.1. Extent of coarticulation (EC) and direction of coarticulation

Extent of coarticulation (EC) is the amount of influence of one phoneme on a neighbouring phoneme. To find the EC of one token, tongue contour of each repetition of each phoneme was plotted. An average tongue contour representing 10 repetitions was obtained for each phoneme in workspace to minimize the variation. Averaged consonant (C) spline and V_1/V_2 spline were considered as an analysis pair. These pairs of mean and standard deviation splines were further evaluated using the function “Diff”. This function “Diff” works based on 2 tailed t-test using the Welch- Satterthwaite equation which is inbuilt in the AAA software. This helps to compare two mean splines and provides Root Mean Square (RMS) distance. The resulting RMS distance value is designated as extent of coarticulation (EC) as it is the distance between the analysis pair (V-C or C-V distance). Hence, extent of coarticulation is the distance between the two consecutive mean tongue contours which indicates the degree of influence of one phoneme on the other.

For example, in the token /akka/, to measure EC between /a_1/ to /k/, the distance between the mean tongue contours of /a_1/ and /k/ needs to be calculated. It requires plotting of the tongue contours of each repetition of the vowel and consonant and find the averages separately. This provides two mean tongue contours; one is for consonant /k/ another for vowel /a/. Finally the function “Diff” as mentioned in previous paragraph provides the distance between these two mean tongue contours and provides RMS distance.

The RMS distance value is indirectly proportional to the magnitude of coarticulation. When the RMS distance between two phonemes is more, it indicates less coarticulation and, on the contrary, less RMS distance signifies greater coarticulation. Also, the direction of coarticulation is inferred based on the RMS value of preceding and following vowels. Here, the effect of consonant is ignored with the assumption of vowel dependent coarticulation in VCV syllable. For example: in the word /$a_1$kka_2/, if the RMS distance between /a_1/ to /k/ is more than the RMS distance of /a_2/ to /k/, it was indicative of anticipatory coarticulation. Carryover coarticulation is inferred when the RMS distance of /a_1/ to /k/ is less than the RMS distance of /a_2/ to /k/.

RMS distance of /a_1/ $\longrightarrow$ /k/ = X

RMS distance of /a_2/ $\longrightarrow$ /k/ = Y

If X < Y = Carryover coarticulation

If X > Y = Anticipatory coarticulation

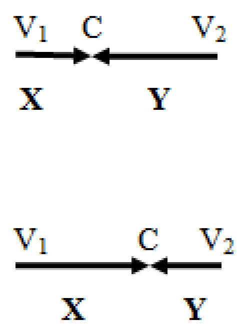


Figure 2.5. Schematic representation of the direction of coarticulation based on the extent of coarticulation.

2.2. Coarticulation resistance

Coarticulation resistance (CR) is the measure of resistance of a phoneme against the influence offered by the neighbouring phonemes; in other words the ability of a phoneme to retain its own identity. In case of a VCV syllabic structure, it is possible to find coarticulation resistance of consonant (CRC) and coarticulation resistance of the preceding and following vowels (CRV). CRC is the ability of a consonant to restrict the coarticulation effect of the preceding and/or the following vowel. CRV is the capacity of the vowel to maintain its own characteristics. Coarticulation resistance was calculated using the formulae given by Zharkova (2007) for both consonants and vowels.

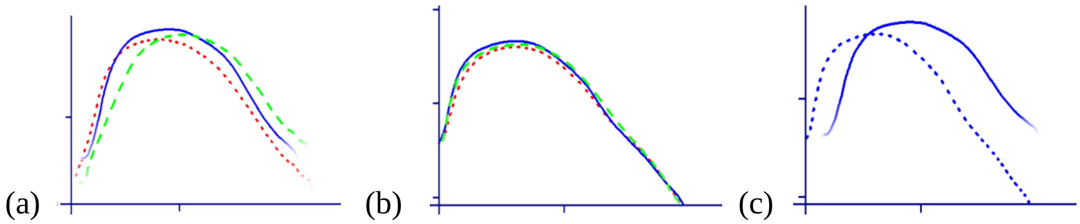
2.2.1. Coarticulation resistance of consonants (CRC)

Coarticulation resistance of consonants (CRC) is the ability of a consonant to restrict the coarticulatory effect of the preceding and/or the following vowel. CRC represents CR of consonants in relation to the surrounding vowels (Zharkova, 2007). It is measured in relation to different vowels in separate VCV sequences. For example, in order to obtain CR of the consonant /k/, we need to consider /k/ in at least two different vowel contexts such as /akka/ and /ikki/. Similarly there are two more other combinations, /akka/ - /ukku/, /ikki/- /ukku/. Hence CR of /k/ is calculated under three circumstances including (/a/-/i/), (/a/-/u/) and (/i/-/u/) as shown in Table 2.2. For each such combination, four RMS distances which includes preceding vowel to consonant and following vowel to consonant, needs to be calculated. Taking the example of /akka/ and /ikki/, the required RMS distances for CR of /k/ are /a_1/-/k/, /k/-/a_2/, /i_1/-/k/ and /k/-/i_2/ [Figure 2.6 (a & b)]. Also, the RMS distance between the mean tongue contour of /k/ in /a/ context and /k/ in /i/ context needs to be calculated [Figure 2.6 (c)]. Similar to /k/, three combinations each are considered for other target consonants and respective RMS distances are measured.

Table. 2.2.

Sample of the tokens and analysis pair for consonant /k/

Token	Analysis Pair	Analysis pair
CRC k(a, i)	a-k; k-a	i-k; k-i
CRC k(a, u)	a-k; k-a	u-k; k-u
CRC k(i, u)	i-k; k-i	u-k; k-u



X axis – Tongue advancement, Y axis – Tongue height

Figure 2.6. (a) Tongue contours of /akka/. (b) Tongue contours of /ikki/. Preceding vowel is indicated as red dotted line, consonant as blue solid line and the following vowel as green dashed line. (c) Tongue contours of consonant /k/ in two vowel environments: blue solid line - in the context of /a/; blue dotted line - in the context of /i/. The anterior tongue is towards the right side.

The RMS distances from the consonant to its surrounding vowels (V_1-C and V_2-C) are proportionate to the degree of CR of the consonant, i.e., the degree to which C retains its identity in a VCV sequence. The V_1-C and the V_2-C RMS distances were computed for each of the tokens. CRC is calculated using the formula given by Zharkova (2007) as follows:

$$CRC_{C\,(V1,\,V2)} = \frac{(C\text{-}V)}{(C_{V1} - C_{V2})}$$

In the above equation, the numerator "C-V" indicates the averaged value of RMS of both contexts (as seen in Table 2.2, first row: average of a-k, k-a, i-k, k-i). The denominator (Cv_1 – Cv_2) was obtained as RMS distance between tongue contour of C in the context of /a/ to the tongue contour of C in the context of /i/ [example: Tongue contour of /k/ in the context of /a/ (/akka/) - Tongue contour of /k/ in the context of /i/ (/ikki/, (Figure 2.6, c)]

2.2.2. Coarticulation resistance of preceding vowel (CRPV)

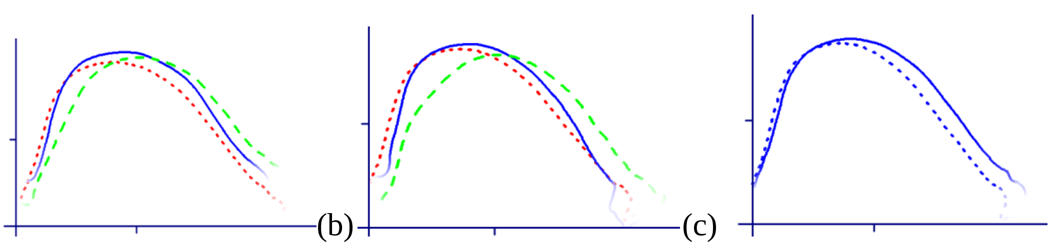
Coarticulation resistance of preceding vowel (CRPV) is the ability of the preceding vowel to maintain its own characteristics and resist the influence of the following neighbouring consonant (Zharkova, 2007). For example, to calculate CR of the preceding vowel /a/, need to consider at least two different consonant contexts such as /akka/ and /agga/. For this, RMS distances of the preceding vowel to consonant are considered for further analysis. As seen in Table 2.3, there are 3 varieties of tokens for vowel /a/. It is possible to take all feasible combinations of consonants, but the present study considered only voiced and unvoiced counterparts of each place of articulation to control the variability. For example, the required RMS distances to calculate CR of vowel /a_1/ are /a_1/-/k/ and /a_1/-/g/ [Figure 2.7 (a & b)] along with the distance between mean tongue contour of preceding vowel /a/ sequencing with /k/ and /a/ sequencing with /g/ [Figure 2.7 (c)].

Table. 2.3.

Sample of the tokens and analysis pair of preceding vowel /a/

Token	Analysis pair	Analysis pair
CRPV a_1(t̪, d̪)	a_1-t̪	a_1-d̪
CRPV a_1(ʈ, ɖ)	a_1-ʈ	a_1-ɖ
CRPV a_1(k, g)	a_1-k	a_1-g

(a) (b) (c)



X axis – Tongue advancement, Y axis – Tongue height.

Figure 2.7. (a) Tongue contours of /akka/. (b) Tongue contours of /agga/. Preceding vowel indicated as red dotted line, consonant as blue solid line and following vowel as green dashed line. (c) Tongue contours of vowel /a/ in two consonant environments: blue solid line – in the context of /k/; blue dotted line – in the context of /g/. The anterior tongue is towards the right side.

The RMS distances from the vowel to the neighbouring consonant (V_1-C and V_2-C) are proportionate to the degree of CR of the vowel, i.e., the degree to which V retains its identity in a

VCV sequence. The V_1-C and the V_2-C RMS distances are computed for each of the tokens. CRPV is calculated using the following formula given by Zharkova (2007).

$$CRPV_{V (C1, C2)} = \frac{(V- C)}{(V_{C1} – V_{C2})}$$

The numerator of the above equation, “V-C” indicates the averaged value of RMS of both contexts (as seen in Table 2.3, first row: average of a_1-k, a_1-g). The denominator (V_{C1}-V_{C2}) is obtained as RMS distance between the mean tongue contour of V in the context of C_1 to the mean tongue contour V in the context of C_2 [Example: tongue contour of /a_1/ in the context of /k/ (/akka/) - Tongue contour of /a_1/ in the context of /g/ (/agga/) (Figure 2.7, c)].

2.2.3. Coarticulation resistance of following vowel (CRFV)

Coarticulation resistance of the following vowel (CRFV) is the ability of the following vowel to maintain its own characteristics and resist the influence of preceding neighbouring consonants. Coarticulation Resistance of the Following Vowel (CRFV) is representing CR of vowel in relation to the neighbouring consonant (Zharkova, 2007). As seen in the above section (section 2.2.2), to calculate CR of the following vowel /a/, two different consonant contexts such as /akka/ and /agga/ are considered and RMS distances of following vowels to consonant are calculated for further analysis. There were 3 varieties of tokens for each following vowel and Table 2.4 depicts the tokens of following vowel /a/.

Table. 2.4.

Sample of the tokens and analysis pair of following vowel /a/

Token	Analysis pair	Analysis pair
CRFV a_2(t̪, d̪)	a_2-t̪	a_2-d̪
CRFV a_2(ʈ, ɖ)	a_2-ʈ	a_2-ɖ
CRFV a_2(k, g)	a_2-k	a_2-g

The analysis procedure is same as in the above described format and CRFV is measured by using the formula given by Zharkova (2007) as follows:

$$CRFV_{V(C1, C2)} = \frac{(V-C)}{(V_{C1} - V_{C2})}$$

"V-C" indicates the averaged value of RMS of both contexts (as seen in Table 2.4, first row: average of a_2-k, a_2-g). (Vc_1-Vc_2) was obtained as RMS distance between the mean tongue contour of V in the context of C_1 to the mean tongue contour V in the context of C_2 [Example: tongue contour of /a_2/ in the context of /k/ (/akka/) - Tongue contour of /a_2/ in the context of /g/ (/agga/)].

Inter judge reliability: 10% of the data was subjected to inter judge reliability. Two speech language pathologists were trained in the analysis of tongue contours using ultrasound imaging and they served as judges for reliability. Judges queries were clarified during the analysis. Cronbach alpha reliability index for inter judge reliability was 0.99.

Intra-judge Reliability: A randomly selected 20% of the data of tongue images i.e. for 6 subjects in each language the images were re-plotted by the investigator. Cronbach alpha reliability index of 0.99 was obtained for intra judge reliability.

Statistical analysis

Main category of dependent variables were extent of coarticulation, coarticulation resistance of consonants, coarticulation resistance of preceding vowel and coarticulation resistance of following vowel. Language was considered as the independent variable. Gender was not considered as a variable for statistical analysis except for hypothesis of gender effect since there was limited variation across gender for most of the parameters. Shapiro- Wilk test was administered to verify normality and data did not follow normality for most of the dependent variables except coarticulation resistance of preceding vowel in dental and velar contexts, and following vowel in retroflex context in Malayalam. Nonparametric tests including Friedman test, Wilcoxon signed rank test, Kruskal- Wallis H test, and Mann Whitney U test were administered based on the conditions. In this study, adjustment of multiple comparisons for Wilcoxon signed ranks test and Mann Whitney U test were not performed to avoid Type I and Type II error as reported by Rothman (1990). Furthermore, details of statistical analysis used to test the hypothesis of each objective are described as follows:

1. Descriptive statistics was executed for all the parameters considered under respective headings.
2. Kruskal Wallis H test was applied to establish the overall effect of dependent variables across language groups. Further, pair wise comparison was executed using Mann Whitney U test between dependent variables, wherever an overall effect was observed in Kruskal Wallis H test.
3. Friedman test was used to obtain the overall effect of dependent variable within each language group. In the presence of any significant difference, Wilcoxon signed ranks test was employed for pair wise comparison of dependent variables.

4. Effect size was measured for each Z value pair wise comparison in Mann Whitney U test and Wilcoxon signed ranks test and was represented as η^2.
5. One way repeated measure analysis of variable (ANOVA) was run on the data which followed all the assumptions of parametric test. The dependent variables, coarticulation resistance of preceding vowel in dental and velar contexts and following vowel in retroflex context in Malayalam were studied using one way repeated measure ANOVA and adjusted Bonferroni post hoc was carried out for pair wise comparisons. Effect size was represented as partial η^2.

CHAPTER IV- RESULTS

The study aimed to investigate the extent and direction of coarticulation and coarticulation resistance of consonants and vowels within the languages, Kannada, Malayalam (Dravidian languages) and Hindi (Indo-Aryan) and across these languages with the following objectives:

1. To investigate the effect of language on coarticulation across Kannada and Malayalam (Dravidian languages) and Hindi (Indo-Aryan)
2. To investigate the effect of spatial measures on coarticulation including:
    - Places of articulation (dental, retroflex and velar stop consonants)
    - Vowel contexts (/a/- low central vowel, /i/- high front vowel, /u/- high back vowel)
    - Voicing of consonants
3. To investigate the effect of gender on coarticulation

Extent of coarticulation (EC) is the amount of influence of one phoneme on a neighbouring phoneme and it is expressed in millimetre (mm) throughout the study. RMS distance between preceding vowel and consonant was considered as EC of the preceding vowel. Similarly, the RMS distance between the following vowel and consonant was considered as EC of the following vowel. EC nearing zero indicates greater coarticulation as the tongue contour of one phoneme tend to moves towards the neighbouring phoneme tongue contour. Conversely, if EC is away from zero, it indicates reduced coarticulation. Extent of coarticulation was compared within and across vowels including the 18 tokens separately for preceding and following contexts (3 vowels X 6 consonants =18).

Comparing EC of the preceding and following vowels was the deciding factor for the direction of coarticulation. It is inferred as anticipatory coarticulation if EC of the following vowel was lesser than the preceding vowel and vise versa for carryover coarticulation. Along with EC of vowels, the tongue contour of each phoneme helps to explain the direction of coarticulation.

Coarticulation resistance of consonant, preceding vowel, and following vowel were calculated using the equation mentioned in method (section 2.2) individually for each subject. Descriptive statistics details are presented in respective tables. Coarticulation resistance of the consonant was analysed by comparing them across different vowel contexts i.e. (/a/, /i/), (/a/, /u/) and (/i/, /u/). Similarly, coarticulation resistance of each preceding and following vowel were based on the comparison across two voicing counterparts in each place of articulation i.e. dentals, retroflexes, and velars.

With this brief overview of the parameters and their measurements, results are explained in detail under each heading. Descriptive statics of each parameter with ultrasound averaged tongue images of each token within languages are discussed.

I. Parameters of coarticulation within languages

1. Kannada

1.1. Extent and direction of coarticulation

Extent of coarticulation across three places of articulation and three corner vowels both in preceding and following phonetic contexts are explained under section 1.1.a Direction of coarticulation is discussed under section 1.1.b as comparison of EC across preceding and following contexts.

1.1.a. Extent of coarticulation (EC) across places of articulation in the preceding and following vowel contexts

Extent of coarticulation of vowels on consonants was analyzed using RMS method. Findings revealed that RMS distance between consonant and the preceding vowel varied across consonants. Table 1.1.a.1 depicts mean, median, and standard deviation of EC in the preceding and following vowel contexts. In the preceding vowel context, distance between the tongue contours of unvoiced retroflex /ʈ/ and high front vowel /i/ was the lowest among all the tokens, whereas, the highest distance was observed between the voiced dental consonant /d̪/ and high back vowel /u/. In the context of vowel /a/, EC was lowest when it preceded dental place of articulation. On the other hand, for vowel /i/, EC was lowest when it preceded unvoiced retroflex /ʈ/ and for vowel /u/, EC was lowest when it preceded unvoiced velar consonant /k/. Hence EC was ranging from a minimum mean value of 0.19 mm to a highest mean distance of 0.82 mm in the preceding vowel context in Kannada.

In the following vowel context, EC was lowest for /i/ compared to other two vowels in combination with all consonants. In Kannada, voiced velar /g/ had highest RMS value when followed by vowel /u/ (Mean and Median = 0.42, SD = 0.24). Standard deviation was high for vowel /a/ and reduced for /i/ in all the consonant contexts. Mean, median and standard deviation are presented in Table 1.1.a.1.

Table. 1.1.a.1.

Extent of coarticulation across places of articulation for preceding and following vowel context (RMS distance in mm from V_1 to C and C to V_2) in Kannada

Token of EC		**/a/**			**/i/**			**/u/**	
	Mean	**Median**	**SD**	**Mean**	**Median**	**SD**	**Mean**	**Median**	**SD**
/V_1t̪/	0.63	0.68	0.27	0.39	0.35	0.18	0.75	0.78	0.32
/V_1d̪/	0.63	0.58	0.32	0.37	0.27	0.13	0.82	0.86	0.27
/V_1ʈ/	0.72	0.46	0.38	0.24	0.19	0.12	0.73	0.60	0.45
/V_1ɖ/	0.76	0.71	0.37	0.23	0.22	0.10	0.81	0.72	0.39
/V_1k/	0.70	0.73	0.29	0.43	0.40	0.19	0.55	0.45	0.32
/V_1g/	0.75	0.76	0.31	0.44	0.42	0.16	0.57	0.54	0.24
/ t̪V_2/	0.34	0.31	0.16	0.23	0.18	0.11	0.36	0.32	0.19
/ d̪V_2/	0.32	0.32	0.12	0.21	0.18	0.10	0.32	0.30	0.11
/ ʈV_2/	0.36	0.32	0.18	0.22	0.18	0.12	0.37	0.33	0.19
/ ɖV_2/	0.39	0.34	0.25	0.25	0.21	0.16	0.35	0.32	0.18
/ kV_2/	0.34	0.27	0.21	0.28	0.27	0.15	0.33	0.31	0.17
/ gV_2/	0.42	0.42	0.24	0.30	0.28	0.17	0.31	0.27	0.17

Note: SD-Standard Deviation

Friedman test was administered to determine the effect of place of articulation of consonants on each vowel separately. Findings showed that EC was significantly different across places of articulation for vowels /i/ [χ^2 (5) = 43.44, p = .001] and /u/ [χ^2 (5) = 20.89, p = .001], but not for vowel /a/ [χ^2 (5) = 9.241, p = .100]. Further, on pair wise comparison using Wilcoxon signed Ranks test for vowels /i/ and /u/ (Table 1.1.a.2), retroflexes were significantly different from dentals and velars when high front vowel /i/ preceded them, however their effect size was less when the comparison was between dental /t̪/ and velar /k/ (η^2 = .39) and high between dental /d̪/ and velar /k/ (η^2 = .64). EC was less for retroflexes compared to dentals and velars which signified more coarticulation for retroflexes; in other words retroflex had greater influence on the preceding vowel. In the context of high back vowel /u/, both cognates of velars were significantly different with lowest EC value compared to voiced and unvoiced counterparts of dentals and unvoiced retroflex. This demonstrates that velars had greater coarticulation with vowel /u/ in the preceding position. Effect size was ranging from .57 to .78 in vowel /u/ context, and the highest effect size was noticed for /ɖ/ and /k/ comparison.

Friedman test was administered to verify variation of EC across consonants for places of articulation with a constant following vowel context. Test statistics showed that there was no significant difference across consonants for following vowel /a/ [χ^2 (5) = 4.362, p= .499], /i/ [χ^2 (5) = 9.524, p= .090], and /u/ [χ^2 (5) = 2.305, p= .806].

Table. 1.1.a.2.

Pair wise comparison of extent of coarticulation of consonants within the context of /i/ and /u/ in Kannada

	/i/		/u/	
Pairs of EC	**|Z|**	**P**	**|Z|**	**P**
V_1t̪ vs V_1d̪	**1.473**	**.141**	**1.203**	**.229**
V_1t̪ vs V_1ʈ	3.142	.02** ↓	0.514	.607
V_1t̪ vs V_1ɖ	3.741	.000*** ↓	0.442	.658
V_1t̪ vs V_1k	1.581	.165	2.66	.008** ↓
V_1t̪ vs V_1g	1.302	.191	2.17	.030* ↓
V_1d̪ vs V_1ʈ	3.202	.002** ↓	0.812	.417
V_1d̪ vs V_1ɖ	3.462	.017* ↓	0.072	.943
V_1d̪ vs V_1k	0.023	.981	3.507	.000*** ↓
V_1d̪ vs V_1g	0.381	.704	3.343	.001*** ↓
V_1ʈ vs V_1ɖ	**0.483**	**.629**	**1.604**	**.109**
V_1ʈ vs V_1k	3.747	.000*** ↑	2.098	.036* ↑
V_1ʈ vs V_1g	4.120	.000*** ↑	1.306	.192
V_1ɖ vs V_1k	4.255	.000*** ↑	3.034	.002** ↑
V_1ɖ vs V_1g	4.234	.000*** ↑	2.767	.006** ↑
V_1k vs V_1g	**.607**	**.544**	**.689**	**.491**

Note: *= p≤ 0.05, **= p≤ 0.01, ***= p≤ 0.001, Upward arrow (↑) shows higher mean for second EC in the pair. Conversely, downward arrow (↓) shows lowest mean for second EC in the pair.

Variations in EC across three preceding and following vowels were analysed using Friedman test of statistics. Results showed that there was a significant difference across preceding vowels with respect to six consonants considered (Table 1.1.a.3). Wilcoxon signed ranks test was used for pair wise comparison and findings were quite interesting. High front vowel /i/ was significantly different from /a/ in all consonant contexts, and was also significantly different from /u/ in all consonant contexts except /k/. Vowel /i/ had reduced EC than /a/ and /u/ in all tokens which indicated higher coarticulation. However, /a/ was significantly different from /u/ only in the context of /d̪/ and /g/. EC was high for /u/ when it preceded voiced dental consonant, whereas, it was less in the voiced velar context. Effect size was highest for /ɖ/ both in (/a/, /i/) and (/i/, /u/) comparisons (both $\eta^2 = .87$). In (/a/, /i/) context, /g/ had lowest effect size ($\eta^2 = .41$). For (/a/, /u/) pair, it was .43 for /d̪/ and .47 for /g/. $|Z|$ and p values are given in the Table 1.1.a.3. In general, /i/ had lowest EC indicating greater coarticulatory influence on the following consonants.

Similarly, comparisons were made across following vowels using Friedman test with the consonant context kept constant. Findings showed significant effect of consonants except in the context of unvoiced velar consonant /k/. Chi square, degrees of freedom and p-values are given in Table 1.1.a.3. Pair wise analysis was performed, where EC for each of the five consonants in the context of /i/ was significantly reduced than /a/ and /u/. EC of voiced velar consonant /g/ in the context of vowel /a/ was significantly greater than the vowel context of /u/ with moderate effect size ($\eta^2 = .52$). Range of η^2 varied from .41 to .75 for (a, i), .56 to .87 for (i, u) contexts.

To conclude, significantly reduced EC and conversely greater coarticulation was seen when vowel /i/ preceded retroflexes. On the other hand, higher EC and least coarticulation was observed when high back vowel /u/ preceded voiced dental /d̪/. There was no significant difference of EC across places of articulation in the context of preceding vowel /a/. In the following context, vowels did not show significant difference across consonants.

Analysis of EC varied across vowels, vowel /i/ had lowest EC and greater coarticulation than vowel /u/ and /a/ in most of the consonant contexts. This finding emphasises greater coarticulatory impact of high front vowel /i/ in the preceding and following contexts.

Table. 1.1.a.3.

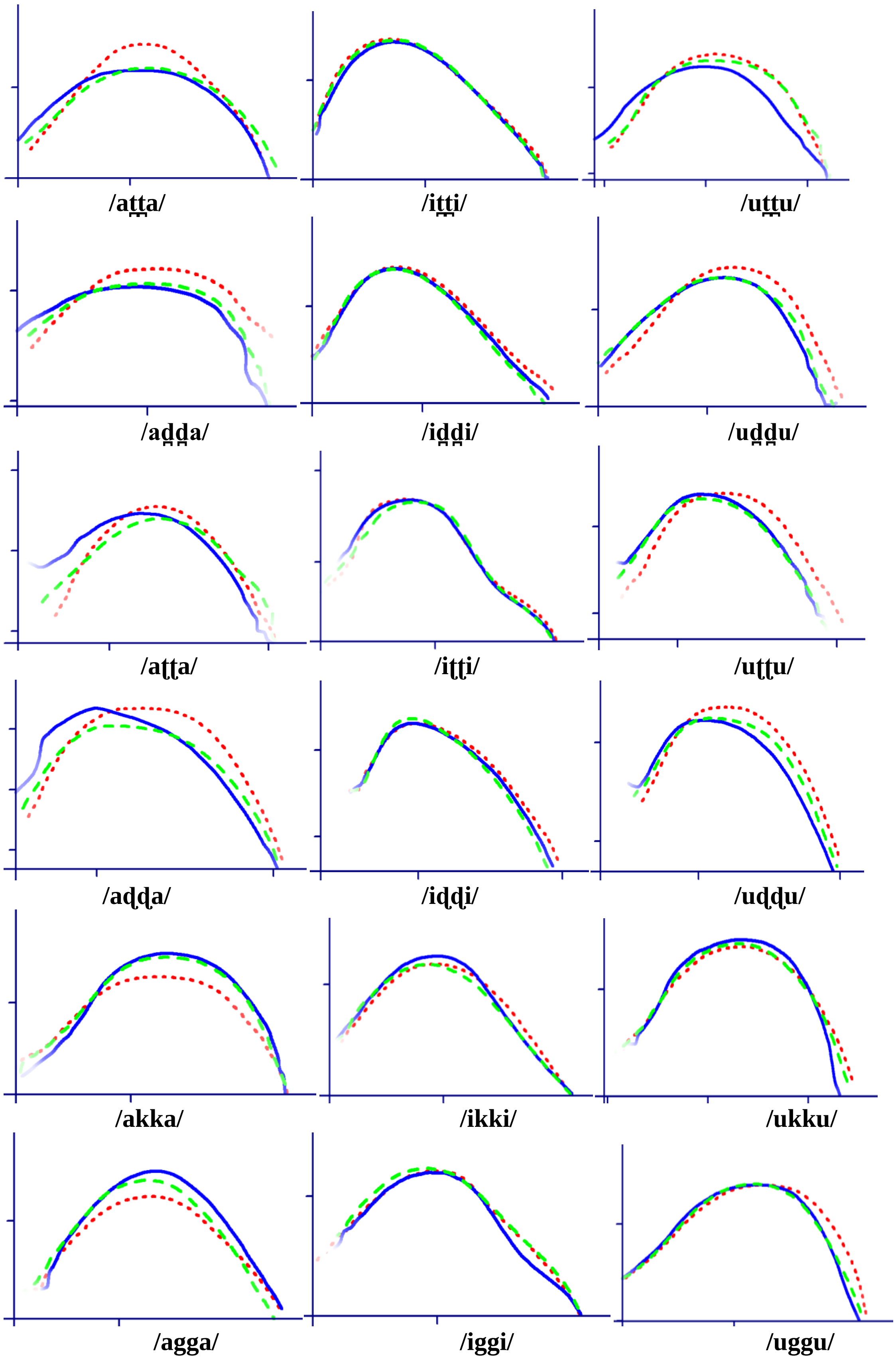
Pair wise comparison of preceding and following vowels within each consonant context in Kannada

Token of EC	χ^2	DF	P	/a/ vs /i/		/a/ vs /u/		/i/ vs /u/	
				|Z|	p	|Z|	P	|Z|	P
/V_1t̪/	20.061	2	.000***	4.186	.000***	↓ 0.442	.658	4.062	.000*** ↑
/V_1d̪/	35.467	2	.000***	4.227	.000***	↓ 2.540	.011* ↑	4.720	.000*** ↑
/V_1ʈ/	25.261	2	.000***	4.371	.000***	↓ 1.358	.175	4.185	.000*** ↑
/V_1ɖ/	45.600	2	.000***	4.782	.000***	↓ 0.782	.434	4.782	.000*** ↑
/V_1k/	11.042	2	.004**	3.836	.000***	↓ 1.903	.057	1.719	.086
/V_1g/	12.600	2	.002**	3.661	.000***	↓ 2.592	.010* ↓	2.273	.023* ↑
/t̪V_2/	16.200	2	.000***	3.302	.001***	↓ 0.154	.877	3.096	.002** ↑
/d̪V_2/	12.867	2	.002**	3.157	.002**	↓ 2.470	.805	3.129	.001*** ↑
/ʈV_2/	22.400	2	.000***	4.134	.000***	↓ 0.854	.393	4.185	.000*** ↑
/ɖV_2/	9.267	2	.010**	2.993	.003**	↓ 0.823	.411	4.782	.013*** ↑
/kV_2/	3.176	2	.204	-	-	-	-	-	-
/gV_2/	8.790	2	.012*	2.283	.022*	↓ 2.859	.004* ↓	2.273	.991

Note: *= $p \leq 0.05$, **= $p \leq 0.01$, ***= $p \leq 0.001$, Upward arrow (↑) shows higher mean during second EC vowel context. Conversely, downward arrow (↓) shows lowest mean during second EC vowel context. DF= Degrees of Freedom.

1.1.c. Direction of coarticulation across three corner vowels and places of articulation

Figure 1.1.b.1 shows tongue contours of the preceding vowel, consonant, and the following vowel in VCV syllables chosen as the stimuli. It is evident that all the consonants were influenced by vowel /i/ and the tongue contours were more drifted towards the trajectory of /i/. This was more evident in the context of velar consonants. Mean tongue contour of /a/ and /u/ neither influenced nor were influenced by consonants except in the context of retroflexes. Vowels /a/ and /u/ mimicked the articulatory gestures of retroflex especially in the following than in the preceding


/at̪t̪a/
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/uʈʈu/
/aɖɖa/
/iɖɖi/
/uɖɖu/
/akka/
/ikki/
/ukku/
/agga/
/iggi/
/uggu/

X axis- Tongue advancement; Y axis- Tongue height

*Figure. 1.1.b.1.*Tongue contours of preceding vowel (red dotted line), consonant (blue filled line) and following vowel (green dashed line) for all 18 tokens in Kannada. The anterior tongue is towards the right side.

vowel context. Tongue tip/blade movement variability was reduced for vowels /a/ and /u/ in dental context and tongue root was relatively stable in the velar context. In both these contexts tongue dorsum was relatively flexible to impact the neighbouring phoneme. RMS distances were measured between mean tongue contours of vowel and consonant in preceding and following contexts. Descriptive statistics was employed for the RMS distance as depicted in Table 1.1.a.1. Correlating figure 1.1.b.1 and Table 1.1.a.1, it can be noted that influence of preceding vowel on consonant was relatively less indicated by higher EC; conversely, influence of the following vowel was greater with reduced EC. This finding is interpreted as anticipatory coarticulation. Anticipatory coarticulation was observed for all the consonant vowel pairs except for a single token of retroflex /iɖɖi/. For /iɖɖi/, mean EC was less for /i/ in the preceding than the following context indicative of carryover coarticulation.

As there was a noticeable difference in EC between preceding and following phonetic contexts, further Wilcoxon signed ranked test was administered. Table 1.1.b.1 depicts pair wise comparison of preceding and following EC combinations. Findings showed significant difference between EC pairs except for retroflexes in the context of vowel /i/. EC values were significantly reduced for following than preceding vowel context indicating a clear pattern of anticipatory coarticulation in Kannada. Effect size was high for most of the tokens ranging from .72 to .87 for /a/, .55 to .71 for /i/ and .56 to .87 for /u/.

Table. 1.1.b.1

Pair wise comparisons of extent of coarticulation in preceding (V_1C) and following vowel (CV_2) in Kannada

Tokens of EC	/a/		/i/		/u/	
	|Z|	**P**	**|Z|**	**P**	**|Z|**	**P**
V_1t̪- t̪V_2	4.741	.000*** ↓	3.898	.000*** ↓	4.432	.000*** ↓
V_1d̪- d̪V_2	4.206	.000*** ↓	3.085	.002** ↓	4.782	.000*** ↓
V_1ʈ- ʈV_2	4.083	.000*** ↓	0.483	.629	3.404	.001*** ↓
V_1ɖ- ɖV_2	4.762	.000*** ↓	0.329	.742	4.597	.000*** ↓
V_1k- kV_2	4.330	.000*** ↓	3.445	.001*** ↓	3.065	.002** ↓
V_1g- gV_2	3.939	.000*** ↓	3.013	.003** ↓	4.165	.000*** ↓

Note: **= $p \leq 0.01$, ***= $p \leq 0.001$, Downward arrow (↓) shows lowest mean EC in the following vowel context (CV_2).

From Figure 1.1.b.1, Tables 1.1.a.1 and 1.1.b.1., it is evident that dentals and velars follow a similar trend i.e. anticipatory coarticulation when neighboured with vowels /a/ and /u/. But there was a conflict of influence or in other words EC was minimal when two highly robust phonemes such as retroflexes and high front vowel occurred adjacent to each other in a VCV syllable pattern.

1.1.c. Comparison of extent of coarticulation (EC) across voicing counterparts

Comparison of EC across voicing counterparts was carried out to analyse the effect of voicing on coarticulation. Mean, median, and standard deviation are provided in Table 1.1.a.1 (section 1.1.a). As shown in section 1.1.a, statistical findings showed no significant difference of voicing on coarticulation in the preceding and following vowel contexts (Red colour-Table.1.1.a.2). Voicing counterparts in three different places of articulation performed similarly across vowel contexts.

1.1.d. Comparison of extent of coarticulation across gender

This section intended to check the null hypothesis of gender differences on coarticulation. Mean Median and standard deviation of EC in both males and females are depicted in Table 1.1.d.1. Mann Whitney U test results showed significant difference across gender only for three tokens. EC of /a-d̪/ ($|Z| = 2.157$, $p = .031$, $\eta^2 = .4$), /i-d̪/ ($|Z| = 2.240$, $p = .025$, $\eta^2 = .41$), and / ɖ-i/ ($|Z| = 2.033$, $p = .042$, $\eta^2 = .37$) were significantly different across gender with higher EC and less coarticulation in females. All other 33 out of 36 tokens were similar for males and females (Appendix II- Table 1).

Table. 1.1.d.1.

Descriptive statistics of extent of coarticulation of preceding (V_1C) and following vowel (CV_2) in mm respectively across gender in Kannada

Tokens of EC		/a/			/i/			/u/		
	Gender	Mean	Median	SD	Mean	Median	SD	Mean	Median	SD
V_1t̪	Male	0.68	0.63	0.24	0.38	0.36	0.18	0.72	0.77	0.26
	Female	0.78	0.72	0.31	0.40	0.36	0.19	0.78	0.82	0.37
t̪V_2	Male	0.32	0.30	0.11	0.23	0.17	0.12	0.31	0.30	0.07
	Female	0.37	0.32	0.20	0.23	0.19	0.11	0.41	0.39	0.26
V_1d̪	Male	0.51	0.47	0.25	0.24	0.23	0.08	0.76	0.81	0.31
	Female	0.76	0.82	0.35	0.35	0.36	0.15	0.87	0.89	0.23
d̪V_2	Male	0.27	0.29	0.11	0.19	0.17	0.07	0.30	0.30	0.11
	Female	0.38	0.36	0.12	0.24	0.22	0.12	0.34	0.32	0.12
V_1ʈ	Male	0.59	0.42	0.36	0.26	0.20	0.13	0.79	0.64	0.47
	Female	0.68	0.82	0.41	0.23	0.18	0.11	0.66	0.53	0.45
ʈV_2	Male	0.32	0.29	0.16	0.20	0.17	0.12	0.38	0.32	0.19
	Female	0.40	0.34	0.20	0.24	0.19	0.12	0.37	0.35	0.20
V_1ɖ	Male	0.70	0.59	0.34	0.23	0.26	0.08	0.80	0.62	0.39
	Female	0.84	0.88	0.41	0.23	0.21	0.12	0.82	0.76	0.41
ɖV_2	Male	0.35	0.32	0.25	0.20	0.17	0.15	0.32	0.28	0.17
	Female	0.43	0.38	0.25	0.31	0.24	0.17	0.38	0.39	0.19
V_1k	Male	0.70	0.74	0.32	0.46	0.43	0.17	0.59	0.44	0.42
	Female	0.71	0.72	0.27	0.41	0.34	0.21	0.51	0.46	0.17
kV_2	Male	0.36	0.26	0.25	0.27	0.28	0.12	0.38	0.35	0.18

	Female	0.32	0.30	0.17	0.30	0.23	0.19	0.29	0.26	0.16
V_1g	Male	0.79	0.73	0.31	0.47	0.48	0.17	0.54	0.54	0.23
	Female	0.71	0.79	0.32	0.41	0.39	0.16	0.61	0.55	0.26
gV_2	Male	0.47	0.48	0.28	0.31	0.30	0.13	0.30	0.27	0.11
	Female	0.38	0.41	0.21	0.30	0.28	0.21	0.33	0.27	0.22

Note: SD- Standard Deviation

1.2. Coarticulation resistance

Coarticulation resistance (CR) was calculated for preceding vowel, consonant and following vowel separately. Descriptive and non parametric tests were administered to analyse the coarticulation resistance pattern in Kannada.

1.2.a. Comparison of Coarticulation Resistance of Consonant (CRC) across three places of articulation

As illustrated in the Table 1.2.a.1, CR was calculated within vowel pairs and mean CR was high for retroflexes in all the three vowel combinations. Dentals and velars exhibited coarticulation resistance differently across vowel pair contexts. All the consonants had higher resistance when it was paired with vowels /a/ and /u/, but not with vowel /i/.

Table. 1.2.a.1.

Descriptive statistics of coarticulation resistance of consonants (CRC) across three vowel combinations in Kannada

	(/a/, /i/)			**(/a/, /u/)**			**(/i/, /u/)**		
CRC	**Mean**	**Median**	**SD**	**Mean**	**Median**	**SD**	**Mean**	**Median**	**SD**
/t̪/	13.72	13.21	5.80	24.71	23.22	10.29	19.65	15.93	15.2
/d̪/	15.51	13.19	8.30	26.08	23.06	12.86	18.86	14.92	11.85
/ʈ/	23.50	21.07	13.00	38.18	34.40	24.40	32.98	25.74	19.24
/ɖ/	26.55	24.09	13.82	43.63	37.73	31.53	29.40	28.26	13.79
/k/	14.43	11.89	10.14	37.77	27.67	22.40	13.47	12.20	7.35
/g/	16.18	13.76	7.97	39.32	32.66	21.97	15.96	12.57	10.52

Note: SD- Standard Deviation

Friedman test was run separately for each vowel pair to appreciate the significant effect of consonant on CR. Results showed significant difference across the consonants in three vowel pairs, /a/ and /i/ [χ^2 (5) = 49.543, p < .001], /a/ and /u/ [χ^2 (5) = 29.048, p < .001], /i/ and /u/ [χ^2 (5) = 50.990, p < .001]. Pair wise comparisons were executed using Wilcoxon signed ranks test and details are given in Table 1.2.a.2. Voiced and unvoiced counterparts of retroflexes were found to have significantly higher coarticulation resistance compared to dentals and velars in all the vowel pair contexts. Voiced velar consonant /g/ had significantly higher CR than dentals in /a/ and /u/ contexts. However, when CRC was calculated in vowel /i/ and /u/ contexts, both voiced and unvoiced counterparts of retroflex significantly resisted coarticulation with higher CR than dentals. Over all, CRC followed a pattern, i.e. retroflex > velars > dentals. Effect size varied from .57 to .77 across tokens in (/a/, /i/) context. However 'η^2' was ranging from .4 to .75 in (/a/, /u/) context, while .4 to .8 was the range for effect size in (/i/, /u/) context.

Table. 1.2.a.2.

Pair wise comparison of coarticulation resistance of consonants (CRC) within three pairs of vowels in Kannada

	(/a/, /i/)		**(/a/, /u/)**		**(/i/, /u/)**	
CRC	**|Z|**	**P**	**|Z|**	**P**	**|Z|**	**P**
/t̪/ vs /d̪/	**0.154**	**.877**	**0.771**	**.441**	**0.483**	**.629**
/t̪/ vs /ʈ/	3.363	.001*** ↑	2.808	.005** ↑	3.445	.001*** ↑
/t̪/ vs /ɖ/	3.795	.000*** ↑	3.795	.000*** ↑	3.260	.001*** ↑
/t̪/ vs /k/	1.080	.280	0.031	.975	2.170	.030* ↑
/t̪/ vs /g/	0.216	.829	2.170	.030* ↑	2.273	.023* ↑
/d̪/ vs /ʈ/	4.001	.000*** ↑	2.972	.003** ↑	3.363	.001*** ↑
/d̪/ vs /ɖ/	3.774	.000*** ↑	4.083	.000*** ↑	2.705	.007** ↑
/d̪/ vs /k/	0.278	.781	0.710	.478	2.376	.018* ↑
/d̪/ vs /g/	0.401	.688	2.314	.021* ↑	2.335	.020* ↑
/ʈ/ vs /ɖ/	**1.738**	**.082**	**1.162**	**.245**	**0.895**	**.371**
/ʈ/ vs /k/	3.178	.001*** ↓	1.759	.079	4.350	.000*** ↓
/ʈ/ vs /g/	3.116	.002** ↓	0.216	.829	4.227	.000*** ↓

↓

/ɖ/ vs /k/	3.857	.000*** ↓	2.808	.005** ↓	4.288	.000***
/ɖ/ vs /g/	4.206	.000*** ↓	1.861	.063	4.330	.000*** ↓
/k/ vs /g/	**0.586**	**.558**	**1.861**	**.063**	**0.319**	**.750**

Note: *= p≤ 0.05, **= p≤ 0.01, ***= p≤ 0.001, Upward arrow (↑) shows higher CRC for the second consonant context. Conversely, downward arrow (↓) shows lowest mean CRC for the second consonant context.

1.2.b. Comparison of Coarticulation Resistance of Consonants (CRC) across voicing counterparts

CRC across voicing counterparts was analysed using Wilcoxon signed ranks test and results are shown in Table 1.2.a.2 (Red colour). It is quite evident that there was no significant difference between voicing counterparts for all three places of articulation within each pair of vowels.

1.2.c. Comparison of Coarticulation Resistance of Consonants (CRC) across gender

Mann Whitney U test was used to verify the effect of gender on coarticulation. There was no significant difference across gender on CRC except for CR of voiced dental consonant in /a/ and /i/ context ($|Z| = 2.883$, $p = .004$, $\eta^2 = .52$) and in /i/ and /u/ context ($|Z| = 2.426$, $p = .015$, $\eta^2 = .44$) depicted in Appendix III- Table 1. Females resisted the influence of neighbouring vowels to a greater extent than males in these two contexts.

Table. 1.2.c.1

Descriptive statistics of coarticulation resistance of consonants (CRC) within vowel pairs across gender in Kannada

		(/a/, /i/)			**(/a/, /u/)**			**(/i/, /u/)**		
CRC	**Gender**	**Mean**	**Median**	**SD**	**Mean**	**Median**	**SD**	**Mean**	**Median**	**SD**
/t̪/	Male	13.00	13.28	4.16	27.81	25.52	8.02	17.18	14.86	5.94
	Female	16.44	14.91	7.43	30.67	25.51	14.68	19.74	17.88	11.35
/d̪/	Male	10.91	10.58	3.14	24.85	21.89	11.54	14.49	14.43	5.19
	Female	18.84	17.15	8.77	30.23	29.26	12.14	23.46	22.89	10.36
/ʈ/	Male	19.68	20.58	4.47	41.53	39.56	17.92	34.92	32.73	14.87
	Female	24.27	22.91	12.9	45.29	39.02	41.67	29.41	25.96	14.89

/ɖ/	Male	27.05	25.31	15.4	46.99	38.12	30.79	27.14	26.13	11.33
	Female	30.36	20.09	21.3	60.89	44.71	45.81	26.85	23.93	8.97
/k/	Male	18.62	12.63	20.4	29.44	23.43	16.42	14.33	12.63	8.43
	Female	12.98	11.01	6.82	34.79	27.08	19.71	12.23	10.31	8.45
/g/	Male	14.17	14.00	3.70	47.09	34.36	25.32	12.47	12.53	3.22
	Female	14.90	12.48	6.59	30.91	27.57	16.10	16.40	12.15	11.20

Note: SD-Standard Deviation

1.2.d. Comparison of Coarticulation Resistance of Preceding Vowel (CRPV) and Following Vowel (CRFV) across places of articulation

Coarticulation Resistance of Vowel (CRV) of both preceding and following vowels were calculated using the equation given by Zharkova (2007). Description of CRPV and CRFV for dentals, retroflexes, and velars are depicted in Table 1.2.d.1. In the preceding context, coarticulation resistance was less for /a/ in all the three consonant contexts. CR was high for vowel /u/ in dental context, whereas, /i/ showed higher CR in the context of retroflexes and velars. Standard deviation was high across all the contexts depicting high variability across participants.

Similar to the preceding phonetic place, /i/ had greater coarticulation resistance followed by /a/ and /u/ in following vowel context specifically in combination with dentals and velars. On the other hand, in the context of retroflexes, /u/ had comparatively greater CR than /i/ and lowest was for /a/.

Table. 1.2.d.1.

Descriptive statistics of coarticulation resistance of preceding vowel (CRPV) and following vowel (CRFV) across places of articulation in Kannada

	Dentals			**Retroflexes**			**Velars**		
CRV	**Mean**	**Median**	**SD**	**Mean**	**Median**	**SD**	**Mean**	**Median**	**SD**
CRPV /a/	18.57	15.40	12.77	15.39	11.97	12.44	24.83	17.55	20.66
CRPV /i/	43.14	30.97	30.64	57.46	46.23	39.54	55.14	32.43	64.65

CRPV /u/	51.42	36.10	51.50	52.76	39.56	40.16	35.38	23.12	48.41
CRFV /a/	19.52	18.03	9.43	10.71	8.10	6.66	16.60	12.36	10.53
CRFV /i/	24.71	20.25	16.08	15.85	13.93	12.69	20.05	20.02	8.29
CRFV /u/	19.34	15.23	14.49	14.44	10.71	11.20	13.75	8.85	11.55

Note: SD-Standard Deviation

Three vowels were compared within each consonant category using Friedman test. Findings demonstrated significant difference across preceding vowels with the three consonant pairs, including dentals [χ^2 (2) = 18.467, p < .001], retroflexes [χ^2 (2) = 33.867, p < .001] and velars [χ^2 (2) = 10.067, p = .007]. Further, pairs were compared using Wilcoxon signed ranks test and the results are illustrated in Table 1.2.d.2. It was clear that CR of /a/ was significantly different from /i/ and /u/ when it preceded dentals and retroflexes. In both these contexts, CR was less for vowel /a/. On the other hand, /i/ had significantly greater coarticulation resistance compared to /a/ and /u/ when it occurred in the preceding phonetic position for retroflexes and velars. Overall, effect size ranged between .4 to .87.

Friedman test was adopted to test the hypothesis of following vowel effect on CR. Results demonstrated significant difference across vowels except in velar context [χ^2 (2) = 5.267, p = .072]. Vowels were significantly different when they followed dentals [χ^2 (2) = 6.867, p = .032] and retroflexes [χ^2 (2) = 12.600, p = .002]. Wilcoxon singed ranks test was used for pair wise analysis within dentals and retroflexes (Table 1.2.d.2). Markedly, vowel /i/ demonstrated significantly greater CR than /a/ and /u/ in both consonant contexts. Also, there was no significant difference between /a/ and /u/ for C. Effect size varied from .4 to moderated value .72.

Table. 1.2.d.2.

Pair wise comparison of coarticulation resistance of preceding vowel (CRPV) and following vowel (CRFV) across places of articulation in Kannada

	/t̪/ & /d̪/		/ʈ/ & /ɖ/		/k/ & /g/	
CRV	**|Z|**	**P**	**|Z|**	**p**	**|Z|**	**P**
CRPV /a/ vs /i/	3.754	.000*** ↑	4.659	.000*** ↑	2.890	.004** ↑
CRPV /a/ vs /u/	0.113	.910	0.545	.586	2.129	.033* ↑
CRPV /i/ vs /u/	3.980	.000*** ↓	4.741	.000*** ↓	0.298	.766
CRFV /a/ vs /i/	3.198	.001*** ↑	3.981	.000*** ↑	-	-
CRFV /a/ vs /u/	0.854	.393	1.925	.054	-	-
CRFV /i/ vs /u/	2.211	.027* ↓	2.722	.006** ↓	-	-

Note: *= p≤ 0.05, **= p≤ 0.01, ***= p≤ 0.001, Upward arrow (↑) shows higher CRPV for the second vowel context. Conversely, downward arrow (↓) shows lowest mean CRPV for the second vowel context.

1.2.e. Comparison of Coarticulation Resistance of Preceding Vowel (CRPV) and Following Vowel (CRFV) across gender

Mann Whitney U test was administered to establish the effect of gender on CRPV and CRFV. In CRPV, results showed no significant effect of gender except on /u/ in the context of retroflexes ($|Z| = 2.592$, $p = .010$, $\eta^2 = .47$) (Appendix IV- Table 1). Mean CRPV of /u/ was greater in males than females.

Null hypothesis for effect of gender on CRFV was tested using Mann Whitney U test. As seen in Appendix V- Table 1, there was no significant effect of gender on CRFV for any of the tokens, resulting in the acceptance of the null hypothesis.

Table. 1.2.e.1

Descriptive statistics of coarticulation resistance of preceding vowel (CRPV) and following vowel (CRFV) across places of articulation across gender in Kannada

		Dentals			**Retroflexes**			**Velars**		
CRV	**Gender**	**Mean**	**Median**	**SD**	**Mean**	**Median**	**SD**	**Mean**	**Median**	**SD**
CRPV /a/	Male	16.33	11.87	12.47	18.37	15.16	15.35	30.49	19.59	24.61
	Female	20.81	18.93	13.10	12.41	9.62	8.12	19.18	15.20	14.49
CRPV	Male	34.13	30.13	17.51	56.54	51.16	34.40	44.78	34.87	35.28

/i/	Female	52.14	52.25	38.26	58.39	34.86	45.32	65.50	30.00	84.75
CRPV /u/	Male	51.95	37.72	56.93	67.26	51.74	45.54	30.84	28.43	26.10
	Female	50.89	34.49	47.46	38.27	30.68	28.57	39.92	19.75	64.26
CRFV /a/	Male	17.21	16.83	9.45	24.68	19.31	18.35	23.34	18.48	17.30
	Female	21.83	21.13	9.15	24.73	21.18	14.09	15.34	13.93	10.08
CRFV /i/	Male	11.40	8.23	7.43	14.73	7.50	13.11	19.43	15.25	14.83
	Female	10.02	7.94	5.96	14.15	10.90	9.36	12.28	11.95	9.29
CRFV /u/	Male	15.96	12.65	8.55	22.53	20.35	7.58	17.55	11.55	14.15
	Female	17.24	12.17	12.47	17.56	17.70	8.46	9.95	7.57	6.73

Note: SD-Standard Deviation

To summarise, in Kannada, there were some interesting patterns of coarticulation. Particularly, there was greater coarticulation for high front vowel /i/ with lowest EC compared to other two vowels in preceding and following contexts. Among consonants, significantly reduced EC and high coarticulation were seen in retroflexes when they preceded /i/ and velars preceded /u/. No significant difference was observed across consonants with each vowel in the following context. Anticipatory coarticulation was the explicit pattern of direction of coarticulation. This was evident in almost all the tokens except retroflexes when they were with high front vowel /i/ in VCV syllable. CRC was predominant for retroflexes followed by dentals and velars. Vowel /i/ had significantly greater coarticulation resistance compared to /a/ and /u/ in the preceding and following phonetic position for velars. Null hypothesis related to places of articulation and vowels was rejected as there was evidence of changes across tokens.

Effect of voicing tested for the parameters, EC and CRC, results showed significant effect only for few tokens among the 36 tokens. Similarly, gender showed no significant effect in many tokens for all the parameters including EC, CRC, CRPV and CRFV. Hence, it is possible to accept the null hypothesis on voicing and gender effect for most of the tokens, except for those which showed difference.

2. Malayalam

2.1. Extent and direction of coarticulation

As explained in section 1.1. for Kannada, extent of coarticulation (EC) and direction of coarticulation are calculated from the obtained RMS distances. Extent of coarticulation across three places of articulation in the context of three corner vowels including both preceding and following phonetic contexts have been explained under sections 2.1.a. Direction of coarticulation is discussed under section 2.1.b.

2.1.a. Extent of coarticulation (EC) across places of articulation in the preceding and following vowel contexts

Descriptive statistics of extent of coarticulation across the three the corner vowels and places of articulation in preceding vowel context are depicted in Table 2.1.a.1. There was clear reduction in EC when high front vowel /i/ preceded all three places of articulation in Malayalam. Among all the 18 tokens, retroflexes preceded by vowel /a/ had greater EC and dentals showed lowest EC when they were preceded by vowel /i/. Overall, EC reduced in the order of retroflexes > velars > dentals, in both vowel /a/ and /u/ contexts. But for /i/, the trend was different and EC was high for velars followed by dentals and lowest for retroflexes.

Contrary to EC in preceding context of Malayalam, there was no clear pattern across three corner vowels and places of articulation in the following vowel context based on descriptive statistics (Table 2.1.a.1). Highest EC was observed for voiced retroflex /ɖ/ when followed by vowel /a/. On the other hand, vowel /i/ following unvoiced dental /t̪/ had lowest EC among all the tokens. Overall, dentals showed lowest extent of coarticulation or maximum coarticulation across vowels. Further statistical analyses were carried out to find the significant effect.

Table. 2.1.a.1.

Extent of coarticulation across places of articulation in preceding and following vowel contexts (RMS distance in mm from V_1 to C and C to V_2) in Malayalam

	/a/			**/i/**			**/u/**		
EC	**Mean**	**Median**	**SD**	**Mean**	**Median**	**SD**	**Mean**	**Median**	**SD**
/V_1t̪/	0.62	0.49	0.23	0.44	0.38	0.23	0.60	0.55	0.35
/V_1d̪/	0.60	0.63	0.24	0.42	0.36	0.20	0.64	0.55	0.30
/V_1ʈ/	0.86	0.90	0.29	0.39	0.36	0.16	0.82	0.87	0.31
/V_1ɖ/	0.85	0.83	0.32	0.43	0.40	0.21	0.80	0.84	0.28
/V_1k/	0.78	0.75	0.31	0.56	0.58	0.22	0.57	0.58	0.22
/V_1g/	0.85	0.81	0.35	0.50	0.49	0.20	0.53	0.56	0.18
/t̪V_2/	0.23	0.21	0.12	0.20	0.20	0.08	0.26	0.27	0.11
/d̪V_2/	0.28	0.25	0.13	0.25	0.22	0.12	0.28	0.26	0.12
/ʈV_2/	0.34	0.32	0.12	0.25	0.21	0.13	0.31	0.29	0.13
/ɖV_2/	0.37	0.39	0.13	0.31	0.26	0.17	0.31	0.29	0.14
/kV_2/	0.32	0.30	0.14	0.34	0.28	0.23	0.29	0.25	0.16
/gV_2/	0.35	0.36	0.17	0.30	0.27	0.15	0.30	0.26	0.14

Note: SD-Standard Deviation

Within and across vowel comparisons were implemented statistically to test the hypothesis of effect of places of articulation and vowels. Indeed, Friedman test showed significant difference across consonants for preceding vowels /a/ [χ^2 (5) = 37.295, p< .001], /i/ [χ^2 (5) = 15.234, p= .009] and /u/ [χ^2 (5) = 27.781, p< .001]. Further, Wilcoxon signed ranks test was administered and findings are represented in Table 2.1.a.2. There was a significant separation of retroflexes and velars from dental consonants in the preceding context of vowel /a/. The same finding was evident in both voiced and unvoiced counterparts of these consonants. Dentals had significantly lowest EC or greater coarticulation compared to velars and retroflexes. However, velars and retroflexes did not have significant difference in the context of vowel /a/. Effect size varied from .4 to .79 within /a/ comparisons.

Within the context of vowel /i/, unvoiced velar consonant /k/ had significantly high EC than dentals and retroflexes. Similarly voiced velar consonant /g/ had significantly higher EC compared to unvoiced retroflex /ʈ/, i.e. velars had lowest coarticulation. Significant effect of EC was observed for retroflexes than other two places of articulation when their neighbourhood was preceded by vowel /u/. EC of retroflexes were significantly higher than velars and dentals. There was no significant difference of EC between velars and dentals in vowel /u/ context. Range of effect size was .43 to .63 for vowel /i/ and .5 to .71 for vowel /u/.

Similar to preceding vowel, Friedman test was administered within each following vowel and findings showed that significant effect was present for vowels /a/ [χ^2 (5) = 25.752, p< .001] and /i/ [χ^2 (5) = 13.058, p< .05]; but not for vowel /u/ [χ^2 (5) = 5.406, p > .05]. Hence, Wilcoxon signed ranks test was used for pair wise analysis within /a/ and /i/. Results are depicted in Table 2.1.a.3. Unvoiced dental consonant /t̪/ was significantly different from other consonants with lowest EC with vowel /a/ in the following context. But voiced dental /d̪/ had significantly higher EC compared to voiced retroflex /ɖ/. Effect size was moderate with η^2 value ranging from .4 to .65 for all places of articulation with vowel /a/ in the following context.

Similar to /a/, EC of /i/ was significantly different in the context of dental /t̪/. But, the significant difference was only with velars and voiced retroflex /ɖ/. Voiced dental /d̪/ showed significantly low EC than retroflex /ɖ/ and velar /k/. Also, retroflex counterparts were significantly different for EC in the context of following vowel /i/ with unvoiced retroflex having low EC than voiced retroflex and followed by velar unvoiced /k/. Effect size was relatively less and varied from .37 to .57.

Table. 2.1.a.2.

Pair wise comparison of extent of coarticulation of consonants within the context of preceding vowel /a/, /i/ and /u/ in Malayalam

Tokens of EC	**/a/**		**/i/**		**/u/**	
	|Z|	**P**	**|Z|**	**P**	**|Z|**	**P**
V_1t̪ vs V_1d̪	**0.463**	**.643**	**0.483**	**.629**	**1.039**	**.299**
V_1t̪ vs V_1ʈ	4.330	.000***↑	0.607	.544	3.013	.003**↓
V_1t̪ vs V_1ɖ	3.394	.001***↑	0.278	.781	2.746	.006**↓
V_1t̪ vs V_1k	2.088	.037* ↑	2.376	.018*↑	0.607	.544
V_1t̪ vs V_1g	2.808	.005** ↑	1.142	.254	0.134	.894
V_1d̪ vs V_1ʈ	4.134	.000***↑	1.224	.221	2.993	.003**↓
V_1d̪ vs V_1ɖ	3.929	.000***↑	0.238	.812	2.746	.006**↓
V_1d̪ vs V_1k	2.396	.017* ↑	3.341	.001***↑	0.257	.797
V_1d̪ vs V_1g	2.766	.006**↑	1.728	.084	1.224	.221
V_1ʈ vs V_1ɖ	**0.884**	**.376**	**0.298**	**.766**	**1.337**	**.181**
V_1ʈ vs V_1k	0.915	.360	3.466	.001***↑	2.952	.003** ↓
V_1ʈ vs V_1g	0.216	.829	2.365	.018* ↑	3.898	.000***↓
V_1ɖ vs V_1k	1.008	.314	2.705	.007**↑	3.013	.003** ↓
V_1ɖ vs V_1g	0.278	.781	1.419	.156	3.774	.000***↓
V_1k vs V_1g	**1.717**	**.086**	**1.039**	**.299**	**1.060**	**.289**

Note: *= p≤ 0.05, **= p≤ 0.01, ***= p≤ 0.001, Upward arrow (↑) shows higher mean EC for the second consonant context. Conversely, downward arrow (↓) shows lowest mean EC for the second consonant context.

Table. 2.1.a.3

Pair wise comparison of extent of coarticulation of consonants within the context of following vowel /a/ and /i/ in Malayalam

Tokens of EC	**/a/**		**/i/**	
	|Z|	**P**	**|Z|**	**P**

V_2t̪ vs V_2d̪	**2.057**	**.040*** ↑	**1.635**	**.102**
V_2t̪ vs V_2ʈ	3.610	.000*** ↑	0.669	.504
V_2t̪ vs V_2ɖ	3.600	.000*** ↑	2.931	.003** ↑
V_2t̪ vs V_2k	3.034	.002** ↑	3.116	.002** ↑
V_2t̪ vs V_2g	2.602	.009** ↑	2.859	.004** ↑
V_2d̪ vs V_2ʈ	1.913	.056	0.195	.845
V_2d̪ vs V_2ɖ	2.643	.008** ↑	2.026	.043* ↑
V_2d̪ vs V_2k	1.142	.254	2.057	.040* ↑
V_2d̪ vs V_2g	1.954	.051	1.615	.106
V_2ʈ vs V_2ɖ	**1.491**	**.136**	**2.016**	**.044*** ↑
V_2ʈ vs V_2k	0.555	.579	2.026	.043* ↑
V_2ʈ vs V_2g	0.422	.673	1.635	.102
V_2ɖ vs V_2k	1.368	.171	0.465	.642
V_2ɖ vs V_2g	0.710	.478	0.504	.614
V_2k vs V_2g	**0.998**	**.318**	**0.757**	**.449**

Note: *= $p \leq 0.05$, **= $p \leq 0.01$, ***= $p \leq 0.001$, Upward arrow(↑) shows higher EC for the second consonant context.

Friedman test was administered to find how EC varies across vowels within each consonant. Results showed significant effect of preceding vowels within consonant (Table. 2.1.a.4). Wilcoxon signed ranks test was conducted for further understanding. EC of preceding vowel /i/ was significantly less than vowel /a/ in all consonant conditions. Similarly, /i/ was significantly different from /u/ with less EC, but it was evident only for retroflexes and voiced dental consonant /d̪/. Vowel /a/ had significantly high EC when compared to /u/ especially in combination with velars and voiced retroflex /ɖ/. |Z| and p values of each pair wise comparison within each consonant is illustrated in Table 2.1.a.4. In general, pattern of EC varied as /a/ > /u/ > /i/, indicating coarticulation decreases in the order of /i/ > /u/ > /a/, i.e. /i/ had maximum impact on the following consonant, whereas /a/ had the lowest effect.

From the statistical results, it has been observed that there is variation in EC of preceding vowel in Malayalam. Pattern of coarticulation of each vowel varied across consonants. Higher EC was noticed for dentals in the context of /a/; for unvoiced velar consonant in the context of /i/; and for retroflex cognates in the context of vowel /u/. In general, there was a clear trend of higher coarticulation for /i/ than /a/ when it was in the preceding phonetic context.

EC for following vowel context was statistically analysed using Friedman test and significant difference was observed only for unvoiced retroflex. Hence, Wilcoxon signed ranks test was administered for retroflexes across vowels. Consequently, significant effect was seen only between vowels /a/ and /i/ with lowest EC in the context of the vowel /i/ (Table. 2.1.a.4).

Table. 2.1.a.4.

Pair wise comparison of extent of coarticulation of preceding and following vowels within each consonant context in Malayalam

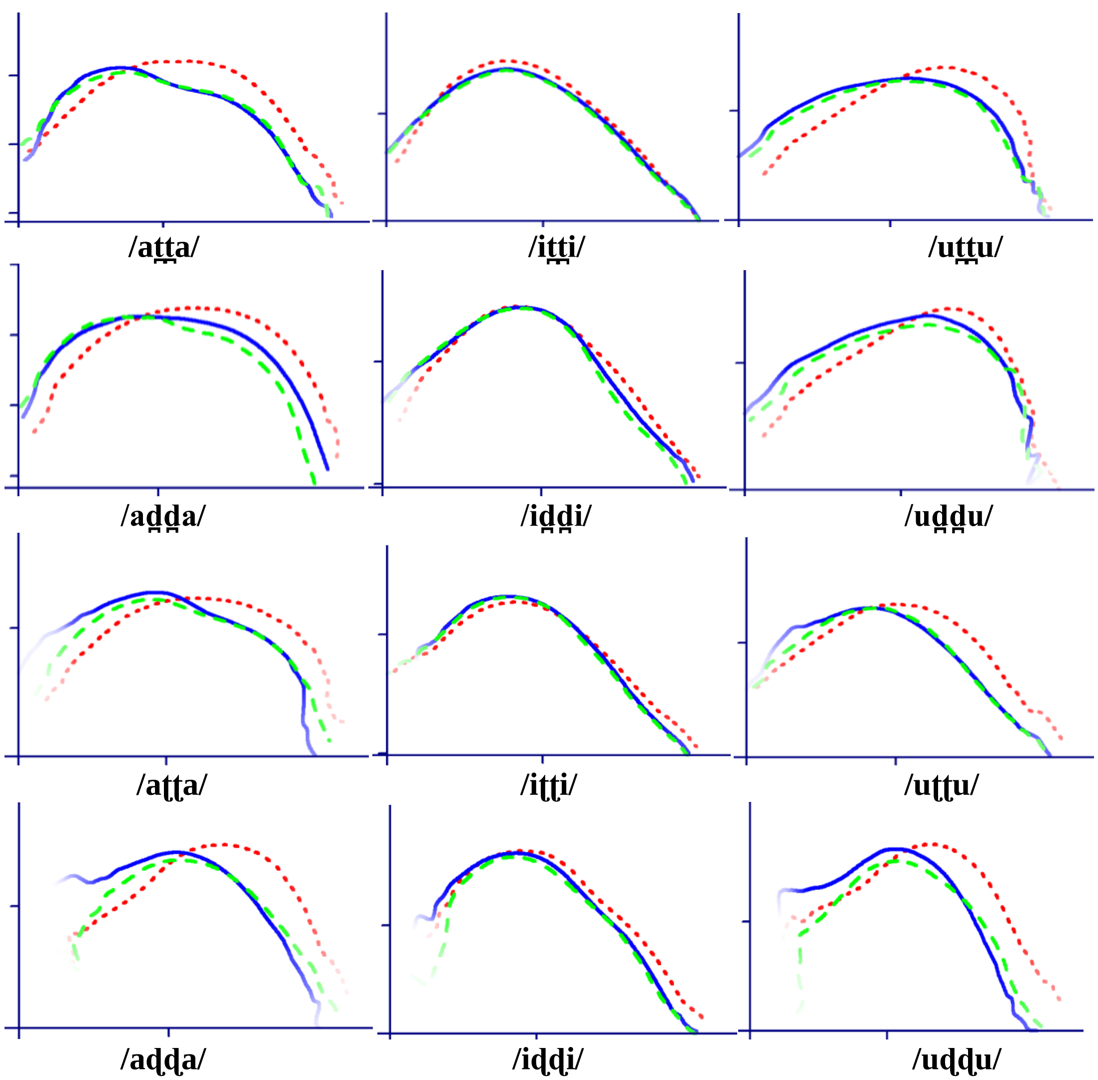
EC	χ^2	**DF**	**P**	**/a/ vs /i/**		**/a/ vs /u/**		**/i/ vs /u/**	
				|Z|	**P**	**|Z|**	**P**	**|Z|**	**P**
/V_1t̪/	6.067	2	.048*	2.887	.004** ↓	0.401	.688	1.656	.098
/V_1d̪/	15.80	2	.000***	2.859	.004** ↓	0.689	.491	2.705	.007** ↑
/V_1ʈ/	22.46	2	.000***	4.227	.000*** ↓	0.051	.959	4.145	.000*** ↑
/V_1ɖ/	21.98	2	.000***	4.271	.000*** ↓	2.098	.036* ↓	4.114	.000*** ↑
/V_1k/	7.200	2	.027*	2.571	.010** ↓	3.219	.001*** ↓	0.113	.910
/V_1g/	20.06	2	.000***	4.083	.000*** ↓	3.918	.000*** ↓	0.504	.614
/t̪V2/	2.235	2	.327	-	-	-	-	-	-
/d̪V2/	2.067	2	.356	-	-	-	-	-	-
/ʈV2/	6.067	2	.048*	2.396	.017* ↓	1.409	.159	1.738	.082
/ɖV2/	5.664	2	.059	-	-	-	-	-	-
/kV2/	0.267	2	.875	-	-	-	-	-	-
/gV2/	2.867	2	.239	-	-	-	-	-	-

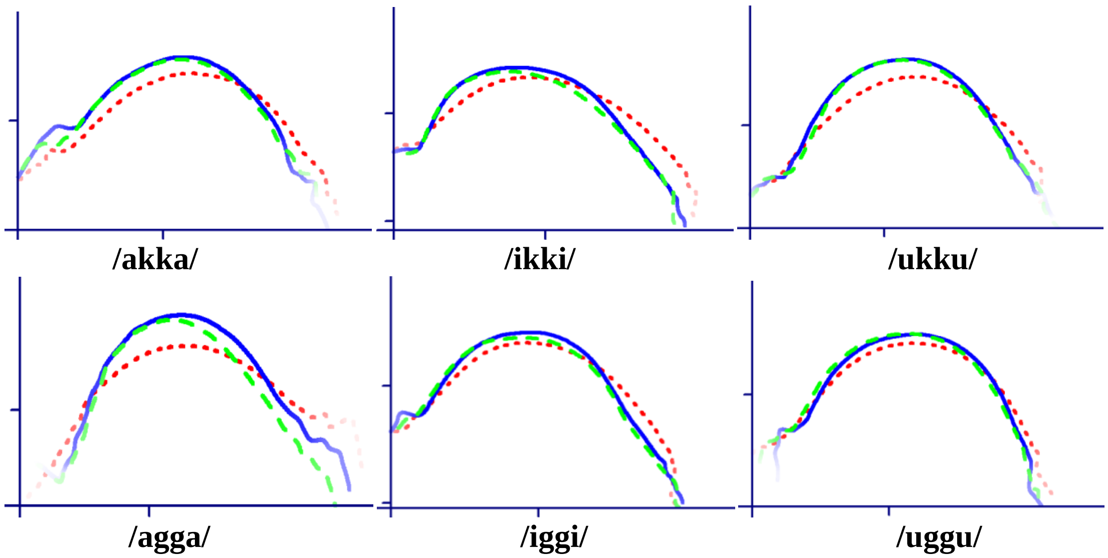
Note: *= $p \leq 0.05$, **= $p \leq 0.01$, ***= $p \leq 0.001$, Upward arrow (↑) shows higher mean EC during second vowel context. Conversely, downward arrow (↓) shows lowest mean EC during second vowel context. DF= Degrees of Freedom.

General trend of lowest EC and higher coarticulation was observed comparatively for unvoiced dental consonant /t̪/ especially when vowels /a/ and /i/ followed it. Despite a clear pattern of high coarticulation for /i/ in the preceding context in Malayalam, it was lacking in the following phonetic context. Therefore, it is appropriate to conclude that vowels have similar nature of coarticulation across consonants in Malayalam in the following vowel context and there is no clear pattern.

2.1.b. Direction of coarticulation across three corner vowels and places of articulation

It is possible to infer the influence of phoneme over the other from the tongue contours. Figure 2.1.b.1, shows that tongue contours of following vowel impact the preceding consonant. Vowels in the preceding context had robust articulatory trajectory across places of articulation except for retroflex context. The distance





X axis- Tongue advancement; Y axis- Tongue height.

*Figure 2.1.b.1.*Tongue contours of preceding vowel (red dotted line), consonant (blue filled line) and following vowel (green dashed line) for all 18 tokens in Malayalam. The anterior tongue is towards the right side.

between each preceding vowel to consonant varied across places of articulation. Similar variation was observed in the context of following vowel also.

Quantitative representation of Figure 2.1.b.1 is depicted in Table 2.1.a.1 and there was identifiable difference between V_1-C and V_2-C. EC was always high for V_1-C than V_2-C indicating vowel dependent high anticipatory coarticulation in Malayalam. Furthermore, statistical analysis was employed to test the hypothesis of directionality of coarticulation.

Pair wise comparison of V_1-C and V_2-C was done using Wilcoxon signed ranks test. Findings showed significant difference across the three corner vowels in both preceding and following vowel contexts for the three places of articulation (Table 2.1.b.1). Interestingly, V_1-C distance was always higher than V_2-C (Table 2.1.a.1). This finding confirms the directionality as anticipatory coarticulation with overall high effect size (η^2 = .4 to .87).

Table. 2.1.b.1.

Pair wise comparisons of extent of coarticulation in preceding (V_1C) and following vowel (CV_2) in Malayalam

Tokens of EC	**/a/**		**/i/**		**/u/**	
	|Z|	**P**	**|Z|**	**P**	**|Z|**	**P**
V_1t̪- t̪V_2	4.782	.000*** ↓	4.186	.000*** ↓	4.515	.000*** ↓
V_1d-d̪V_2	4.268	.000*** ↓	3.137	.002** ↓	4.535	.000*** ↓
V_1ʈ-ʈV_2	4.741	.000*** ↓	3.075	.002** ↓	4.618	.000*** ↓
V_1ɖ-ɖV_2	4.576	.000*** ↓	2.047	.041* ↓	4.515	.000*** ↓
V_1k-kV_2	4.494	.000*** ↓	3.271	.001*** ↓	4.227	.000*** ↓
V_1g-gV_2	4.720	.000*** ↓	3.968	.000*** ↓	3.939	.000*** ↓

Note: *= $p \leq 0.05$, **= $p \leq 0.01$, ***= $p \leq 0.001$, Downward arrow (↓) shows lowest mean EC during following vowel context (CV_2).

2.1.c. Comparison of extent of coarticulation across voicing counterparts

Effect of voicing was measured using Wilcoxon signed ranks test across voicing counterparts both in preceding and following vowel contexts. Mean, median, and standard deviation are depicted in Table 2.1.a.1. Pair wise analysis was done under the section of 2.1.a for preceding following vowel contexts. Significant difference of voicing was observed only for dentals. EC of voiced dental consonant was greater than unvoiced counterpart in the following vowel /a/ context ($|Z|$ = 2.057, p = .040, η^2= .37). All other $|Z|$ and p values are presented in Table 2.1.a.2 and 2.1.a.3 (Red colour).

2.1.d. Comparison of extent of coarticulation across gender

Table 2.1.d.1 represents the descriptive statistics of EC across gender. Mann-Whitney U test was administered to establish the gender effect on EC. Findings showed that there were differences for three tokens out of 36 including /a_1/-/t̪/ [$|Z|$ = 2.012, p = .044, η^2 = .37], /a_1/-/ʈ/, [$|Z|$ = 2.261, p = .024, η^2= .41] and /u_2/-/t̪/ [$|Z|$ = 2.219, p = .026, η^2 = .4] across gender (Appendix II- Table 2). Females showed significantly higher EC than males for these three tokens signalling greater coarticulation in males.

Table. 2.1.d.1.

Descriptive statistics of extent of coarticulation of preceding (V_1C) and following vowel (CV_2) in mm respectively across gender in Malayalam

Tokens of EC	Gender	/a/			/i/			/u/		
		Mean	**Median**	**SD**	**Mean**	**Median**	**SD**	**Mean**	**Median**	**SD**
V_1t̪	Male	0.52	0.48	0.18	0.40	0.37	0.19	0.53	0.53	0.17
	Female	0.72	0.79	0.25	0.49	0.39	0.27	0.57	0.58	0.42
t̪V_2	Male	0.19	0.18	0.07	0.21	0.23	0.09	0.22	0.20	0.10
	Female	0.27	0.22	0.15	0.21	0.20	0.09	0.31	0.31	0.12
V_1d̪	Male	0.56	0.47	0.21	0.40	0.37	0.17	0.61	0.58	0.13
	Female	0.65	0.68	0.27	0.46	0.37	0.24	0.67	0.62	0.38
d̪V_2	Male	0.27	0.21	0.14	0.27	0.24	0.10	0.29	0.23	0.15
	Female	0.30	0.25	0.13	0.24	0.21	0.14	0.28	0.28	0.11
V_1ʈ	Male	0.73	0.78	0.29	0.39	0.35	0.18	0.77	0.76	0.28
	Female	0.99	0.97	0.25	0.41	0.42	0.16	0.87	0.89	0.34
ʈV_2	Male	0.31	0.32	0.11	0.30	0.23	0.15	0.32	0.32	0.16
	Female	0.37	0.33	0.14	0.20	0.17	0.10	0.31	0.26	0.12
V_1ɖ	Male	0.84	0.70	0.36	0.49	0.47	0.21	0.78	0.78	0.28
	Female	0.87	0.88	0.26	0.37	0.29	0.21	0.83	0.83	0.23
ɖV_2	Male	0.37	0.41	0.16	0.30	0.24	0.17	0.33	0.30	0.15

	Female	0.38	0.38	0.12	0.33	0.29	0.18	0.30	0.29	0.13
V_1k	Male	0.83	0.80	0.32	0.53	0.48	0.23	0.64	0.67	0.18
	Female	0.74	0.74	0.32	0.61	0.60	0.22	0.52	0.53	0.25
kV_2	Male	0.30	0.31	0.12	0.35	0.25	0.29	0.26	0.19	0.16
	Female	0.34	0.29	0.16	0.35	0.38	0.16	0.33	0.28	0.16
V_1g	Male	0.83	0.83	0.33	0.56	0.50	0.19	0.52	0.56	0.18
	Female	0.88	0.79	0.39	0.46	0.49	0.21	0.55	0.54	0.20
gV_2	Male	0.31	0.27	0.15	0.32	0.26	0.21	0.30	0.25	0.20
	Female	0.39	0.37	0.20	0.29	0.30	0.08	0.32	0.30	0.08

Note: SD- Standard Deviation

2.2.Coarticulation resistance

Coarticulation resistance was calculated from EC values of different contexts. Coarticulation resistance of consonant, preceding vowel, and following vowel were calculated separately and has been discussed under each heading.

2.2.a. Coarticulation Resistance of Consonant (CRC) across three places of articulation

Coarticulation resistance of consonants were calculated in three vowel pair conditions, including /a/ and /i/; /a/ and /u/; /i/ and /u/. Descriptive statistics are shown in Table 2.2.a.1 and comparison was established within each vowel pair. Notably, retroflexes had higher coarticulation resistance than the other two places of articulation with vowels (/a/, /i/) and (/i/, /u/). However in (/a/, /u/) context, velars showed highest CRC than retroflexes.

Table 2.2.a.1.

Descriptive statistics of coarticulation resistance of consonant (CRC) across three vowel combinations in Malayalam

	(/a/, /i/)			(/a/, /u/)			(/i/, /u/)		
CRC	**Mean**	**Median**	**SD**	**Mean**	**Median**	**SD**	**Mean**	**Median**	**SD**
/t̪/	12.27	11.30	4.88	21.78	20.74	8.60	15.68	13.39	7.56

/d̪/	14.02	12.61	6.15	24.72	22.64	10.70	18.67	13.61	13.78
/ʈ/	22.52	19.93	11.24	36.01	35.38	21.04	34.33	31.04	17.34
/ɖ/	26.97	25.54	12.26	41.51	41.50	13.32	32.71	28.27	14.05
/k/	15.42	14.52	5.85	45.20	39.36	24.57	14.78	13.42	7.78
/g/	17.48	14.89	7.73	44.74	37.27	20.43	17.06	12.74	12.00

Note: SD- Standard Deviation

Effect of places of articulation on CRC was measured within each vowel pair using Friedman test and results showed significant effect for vowel pairs (/a/, i/) [χ^2 (5) = 42.24, p < .001], (/a/, /u/) [χ^2 (5) = 59.08, p< .001] and (/i/, /u/) [χ^2 (5) = 65.23, p< .001] combinations. Besides, pair wise comparisons of consonants were obtained using Wilcoxon signed ranks test within each vowel pair (Table 2.2.a.2). Within (/a/, /i/) category, retroflexes were significantly different from velars and dentals with high CRC. Similarly, counterparts of retroflexes were significantly different as an effect of voicing (further discussed in section 2.2.b). Unvoiced dental consonant was significantly different from voiced velar with lowest CRC under the same category. All comparisons were effective and effect size extended from .4 to .85.

However, in (/a/, /u/) category, dentals were significantly different from retroflexes and velars: dentals had lowest CRC. Both retroflex and velar places of articulation were found to have similar resistance of coarticulation. Unvoiced retroflex had significantly less CRC than its voiced counterpart and voiced velar /g/.

Table. 2.2.a.2.

Pair wise comparison of coarticulation resistance of consonants (CRC) within three pairs of vowels in Malayalam

	/a/ & /i/		**/a/ & /u/**		**/i/ & /u/**	
CRC	**|Z|**	**P**	**|Z|**	**p**	**|Z|**	**P**
/t̪/ vs /d̪/	**1.265**	**.206**	**1.388**	**.165**	**1.471**	**.141**
/t̪/ vs /ʈ/	4.350	.000*** ↑	3.774	.000*** ↑	4.432	.000*** ↑
/t̪/ vs /ɖ/	4.638	.000*** ↑	4.638	.000*** ↑	4.741	.000*** ↑

/t̪/ vs /k/	1.594	.111	3.898	.000*** ↑	0.195	.845
/t̪/ vs /g/	2.602	.009** ↑	4.679	.000*** ↑	0.195	.845
/d̪/ vs /ʈ/	4.247	.000*** ↑	3.322	.001*** ↑	4.042	.000*** ↑
/d̪/ vs /ɖ/	4.515	.000*** ↑	4.535	.000*** ↑	4.165	.000*** ↑
/d̪/ vs /k/	0.668	.504	3.281	.001*** ↑	0.854	.393
/d̪/ vs /g/	1.759	.079	4.124	.000*** ↑	1.162	.245
/ʈ/ vs /ɖ/	**2.232**	**.026*** ↑	**2.314**	**.021*** ↑	**0.648**	**.517**
/ʈ/ vs /k/	3.075	.002** ↓	1.759	.079	3.939	.000*** ↓
/ʈ/ vs /g/	2.170	.030* ↓	2.005	.045* ↑	3.671	.000*** ↓
/ɖ/ vs /k/	3.754	.000*** ↓	0.586	.558	4.330	.000*** ↓
/ɖ/ vs /g/	3.260	.001*** ↓	0.422	.673	4.103	.000*** ↓
/k/ vs /g/	**0.915**	**.360**	**0.072**	**.943**	**0.483**	**.629**

Note: *= p≤ 0.05, **= p≤ 0.01, ***= p≤ 0.001, Upward arrow (↑) shows higher CRC for the second consonant context. Conversely, downward arrow (↓) shows lowest mean CRC for the second consonant context.

Similar to (/a/, /i/) context, retroflexes were noticed to have significantly higher CRC than dentals and velars in (/i/, /u/) pair calculation. Range of effect size of (/a/, /u/) category was .36 to .85 and for (/i/, /u/), it was .67 to .87. General trend of high coarticulation resistance was observed for retroflexes in all the three vowel combinations, whereas, other two places of articulation performed differently.

2.2.b. Comparison of Coarticulation Resistance of Consonant (CRC) across voicing counterparts

Effect of voicing on CRC was analysed using Wilcoxon signed ranks pair wise test and findings showed that there was significant difference among retroflexes both in (/a/, /i/) and (/a/, /u/) vowel pair context in Malayalam (Table 2.2.a.2, Red colour). Voiced retroflex had greater CRC than unvoiced retroflex in these vowel pair contexts. Other two consonant counterparts behaved similarly in all the three vowel pair contexts.

2.2.c. Comparison of Coarticulation Resistance of Consonant (CRC) across gender

As represented in Table 2.2.c.1, CRC was moreover similar across gender. Mann Whitney U test was used to find statistical effect of gender on CRC and confirmed that there was no significant difference between gender groups (Appendix III- Table 2). All the six consonants resisted the influence of nearby phonemes similarly in both males and females.

Table 2.2.c.1

Descriptive statistics of coarticulation resistance of consonant (CRC) within vowel pairs across gender in Malayalam

		(/a/, /i/)			(/a/, /u/)			(/i/, /u/)		
CRC	**Gender**	**Mean**	**Median**	**SD**	**Mean**	**Median**	**SD**	**Mean**	**Media**	**SD**
/t̪/	Male	10.00	9.57	3.71	17.99	19.21	6.37	12.18	11.72	5.40
	Female	14.56	14.09	4.95	25.58	24.54	9.04	19.19	16.30	7.94
/d̪/	Male	11.24	10.93	3.73	22.84	20.61	8.21	12.55	12.09	4.63
	Female	16.80	16.25	6.93	26.62	26.59	12.74	24.81	20.95	17.0
/ʈ/	Male	20.31	19.08	8.24	32.36	31.01	14.25	25.94	23.98	10.1
	Female	24.75	21.21	13.55	39.68	35.99	26.18	42.73	44.00	19.2
/ɖ/	Male	25.50	22.91	8.51	38.94	39.24	13.79	25.37	24.16	8.03
	Female	28.45	26.51	14.01	44.10	43.11	12.77	40.06	31.49	15.1
/k/	Male	16.96	14.51	6.07	47.88	40.42	23.32	17.39	14.50	9.17
	Female	13.90	14.54	5.40	42.53	35.90	26.29	12.18	11.99	5.19
/g/	Male	17.07	13.78	6.22	39.42	34.52	17.06	16.48	12.50	12.1
	Female	17.90	15.61	9.21	50.07	50.68	22.65	17.66	12.88	12.2

Note: SD-Standard Deviation

2.2.d. Comparison of Coarticulation Resistance of Preceding Vowel (CRPV) following vowel (CRFV) across three corner vowels

Here, coarticulation resistance was measured across vowels when they preceded and followed the consonants in VCV syllable. Resistance of each vowel was calculated by comparing it in different consonants contexts. Hence, CRPV and CRFV are discussed under three consonant categories as depicted in Table 2.2.d.1. Mean CRPV and CRFV were high for /i/ followed by /u/ and was lowest for /a/. This was indeed common in all the three consonant categories, (/t̪/, /d̪/), (/ʈ/, /ɖ/), and (/k/, /g/).

Table. 2.2.d.1.

Descriptive statistics of coarticulation resistance of preceding vowel (CRPV) and following vowel (CRFV) within dentals, retroflexes and velars in Malayalam

	Dentals			**Retroflexes**			**Velars**		
CRV	**Mean**	**Median**	**SD**	**Mean**	**Median**	**SD**	**Mean**	**Median**	**SD**
CRPV /a/	23.67	17.34	18.63	30.54	25.35	21.48	35.09	30.30	23.62
CRPV /i/	49.17	36.80	39.37	79.74	65.59	81.60	69.59	46.87	56.68
CRPV /u/	41.29	24.57	48.55	60.19	53.95	35.43	37.93	31.93	23.15
CRFV /a/	9.16	9.51	4.67	15.05	12.90	8.47	14.79	12.80	10.07
CRFV /i/	13.87	13.83	6.97	19.05	15.55	12.89	17.16	13.41	13.54
CRFV /u/	15.86	13.02	9.456	19.19	17.24	10.00	14.69	12.40	7.66

Note: SD- Standard Deviation

Further, detailed statistics was carried out to test the hypothesis of effect of vowel on coarticulation parameter i.e. CRPV. Here, the data followed normality except in the context of retroflex. Therefore, the parametric test one way repeated measure ANOVA was used for dentals and velars, whereas, the non parametric Friedman test was implemented as a statistical tool for retroflexes. Greenhouse Geisser correction was considered since sphericity was violated for repeated measure ANOVA for both dental and velar categories. There was a significant effect of vowels on CRPV within the dental category [F (1.392, 40.356) = 4.246, p = .034, η^2 = .463]. Post hoc comparisons using the adjusted Bonferroni test indicated that the mean CRPV for /i/ (M = 49.17, SD = 39.37) was significantly different than /a/ (M = 23.67, SD = 18.63). However, /u/ (M = 41.29, SD = 48.55) did not significantly differ from the other two vowels. Similarly, effect of CRPV was shown in the context of velars [F (1.39, 40.302) = 8.387, p = .003, η^2 = .806]. Further, adjusted Bonferroni Post hoc test explicated that CRPV of /i/ was significantly different with high mean (M = 69.59, SD = 56.68) compared to other two vowels /a/ (M = 35.09, SD = 23.62) and /u/ (M = 37.93, SD = 23.15).

As explained previously, Friedman test was administered to observe the effect of CRPV in the context of retroflexes and results showed that there was significant difference among vowels [χ^2 (2) = 16.267, p< .001]. Further, Wilcoxon pair wise analysis was administered and significant difference was found between /a/ and /i/ [|Z| = 3.857, p < .001, η^2 = .7] and /u/ and /a/ [|Z| = 3.445, p = .001, η^2 = .62]. In both the conditions, /a/ had lowest CRPV than other two vowels. Overall, these results suggested that vowel /i/ had high CRPV in all the consonant contexts in Malayalam.

Similar to CRPV, CRFV was calculated based on the EC values obtained in following vowel contexts. Mean, median, and standard deviation values are shown in Table 2.2.d.1. Here, normality was observed only for retroflex data and one way repeated measure ANOVA was conducted to analyse the effect of CRFV. It was found that there was no significant effect of CRFV on retroflex [F (2, 58) = 1.575, p =.216]. Friedman test was administered for other two places of articulation since they did not follow the assumptions of parametric test. The findings revealed CRFV to be significantly different with dentals [χ^2 (2) = 12.800, p=.002], but, not for velars [χ^2 (2) = 1.400, p=.497]. Hence, on pair wise vowel contexts comparison for dentals and the results indicated differences between /a/ and /i/ [|Z| = 2.993, p =.003, η^2 =.54] and /u/ and /a/ [|Z| = 2.972, p =.003, η^2= .54]. Vowel /a/ had lowest CR than other two vowels.

2.2.e. Comparison of Coarticulation Resistance of Preceding Vowel (CRPV) and Following Vowel (CRFV) across gender

Descriptive statistics of CRPV and CRFV across gender has been illustrated in Table 2.2.e.1 and statistical comparison of gender was executed using Mann Whitney U test. Only CRPV of /a/ in the context of retroflexes was significantly different with higher mean CRPV for females than males. This was among the 9 tokens considered including three vowel contexts across three places of articulation. Test statistics of CRPV of /a/ in retroflexes was |Z| = 2.178, p =.029 and values of other vowels given in Appendix IV- Table 2. However, test statistics accepted null hypothesis and proved that there was no significant difference across gender for coarticulation resistance of following vowel (Appendix V- Table 2).

Table 2.2.e.1

Descriptive statistics of coarticulation resistance of preceding vowel (CRPV) and following vowel (CRFV) with dentals, retroflexes and velars across gender in Malayalam

		Dentals			**Retroflexes**			**Velars**		
CRV	**Gender**	**Mean**	**Median**	**SD**	**Mean**	**Median**	**SD**	**Mean**	**Median**	**SD**
CRPV /a/	Male	33.26	28.10	22.53	25.49	19.89	16.13	37.09	30.98	26.02
	Female	27.83	25.19	20.79	21.87	13.17	21.27	33.10	29.63	21.69
CRPV /i/	Male	44.46	35.63	30.61	79.31	69.41	31.85	67.55	44.49	55.82
	Female	53.90	41.49	47.18	80.18	81.97	103.90	71.64	51.64	59.41
CRPV	Male	32.99	22.66	24.73	58.27	58.68	30.47	33.96	26.81	18.64

/u/	Female	49.59	29.42	64.22	62.12	61.54	36.97	41.91	36.02	27.01
CRFV /a/	Male	8.35	9.04	3.51	16.19	13.77	9.81	15.53	12.18	10.74
	Female	9.98	9.87	5.60	13.92	12.57	7.05	14.06	13.41	9.67
CRFV/ i/	Male	14.11	11.72	8.68	16.49	13.28	14.40	17.86	13.69	13.50
	Female	13.63	14.37	5.01	21.60	18.46	11.10	16.46	12.10	14.02
CRFV/ u/	Male	15.20	11.45	10.62	19.52	16.66	12.03	13.91	11.73	7.88
	Female	16.52	14.28	8.44	18.86	18.63	7.89	15.47	13.07	7.63

Note: SD-Standard Deviation

To summarize the pattern of coarticulation in Malayalam, there was a general trend of lowest EC and higher coarticulation for dentals in vowel /a/ and /i/ contexts. There was a clear pattern of high coarticulation for /i/ in the preceding context and not in the following context. Anticipatory coarticulation was apparent compared to carry over coarticulation in Malayalam as observed in Kannada. Among consonants, retroflexes had greater coarticulation resistance. Vowel /i/ had high CRPV, whereas, both /i/ and /u/ had greater CRFV in Malayalam. Since there was a significant difference between places of articulation and vowels in the extent of coarticulation and coarticulation resistance, the null hypothesis of effect of places of articulation and vowel on coarticulation is rejected.

Effect of voicing was observed for few tokens especially for the extent of coarticulation. Gender effect was trivial in Malayalam. Hence, the null hypothesis of voicing and gender were accepted for those tokens which did not show any statistical difference.

3. Hindi

3.1. Extent and direction of coarticulation

Extent and direction of coarticulation were studied across three corner vowels and places of articulation both in preceding and following vowels (section 3.1.a) contexts in Indo Aryan language, Hindi. Direction of coarticulation was inferred from the extent of coarticulation in V_1 to C and V_2 to C contexts and is explained under section 3.1.b.

3.1.a. Extent of coarticulation (EC) across places of articulation in preceding and following vowel contexts

Extent of coarticulation was studied across consonants in the preceding and following vowel contexts. Mean, median, and standard deviation of extent of coarticulation across three places of articulation in the three following vowel contexts are depicted in Table 3.1.a.1. Trend of EC changed based on the vowel and consonant contexts. In the preceding context, EC was highest for /u/- /t̪/ and lowest for /i/-/ɖ/ among all the tokens. On the whole, the value of mean EC ranged between .29 to .64 mm in Hindi. In the following vowel context, mean EC varied across consonants; retroflexes had highest EC both in the context of /a/ and /i/. Comparatively mean EC was reduced for all the six consonants when they were followed by vowel /i/, i.e. vowel /i/ had greater coarticulation than other two vowels.

Table. 3.1.a.1.

Extent of coarticulation across places of articulation in preceding and following vowel contexts (RMS distance in mm from V_1 to C and C to V_2) in Hindi

Token of EC	**/a/**			**/i/**			**/u/**		
	Mean	**Median**	**SD**	**Mean**	**Median**	**SD**	**Mean**	**Median**	**SD**
/V_1t̪/	0.49	0.51	0.16	0.33	0.30	0.12	0.64	0.64	0.24
/V_1d̪/	0.60	0.65	0.18	0.30	0.28	0.13	0.51	0.49	0.23
/V_1ʈ/	0.59	0.52	0.31	0.31	0.29	0.16	0.53	0.46	0.32
/V_1ɖ/	0.58	0.58	0.29	0.29	0.24	0.23	0.46	0.38	0.29
/V_1k/	0.62	0.59	0.23	0.40	0.37	0.17	0.41	0.42	0.16
/V_1g/	0.62	0.62	0.27	0.36	0.35	0.17	0.38	0.34	0.16
/t̪V_2/	0.32	0.29	0.12	0.26	0.22	0.14	0.31	0.30	0.15
/d̪V_2/	0.34	0.29	0.21	0.27	0.26	0.10	0.35	0.31	0.21
/ʈV_2/	0.46	0.42	0.20	0.31	0.33	0.13	0.32	0.30	0.14

/ɖV₂/	0.51	0.41	0.46	0.34	0.31	0.14	0.34	0.29	0.19
/kV₂/	0.36	0.35	0.16	0.26	0.25	0.11	0.32	0.31	0.13
/gV₂/	0.36	0.32	0.18	0.26	0.28	0.11	0.37	0.30	0.19

Note: SD-Standard Deviation

Friedman test was used for comparisons of consonants in each vowel context and results showed that there was significant effect of vowel in the preceding context on EC. To point out, consonants behaved differently with each vowel; /a/ [χ^2 (5) = 11.225, p= .047], /i/ [χ^2 (5) = 12.874, p= .025] and /u/ [χ^2 (5) = 24.545, p< .001]. Hence, pair wise consonant analysis was done using Wilcoxon signed ranks test. Details are given in Table 3.1.a.2. In the preceding vowel context of /a/, EC was significantly less for unvoiced dental /t̪/ than its voiced counterpart. Similarly, unvoiced dental was significantly different with lowest EC than velars (η^2 = .35 to .59). However, vowel /i/ in preceding context showed different trend, where voiced retroflex /ɖ/ had significantly reduced EC than velar cognates and voiced dental /d̪/. Also, voiced dental /d̪/ had significantly less EC than unvoiced velar /k/ (η^2 = .38 to .51). Likewise, voiced and unvoiced pair of dentals was significantly different from other consonants in the context of /u/ except for /d̪/ verses /ʈ/. Dentals had higher EC than other consonants when preceded by /u/ (η^2 = .36 to .78).

Table. 3.1.a.2.

Pair wise comparison of extent of coarticulation of consonants with the context of /a/, /i/ and /u/ in Hindi

	/a/		**/i/**		**/u/**	
EC	**|Z|**	**P value**	**|Z|**	**P**	**|Z|**	**P value**
V_1t̪ vs V_1d̪	**3.229**	**.001***↑**	**0.915**	**.360**	**2.451**	**.014** ↓**
V_1t̪ vs V_1ʈ	1.296	.195	0.823	.411	1.994	.046*↓
V_1t̪ vs V_1ɖ	1.738	.082	2.088	.037*↓	3.412	.001** ↓
V_1t̪ vs V_1k	2.530	.011*↑	1.316	.188	4.277	.000** ↓
V_1t̪ vs V_1g	1.964	.049*↑	0.915	.360	3.988	.000** ↓

V_1d̪ vs V_1ʈ	0.720	.472	0.216	.829	0.192	.848
V_1d̪ vs V_1ɖ	0.154	.877	1.275	.202	2.331	.020* ↓
V_1d̪ vs V_1k	0.051	.959	2.355	.019* ↑	1.970	.049* ↓
V_1d̪ vs V_1g	0.465	.642	1.810	.070	2.403	.016* ↓
V_1ʈ vs V_1ɖ	**0.720**	**.472**	**1.059**	**.289**	**0.913**	**.361**
V_1ʈ vs V_1k	0.576	.565	1.903	.057	1.490	.136
V_1ʈ vs V_1g	0.586	.558	1.378	.168	1.850	.064
V_1ɖ vs V_1k	0.072	.943	2.822	.005* ↑	0.384	.701
V_1ɖ vs V_1g	0.586	.558	2.653	.008* ↑	0.072	.943
V_1k vs V_1g	**0.237**	**.813**	**0.915**	**.360**	**1.105**	**.269**

Note: *= $p \leq 0.05$, **= $p \leq 0.01$, ***= $p \leq 0.001$, Upward arrow (↑) shows higher mean EC for second EC in the pair. Conversely, downward arrow (↓) shows lowest mean EC for second EC in the pair.

Similar to preceding vowel context, Friedman test was adapted to analyse the effect of EC with each vowel in the following context. Significant effect was observed only with vowel /a/ [χ^2 (5) = 20.272, p = .001] and not for vowels /i/ [χ^2 (5) = 10.533, p = .061] and /u/ [χ^2 (5) = 4.047, p = .543]. Therefore, Wilcoxon signed ranks pair wise comparisons were executed with vowel /a/ and findings are given in Table 3.1.a.3. Retroflexes were significantly different with highest EC than velars and dentals.

Table. 3.1.a.3.

Pair wise comparison of extent of coarticulation of consonants within the context of /a/ in Hindi

	/a/	
Token of EC	**|Z|**	**P**
V_2t̪ vs V_2d̪	**0.123**	**.902**
V_2t̪ vs V_2ʈ	2.684	.007** ↑
V_2t̪ vs V_2ɖ	2.376	.018* ↑
V_2t̪ vs V_2k	0.987	.323
V_2t̪ vs V_2g	0.864	.388
V_2d̪ vs V_2ʈ	2.705	.007** ↑
V_2d̪ vs V_2ɖ	2.314	.021* ↑
V_2d̪ vs V_2k	0.802	.422
V_2d̪ vs V_2g	0.545	.586
V_2ʈ vs V_2ɖ	**0.257**	**.797**

V_2ʈ vs V_2k	2.294	.022* ↓
V_2ʈ vs V_2g	2.232	.026* ↓
V_2ɖ vs V_2k	2.098	.036* ↓
V_2ɖ vs V_2g	1.979	.048* ↓
V_2k vs V_2g	**0.113**	**.910**

Note: *= p≤ 0.05, **= p≤ 0.01, Upward arrow (↑) shows higher mean for second EC in the pair. Conversely, downward arrow (↓) shows lowest mean for second EC in the pair.

EC of preceding vowel and following vowel comparisons were established using Friedman test and further, pair wise comparisons were implied using Wilcoxon signed ranks test (Table 3.1.a.4). In the preceding context, EC was significantly reduced for vowel /i/ than vowel /a/ in all the six consonant contexts. Also it was significantly reduced for vowel /i/ than vowel /u/ except in the context of velars. EC of /a/ and /u/ were significantly different in combination with velar consonants where /u/ had lowest EC, but had highest EC when neighboured with unvoiced dental consonant.

In the following vowel context, /a/ was significantly different with highest EC in the context of unvoiced retroflex /ʈ/. Likewise, for voiced retroflex with following vowel /a/ was significantly different with high EC than /u/. Also, in the context of velars, /a/ was significantly different from /i/ with higher EC. Vowel /i/ had lowest EC than vowel /u/ when it followed voiced velar consonant /g/.

Table. 3.1.a.4.

Pair wise comparison of extent of coarticulation of preceding vowels and following vowels in each consonant context in Hindi

Token of EC	**χ^2**	**DF**	**P**	**/a/ vs /i/**		**/a/ vs /u/**		**/i/ vs /u/**	
				|Z|	**P**	**|Z|**	**P**	**|Z|**	**P**
/V_1t̪/	36.867	2	.000***	3.826	.000*** ↓	3.353	.001*** ↑	4.782	.000*** ↑
/V_1d̪/	30.467	2	.000***	4.659	.000*** ↓	1.892	.058	3.672	.000*** ↑
/V_1ʈ/	15.800	2	.000***	4.001	.000*** ↓	0.730	.465	2.808	.005** ↑
/V_1ɖ/	22.235	2	.000***	4.357	.000*** ↓	2.057	.040 ↓	3.343	.001*** ↑

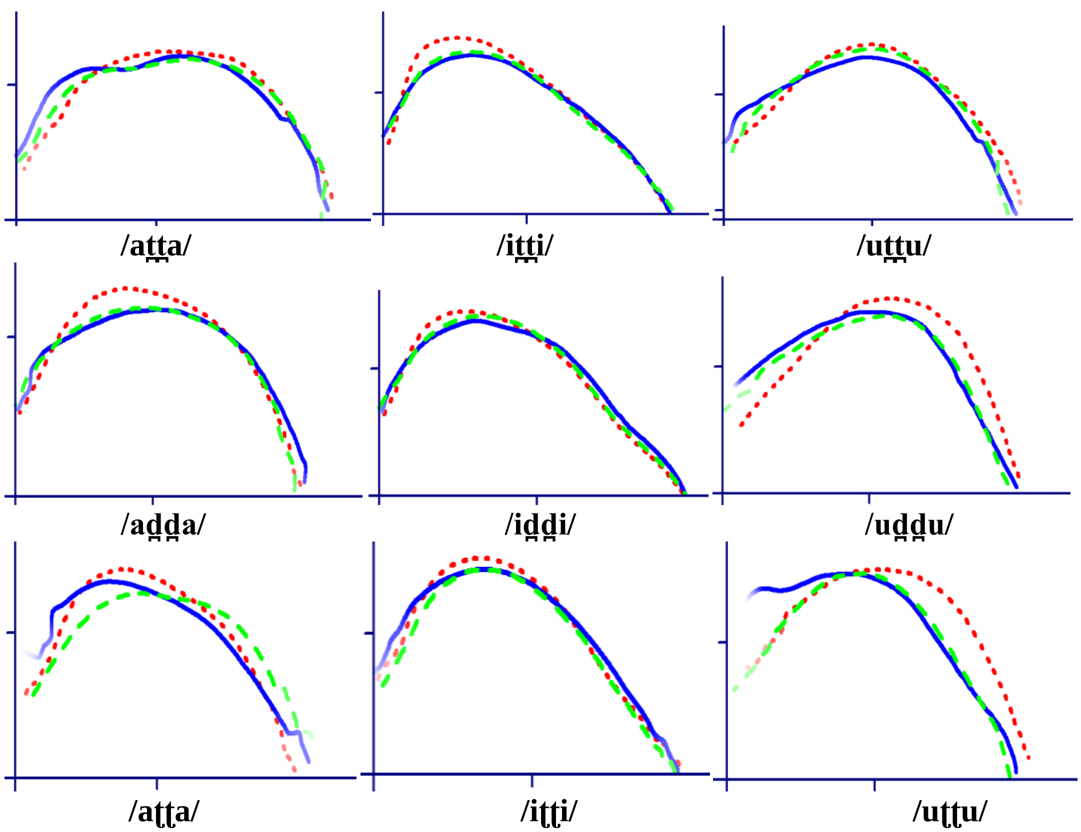
/V_1k/	18.067	2	.000***	3.569	.000*** ↓	3.507	.000***	0.206	.837
/V_1g/	12.867	2	.002**	3.404	.001*** ↓	3.569	.000*** ↓	0.566	.572
/t̪V_2/	4.200	2	.122	-	-	-	-	-	-
/d̪V_2/	1.867	2	.393	-	-	-	-	-	-
/ʈV_2/	20.067	2	.000***	3.507	.000*** ↓	3.589	.000*** ↓	0.123	.902
/ɖV_2/	6.067	2	.048*	1.646	.100	2.232	.026* ↓	0.494	.622
/kV_2/	9.800	2	.007**	3.137	.002** ↓	1.389	.165	1.892	.058
/gV_2/	7.916	2	.019**	2.433	.015* ↓	0.339	.734	2.859	.004** ↑

Note: *= p≤ 0.05, **= p≤ 0.01, ***= p≤ 0.001, Upward arrow (↑) shows higher mean EC during second vowel context. Conversely, downward arrow (↓) shows lowest mean EC during second vowel context. DF= Degrees of Freedom.

In Hindi, there were variations of EC across consonants and vowels. Among consonants, retroflexes were significantly different with highest EC than velars and dentals. Vowel /a/ had higher EC and lower coarticulation than vowel /i/ and /u/.

3.1.b. Direction of coarticulation across three corner vowels and places of articulation

Direction of coarticulation was calculated as a comparison of EC in the preceding and following vowel contexts. Average tongue contour of each phoneme in VCV syllable has been depicted in Figure 3.1.b.1. Tongue contour of dentals and velars were influenced by neighbouring vowel irrespective of whether preceding or following. However, retroflex were resisting the neighbouring vowel effect and conversely impacted the vowel trajectory. This pattern was more evident for the tongue contour of the following vowel.


/at̪t̪a/
/it̪t̪i/
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/ad̪d̪a/
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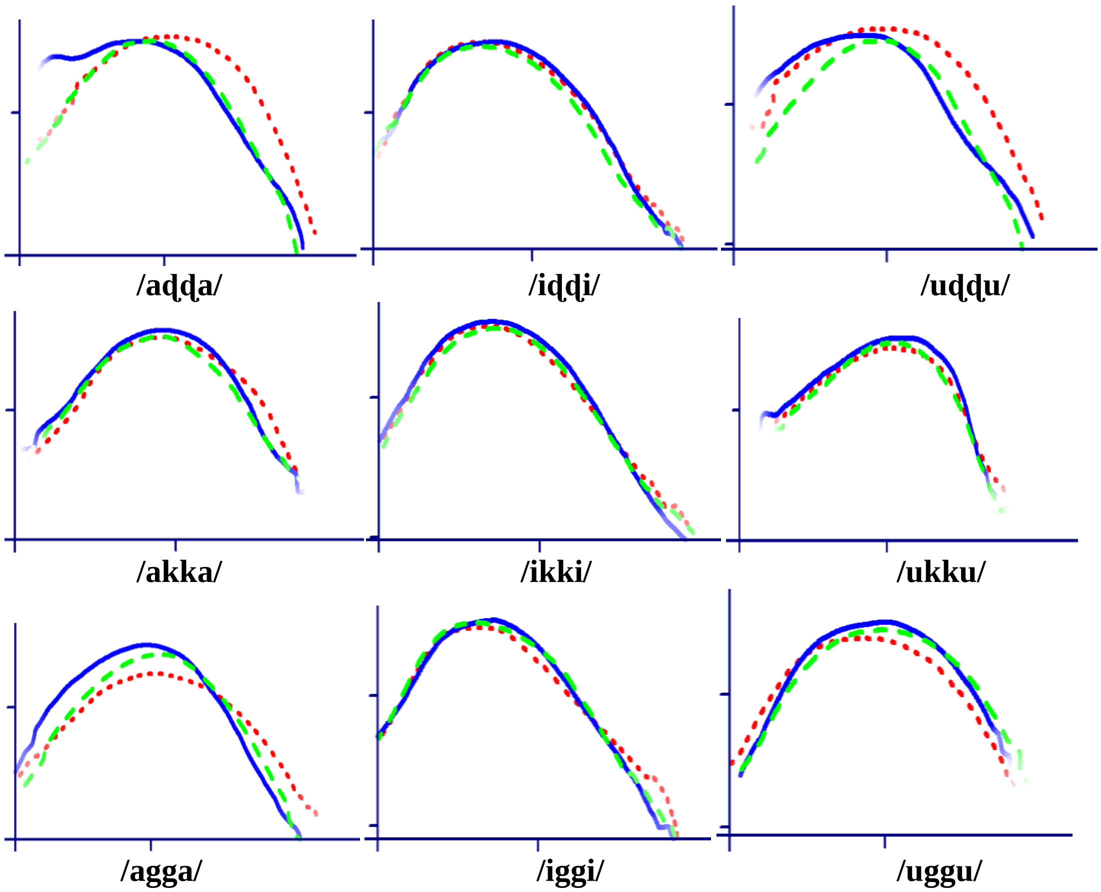

X axis- Tongue advancement; Y axis- Tongue height.

Figure. 3.1.b.1. Tongue contours of preceding vowel (red dotted line), consonant (blue filled line) and following vowel (green dashed line) for all 18 tokens in Hindi. The anterior tongue is towards the right side.

Combining details from both Figure 3.1.b.a and Table 3.1.a.1, EC from preceding vowel to consonant was higher than EC in the following vowel condition. Given this, there was significant indication of anticipatory coarticulation. There were two tokens of retroflexes in the context of /i/ that did not follow the trend of anticipatory direction of coarticulation. The distance between the consonant /ʈ/ and vowel /i/, in both preceding and following contexts were same, and the mean EC was 0.31 mm.

Furthermore, pair wise comparisons of extent of preceding and following vowels were carried out using Wilcoxon signed ranks test. Among 18 tokens, 15 tokens showed significant difference in EC between V_1C and CV_2 and confirmed anticipatory direction of coarticulation with lesser

EC from the following vowel to consonant except for /iɖi/ (Table 3.1.b.1). Interestingly, directionality was more towards carryover coarticulation for /iɖi/ with lesser EC in preceding vowel context than the following.

Table. 3.1.b.1.

Pair wise comparisons of extent of coarticulation in preceding (V_1C) and following vowel (CV_2) in Hindi

Tokens of EC	**/a/**		**/i/**		**/u/**	
	|Z|	**P**	**|Z|**	**P**	**|Z|**	**P**
V_1t̪- t̪V_2	3.569	.000*** ↓	2.695	.007** ↓	4.782	.000*** ↓
V_1d̪-d̪V_2	4.206	.000*** ↓	1.121	.262	3.486	.000*** ↓
V_1ʈ-ʈV_2	2.623	.009** ↓	0.093	.926	3.260	.001*** ↓
V_1ɖ-ɖV_2	1.964	.049** ↓	2.705	.007** ↑	2.293	.022* ↓
V_1k-kV_2	3.939	.000*** ↓	3.764	.000*** ↓	2.088	.037* ↓
V_1g-gV_2	3.384	.001*** ↓	2.684	.007** ↓	0.442	.658

Note: *= $p \leq 0.05$, **= $p \leq 0.01$, ***= $p \leq 0.001$, Downward arrow (↓) shows lowest mean EC during following vowel context (CV_2). Upward arrow (↑) shows higher mean EC during following vowel context (CV_2).

3.1.c. Comparison of extent of coarticulation across voicing counterparts

Extend of coarticulation was studied across voicing counterpart under the section of 3.1.a.2 for the preceding vowel and in 3.1.a.3 for the following vowel. In fact, it was noticeable that voiced dental /d̪/ had higher EC and was significantly different from unvoiced /t̪/ when preceded by vowels /a/ and /u/ (Table 3.1.a.2). There was no significant effect of voicing on EC, when the vowel followed the consonant (Table 3.1.a.3).

3.1.d. Comparison of extent of coarticulation across gender

As seen in other languages, effect of gender on EC was observed for very few tokens. Mann Whitney U test showed that males and females significantly differed for /i_1/ to /ɖ/ [|Z| = 3.007, p = .003, η^2 = .55], /i_2/ to /t̪/ [|Z| = 2.800, p = .005, η^2 = .51] and /u_2/ to /ʈ/ [|Z| = 2.841, p = .004, η^2 = .52]. These three tokens were significantly different among the 36 tokens considered where EC was less for females than males (Appendix II- Table 3).

Table. 3.1.e.1.
Descriptive statistics of extent of coarticulation of preceding (V_1C) and following vowel (CV_2) in mm respectively across gender in Hindi

Tokens of EC	Gender	/a/			/i/			/u/		
		Mean	**Median**	**SD**	**Mean**	**Median**	**SD**	**Mean**	**Median**	**SD**
V_1t̪	Male	0.51	0.52	0.12	0.36	0.32	0.12	0.67	0.65	0.22
	Female	0.47	0.49	0.20	0.30	0.27	0.12	0.63	0.56	0.28
t̪V_2	Male	0.34	0.30	0.13	0.33	0.29	0.15	0.32	0.29	0.16
	Female	0.32	0.30	0.12	0.20	0.18	0.11	0.32	0.33	0.16
V_1d̪	Male	0.61	0.66	0.17	0.36	0.32	0.16	0.52	0.50	0.20
	Female	0.60	0.65	0.21	0.25	0.27	0.09	0.51	0.56	0.27
d̪V_2	Male	0.36	0.31	0.19	0.27	0.26	0.11	0.33	0.31	0.16

	Female	0.34	0.28	0.24	0.28	0.26	0.10	0.39	0.35	0.26
V_1ʈ	Male	0.51	0.44	0.24	0.29	0.31	0.12	0.59	0.49	0.38
	Female	0.69	0.62	0.36	0.33	0.26	0.20	0.48	0.41	0.27
ʈV_2	Male	0.48	0.43	0.19	0.33	0.36	0.13	0.40	0.37	0.13
	Female	0.44	0.37	0.22	0.30	0.32	0.14	0.25	0.21	0.13
V_1ɖ	Male	0.55	0.57	0.19	0.32	0.28	0.11	0.51	0.39	0.29
	Female	0.63	0.59	0.37	0.28	0.21	0.32	0.42	0.29	0.30
ɖ V_2	Male	0.53	0.55	0.16	0.39	0.39	0.15	0.35	0.30	0.13
	Female	0.51	0.49	0.14	0.41	0.41	0.13	0.34	0.24	0.24
V_1k	Male	0.61	0.60	0.22	0.42	0.39	0.20	0.43	0.43	0.17
	Female	0.64	0.58	0.26	0.38	0.33	0.16	0.39	0.42	0.17
kV_2	Male	0.40	0.37	0.15	0.27	0.26	0.10	0.34	0.34	0.15
	Female	0.34	0.32	0.18	0.26	0.26	0.14	0.31	0.27	0.12
V_1g	Male	0.64	0.63	0.29	0.41	0.40	0.21	0.35	0.31	0.17
	Female	0.60	0.59	0.27	0.31	0.29	0.12	0.42	0.41	0.14
gV_2	Male	0.34	0.29	0.20	0.27	0.28	0.12	0.41	0.42	0.20
	Female	0.39	0.36	0.18	0.26	0.30	0.11	0.33	0.27	0.20

Note: SD- Standard Deviation

3.2.Coarticulation resistance

Coarticulation resistance of consonants, preceding vowel, and following vowel are calculated separately and discussed. Coarticulation resistance was analysed across consonants; coarticulation resistance of preceding and following vowels was studied across vowels for each places of articulation.

3.2.a. Comparison of Coarticulation Resistance of Consonants (CRC) across three places of articulation

Coarticulation resistance of consonant was explored as a comparison of two different vowel contexts. Hence, there were three vowel pairs and have been explained in Table 3.2.a.1. Coarticulation resistance was high for retroflexes in all three vowel pair contexts. Lowest resistance was observed for unvoiced velar consonant in the context of vowels /i/ and /u/.

Table. 3.2.a.1.

Descriptive statistics of coarticulation resistance of consonant (CRC) across three vowel combinations in Hindi

	(/a/, /i/)			**(/a/, /u/)**			**(/i/, /u/)**		
CRC	**Mean**	**Median**	**SD**	**Mean**	**Median**	**SD**	**Mean**	**Median**	**SD**
/t̪/	14.17	12.85	6.17	23.11	23.08	9.02	24.82	20.92	22.65
/d̪/	17.65	13.52	10.39	25.98	22.26	15.69	18.93	15.70	12.46
/ʈ/	26.00	21.72	16.94	35.11	28.09	18.55	32.46	20.88	24.72
/ɖ/	23.97	23.82	9.19	35.44	27.81	34.18	28.48	30.00	16.36
/k/	12.05	10.87	6.29	35.00	25.75	22.76	12.35	11.37	5.69
/g/	16.53	13.68	10.13	34.22	26.69	22.47	16.37	13.75	11.06

Note: SD- Standard Deviation

Further, Friedman test was adopted to inspect the null hypothesis of CR across consonants. Results showed that there were significant differences among consonants in each vowel pair categories including vowels /a/ and /i/ [χ^2 (5) = 48.095, p < .001], /a/ and /u/ [χ^2 (5) = 14.267, p =.014] and /i/ and /u/ [χ^2 (5) = 33.657, p < .001]. Hence, pair wise comparisons were made using Wilcoxon signed ranks test within each vowel category (Table 3.2.a.2). Interestingly, coarticulation resistance of retroflexes were significantly higher than dentals and velars in the vowel pair of /a/ and /i/ with the effect size range 0.47 to 0.84. Within the same vowel pair context, /k/ had significantly higher CRC than /g/ and lower than /d̪/.

Table. 3.2.a.2.

Pair wise comparison of coarticulation resistance of consonants (CRC) with three pairs of vowels in Hindi

	a & i		**a & u**		**i & u**	
CRC	**|Z|**	**P**	**|Z|**	**p**	**|Z|**	**p**
/t̪/ vs /d̪/	**1.861**	**.063**	**0.319**	**.750**	**1.779**	**.075**
/t̪/ vs /ʈ/	4.309	.000*** ↑	2.643	.008** ↑	0.854	.393
/t̪/ vs /ɖ/	4.062	.000*** ↑	2.520	.012* ↑	1.368	.171

/t̪/ vs /k/	1.717	.086	2.396	.017* ↑	3.322	.001*** ↓
/t̪/ vs /g/	0.710	.478	2.005	.045* ↑	1.923	.054
/d̪/ vs /ʈ/	3.240	.001*** ↑	2.561	.010** ↑	2.396	.017* ↑
/d̪/ vs /ɖ/	3.075	.002** ↑	1.923	.054	2.972	.003** ↑
/d̪/ vs /k/	3.342	.001*** ↓	2.232	.026* ↑	2.746	.006** ↓
/d̪/ vs /g/	0.586	.558	1.491	.136	1.203	.229
/ʈ/ vs /ɖ/	**0.237**	**.813**	**0.833**	**.405**	**0.257**	**.797**
/ʈ/ vs /k/	4.576	.000*** ↓	0.072	.943	4.042	.000*** ↓
/ʈ/ vs /g/	3.137	.002** ↓	1.039	.299	2.725	.006** ↓
/ɖ/ vs /k/	4.494	.000*** ↓	0.730	.465	4.206	.000*** ↓
/ɖ/ vs /g/	2.952	.003** ↓	0.483	.629	2.972	.003** ↓
/k/ vs /g/	**2.581**	**.010**** ↓	**0.668**	**.504**	**1.656**	**.098**

Note: *= p≤ 0.05, **= p≤ 0.01, ***= p≤ 0.001, Upward arrow (↑) shows higher CRC for the second consonant context. Conversely, downward arrow (↓) shows lowest mean CRC for the second consonant context.

In the context of vowels /a/ and /u/, unvoiced dental consonant /t̪/ had significantly low CR than retroflexes and velars. Voiced dental consonant was significantly different from unvoiced retroflex and unvoiced velars with lowest CR. Retroflexes were significantly different from velar cognates and voiced dental consonants, retroflexes had high CR when neighboured with /i/ and /u/. Also, dentals had significantly high CRC than /k/. Effect size was .36 to .48 for (/a/, /u/) and .44 to .77 for (/i/, /u/) context. In conclusion, retroflexes had higher CRC than other consonants in all the three vowel pairs considered. Other consonants did not show any trend across conditions.

3.2.b. Comparison of Coarticulation Resistance of Consonants (CRC) across voicing counterparts

Effect of voicing on CRC was investigated using Wilcoxon signed ranks test and results showed that unvoiced velar consonant /k/ was significantly different from its voiced equivalent /g/ only with the vowel pair /a/ and /i/ (Table. 3.2.a.2). Mean CRC was high for /k/ than /g/ (Table.

3.2.a.1). The other two places of articulation did not vary significantly across the voicing dimension.

3.2.c. Comparison of Coarticulation Resistance of Consonants (CRC) across gender

There was not much visible difference of CRC across gender based on descriptive statistics (Table 3.2.c.1). Mann Whitney U test was administered to analyse the effect of gender on CRC. Similar to other parameters there was no significant difference of CRC for all the tokens across males and females and depicted in Appendix III- Table 3.

Table 3.2.c.1

Descriptive statistics of coarticulation resistance of consonant (CRC) within vowel pairs across gender in Hindi

		(/a/, /i/)			**(/a/, /u/)**			**(/i/, /u/)**		
CRC	**Gender**	**Mean**	**Median**	**SD**	**Mean**	**Median**	**SD**	**Mean**	**Median**	**SD**
/t̪/	Male	14.28	11.77	7.10	24.31	23.38	9.54	26.76	21.32	28.55
	Female	14.07	12.99	5.35	21.93	22.81	8.63	22.89	20.52	15.49
/d̪/	Male	14.17	12.59	7.07	27.68	22.23	19.05	18.11	19.16	7.96
	Female	21.13	16.42	12.16	24.28	22.31	11.89	19.75	15.07	16.04
/ʈ/	Male	25.54	15.92	10.54	33.58	29.00	16.37	39.95	23.08	28.14
	Female	26.48	18.85	20.48	36.65	27.83	20.98	24.97	18.50	18.82
/ɖ/	Male	23.06	23.58	7.41	35.87	32.99	14.07	30.57	30.55	19.87
	Female	24.90	24.57	10.88	35.02	29.34	46.86	26.40	29.96	12.27
/k/	Male	10.22	10.52	2.59	35.45	29.96	18.89	12.48	12.62	4.51
	Female	13.90	11.38	8.26	35.55	35.44	25.00	12.23	9.47	6.84
/g/	Male	15.60	13.72	7.70	35.23	26.91	23.93	15.88	12.89	11.69
	Female	17.47	13.64	12.32	33.22	26.49	21.71	16.88	14.62	10.80

Note: SD-Standard Deviation

3.2.d. Comparison of Coarticulation Resistance of Preceding Vowel (CRPV) and Following Vowel (CRFV) across three corner vowels

Coarticulation resistance across preceding vowels was calculated to know the tendency of segmenting with different consonants. Table 3.2.d.1 explains the descriptive statistics of coarticulation resistance of preceding and following vowels with dentals, retroflexes, and velars. Based on the mean value, CRPV decreased in the order /i/ > /u/ > /a/ in the three consonant places of articulation considered.

Similar to preceding vowels, following vowels were also studied across vowels with three places of articulation. Table 3.2.d.1 depicts the mean, median, and standard deviation of CRFV. Vowel /i/ had highest CRFV (Mean = 29.05, Median = 24.23) in the context of retroflexes and vowel /a/ had lowest value (Mean = 11.05, Median = 8.46) with velars.

Table. 3.2.d.1.

Descriptive statistics of coarticulation resistance of preceding vowel (CRPV) within dentals, retroflexes and velars in Hindi

	Dentals			**Retroflexes**			**Velars**		
CRV	**Mean**	**Median**	**SD**	**Mean**	**Median**	**SD**	**Mean**	**Median**	**SD**
CRPV /a/	15.80	12.42	10.12	16.29	12.47	13.49	20.99	15.89	16.56
CRPV /i/	29.18	25.77	18.59	38.08	31.21	38.01	47.29	34.98	65.54
CRPV /u/	27.19	21.06	16.94	31.31	21.20	33.59	16.16	12.05	9.33
CRFV /a/	12.16	11.17	5.98	16.97	12.56	13.88	11.05	8.46	9.27
CRFV /i/	15.36	12.62	8.26	29.05	24.23	24.15	15.50	13.45	8.17
CRFV /u/	15.89	14.60	8.15	21.16	17.32	16.49	13.08	11.81	6.21

Note: SD- Standard Deviation

Variation of CRPV across vowels was scrutinised within each consonant place of articulation using Friedman test. Results showed significant effect of vowel for dentals [χ^2 (2) = 13.067, p =.001], retroflexes [χ^2 (2) = 12.800, p =.002], and velars [χ^2 (2) = 17.267, p < .001]. Wilcoxon signed ranks test was used to compare vowels and results revealed interesting findings. As given in Table 3.2.d.2, CR of /i/ was significantly different from /u/ and /a/, whereas /a/ and /u/ were not significantly different.

Similarly, Friedman test was administered to establish the effect of following vowel with each consonant context. There was significant difference across vowels only for velars [χ^2 (2) = 8.067, p = .018] and not for dentals [χ^2 (2) = 1.867, p = .393] and retroflexes [χ^2 (2) = 5.267, p = .072]. Further, Wilcoxon signed ranks pair wise test was executed only for velars and observed that there was significant difference of /i/ from /a/ (η^2 = .44) and /u/ (η^2 = .36). As given in Table 3.2.d.2, CRFV was high for /i/ than /a/ and /u/.

Table. 3.2.d.2.

Pair wise comparison of Coarticulation Resistance of Preceding Vowel (CRPV) with dental, retroflex and velar consonants in Hindi

	Dentals		**Retroflexes**		**Velars**	
CRV	**|Z|**	**P**	**|Z|**	**P**	**|Z|**	**P**
CRPV /a/ vs /i/	3.466	.001*** ↑	3.548	.000*** ↑	2.890	.004** ↑
CRPV /a/ vs /u/	0.195	.845	0.689	.491	1.368	.171
CRPV /i/ vs /u/	3.363	.001*** ↓	2.787	.005** ↓	4.186	.000*** ↓
CRFV /a/ vs /i/	-	-	-	-	2.437	.015* ↑
CRFV /a/ vs /u/	-	-	-	-	1.347	.178
CRFV /i/ vs /u/	-	-	-	-	1.985	.047* ↓

Note: **= p≤ 0.01, ***= p≤ 0.001, Upward arrow (↑) shows higher CRPV for the second vowel context. Conversely, downward arrow (↓) shows lowest mean CRPV for the second vowel context.

3.2.e. Comparison of Coarticulation Resistance of Preceding Vowel (CRPV) and Following Vowel (CRFV) across gender

Mann Whitney U test was adopted to study the effect of gender on CRPV and CRFV. Findings showed that there was no significant difference between males and females with respect to CRPV except for vowel /a/ when it preceded retroflexes (|Z| = 2.012, p = .044, η^2 = .37) and |Z| and p values of other vowels are depicted in Appendix IV- Table 3. Males had higher CRPV than females (Table 3.2.e.1).

Based on descriptive statistics (Table 3.2.e.1), CRFV of males and females were moreover similar. However, significant effect of gender on CRFV was explored using Mann Whitney U test. Obtained results showed that both males and females behaved similarly for CRFV (Appendix V- Table 3). Hence the null hypothesis that there is no significant difference across gender for CRFV is accepted.

Table 3.2.e.1

Descriptive statistics of coarticulation resistance of preceding vowel (CRPV) and following vowel (CRFV) within dentals, retroflexes and velars across gender in Hindi

		Dentals			**Retroflexes**			**Velars**		
CRV	**Gender**	**Mean**	**Median**	**SD**	**Mean**	**Median**	**SD**	**Mean**	**Median**	**SD**
CRPV /a/	Male	17.06	13.72	11.55	19.97	18.03	17.61	23.49	16.12	19.69
	Female	14.56	11.62	8.69	12.61	11.93	7.82	18.49	15.67	12.93
CRPV /i/	Male	29.96	22.52	20.13	25.17	27.43	11.26	34.30	35.82	16.50
	Female	28.40	27.46	17.60	51.00	37.71	50.10	60.30	28.09	90.91
CRPV /u/	Male	28.75	20.69	20.30	41.15	24.82	44.19	16.50	12.03	10.55
	Female	25.64	21.44	13.33	21.48	15.14	13.33	15.83	12.08	8.30
CRFV /a/	Male	12.66	11.18	5.47	17.07	11.86	14.35	8.89	6.66	4.42
	Female	11.65	11.15	6.61	16.87	13.55	13.90	13.20	8.60	12.18
CRFV /i/	Male	14.99	11.55	7.95	27.51	25.59	15.92	13.42	10.34	6.18
	Female	15.72	13.68	8.83	30.58	22.88	30.82	17.58	13.80	9.53
CRFV /u/	Male	16.94	16.85	8.28	26.76	19.69	21.23	12.38	11.81	4.49
	Female	14.84	12.73	8.17	15.56	14.39	6.77	13.79	12.12	7.65

Note: SD-Standard Deviation

As observed in Dravidian languages, Hindi also had some interesting patterns of coarticulation. Null hypothesis of effect of places of articulation and vowels were rejected since there were significant effect of places of articulation and vowels. Retroflexes were significantly different from velars and dentals; retroflexes had highest EC than other two places of articulation with /a/ context. Also, vowel /a/ was significantly different from /i/ and /u/ with high EC. Among the tokens considered, most of them showed anticipatory coarticulation except /iɖi/. Retroflexes and high front vowel /i/ had significantly high coarticulation resistance. In Hindi, effect of voicing and gender was observed for few tokens as seen in Kannada and Malayalam. Hence, the null hypothesis of voicing and gender are accepted except for few tokens which showed significant difference.

II. Study of parameters of coarticulation across languages

In this section, the parameters of coarticulation under study are first compared across the two Dravidian languages, Kannada and Malayalam. This is followed by comparison between the Dravidian languages and Hindi; i.e. between Kannada and Hindi, followed by Malayalam and Hindi.

4.1. Extent and direction of coarticulation

This section intends to test the hypothesis of effect of language on coarticulation parameters. Extent of coarticulation was studied across languages for each token both in preceding and following vowel contexts. Over all, statistical analysis was conducted and further, pair wise analysis was used when necessary. Description of direction of coarticulation across languages was accounted based on the established data from each language.

4.1.a. Extent of coarticulation (EC) across places of articulation in preceding vowel context

Descriptive statistics of EC in the preceding and following vowel contexts were compared across languages (Table 4.1.a.1). Distance between preceding vowel and consonant was more in Dravidian languages i.e. Kannada and Malayalam than Indo Aryan language Hindi for most of the stimulus tokens. Distances from vowel /i/ to retroflexes, vowel /u/ to dental /t̪/ were comparatively high for Hindi speakers. Among the three languages, Malayalam had highest EC for 12 tokens out of 18 tokens considered. However, EC of the following vowels did not show much variation across languages and this indicated similarity of EC in the following vowel contexts. As seen in Table 4.1.a.1, mean EC was distributed from .20 to .51 mm across languages.

Table. 4.1.a.1.

Extent of coarticulation across places of articulation in preceding and following vowel contexts (RMS distance in mm from V_1 to C and C to V_2) in three languages

Tokens of EC	**Language**	**/a/**			**/i/**			**/u/**		
		Mean	**Median**	**SD**	**Mean**	**Median**	**SD**	**Mean**	**Median**	**SD**
/V_1t̪/	K	0.63	0.68	0.27	0.39	0.35	0.18	0.75	0.78	0.32
	M	0.62	0.49	0.23	0.44	0.38	0.23	0.60	0.55	0.35
	H	0.49	0.51	0.16	0.33	0.30	0.12	0.64	0.64	0.24
/V_1d̪/	K	0.63	0.58	0.32	0.37	0.27	0.13	0.82	0.86	0.27
	M	0.60	0.63	0.24	0.42	0.36	0.20	0.64	0.55	0.30
	H	0.60	0.65	0.18	0.30	0.28	0.13	0.51	0.49	0.23
/V_1ʈ/	K	0.72	0.46	0.38	0.24	0.19	0.12	0.73	0.60	0.45
	M	0.86	0.90	0.29	0.39	0.36	0.16	0.82	0.87	0.31
	H	0.59	0.52	0.31	0.31	0.29	0.16	0.53	0.46	0.32
/V_1ɖ/	K	0.76	0.71	0.37	0.23	0.22	0.10	0.81	0.72	0.39
	M	0.85	0.83	0.32	0.43	0.40	0.21	0.80	0.84	0.28
	H	0.58	0.58	0.29	0.29	0.24	0.23	0.46	0.38	0.29
/V_1k/	K	0.70	0.73	0.29	0.43	0.40	0.19	0.55	0.45	0.32
	M	0.78	0.75	0.31	0.56	0.58	0.22	0.57	0.58	0.22
	H	0.62	0.59	0.23	0.40	0.37	0.17	0.41	0.42	0.16
/V_1g/	K	0.75	0.76	0.31	0.44	0.42	0.16	0.57	0.54	0.24
	M	0.85	0.81	0.35	0.50	0.49	0.20	0.53	0.56	0.18
	H	0.62	0.62	0.27	0.36	0.35	0.17	0.38	0.34	0.16
/V_2t̪/	K	0.34	0.31	0.16	0.23	0.18	0.11	0.36	0.32	0.19
	M	0.23	0.21	0.12	0.20	0.20	0.08	0.26	0.27	0.11
	H	0.32	0.29	0.12	0.26	0.22	0.14	0.31	0.30	0.15
/V_2d̪/	K	0.32	0.32	0.12	0.21	0.18	0.10	0.32	0.30	0.11
	M	0.28	0.25	0.13	0.25	0.22	0.12	0.28	0.26	0.12
	H	0.34	0.29	0.21	0.27	0.26	0.10	0.35	0.31	0.21
/V_2ʈ/	K	0.36	0.32	0.18	0.22	0.18	0.12	0.37	0.33	0.19
	M	0.34	0.32	0.12	0.25	0.21	0.13	0.31	0.29	0.13
	H	0.46	0.42	0.20	0.31	0.33	0.13	0.32	0.30	0.14
/V_2ɖ/	K	0.39	0.34	0.25	0.25	0.21	0.16	0.35	0.32	0.18
	M	0.37	0.39	0.13	0.31	0.26	0.17	0.31	0.29	0.14
	H	0.51	0.41	0.46	0.34	0.31	0.14	0.34	0.29	0.19
/V_2k/	K	0.34	0.27	0.21	0.28	0.27	0.15	0.33	0.31	0.17
	M	0.32	0.30	0.14	0.34	0.28	0.23	0.29	0.25	0.16
	H	0.36	0.35	0.16	0.26	0.25	0.11	0.32	0.31	0.13
/V_2g/	K	0.42	0.42	0.24	0.30	0.28	0.17	0.31	0.27	0.17
	M	0.35	0.36	0.17	0.30	0.27	0.15	0.30	0.26	0.14
	H	0.36	0.32	0.18	0.26	0.28	0.11	0.37	0.30	0.19

Note: SD- Standard deviation; K-Kannada, M- Malayalam, H- Hindi

Kruskal-Wallis H test was administered to test the effect of language on EC in the preceding vowel context. Results established that there was a significant effect of language except for few tokens such as /a-d̪/, /a-k/, /i-t̪/ and /u-t̪/. Hence pair wise language comparison was executed using Mann Whitney U test for those tokens which showed significant difference. (Table 4.1.a.2). Findings revealed that Dravidian languages were significantly different for /a-ʈ/, /i-d̪/, /i-ʈ/, /i-ɖ/ and /i-k/ with high EC in Malayalam. However, Malayalam had lowest EC for /u-d̪/. When compared across language families, Hindi had reduced EC than Kannada for /a-t̪/, /i-g/, /u-d̪/, /u-ɖ/ and /u-g/. Similarly, EC of Hindi speakers was significantly reduced than Malayalam speakers except for /a/-/t̪/ and /u/- /d̪/. Effect size for EC was less when compared across languages. It varied from .3 to .51 for comparison across Malayalam and Kannada. Hindi and Kannada comparison had narrow range (η^2 = .42 to .51) than Hindi and Malayalam (η^2 = .29 to .53).

Overall effect of language on following vowel was explored using Kruskal-Wallis H test and findings showed significant difference only for three tokens, /a-t̪/, /i-d̪/, and /i-ɖ/ (Table 4.1.a.2). Further, Mann Whitney U test was adopted to make pair wise comparisons across languages. Results revealed that Hindi had significantly reduced EC in vowel /i/ context than Kannada. However, EC of vowel /a/ context was significantly reduced for Malayalam than Kannada and Hindi. Overall effect size varied from .33 to .45.

Table. 4.1.a.2.

Comparison of extent of coarticulation (EC) from preceding and following vowels to consonant across languages

Tokens of EC	χ^2	**DF**	**P**	**K vs M**		**K vs H**		**M vs H**	
				|Z|	**P**	**|Z|**	**P**	**|Z|**	**p**
a_1- t̪	12.646	2	.002**	1.649	.099	3.726	.000*** ↓	1.538	.124
a_1- d̪	0.086	2	.958	-	-	-	-	-	-
a_1- ʈ	11.392	2	.003**	2.462	.014* ↑	0.044	.965	3.341	.001*** ↓
a_1- ɖ	9.748	2	.008**	1.094	.274	1.722	.085	3.230	.001*** ↓
a_1-k	3.946	2	.139	-	-	-	-	-	-
a_1-g	6.945	2	.031*	1.057	.290	1.523	.128	2.632	.008** ↓
i_1- t̪	4.395	2	.111	-	-	-	-	-	-
i_1- d̪	8.081	2	.018*	2.506	.012* ↑	0.288	.773	2.388	.017* ↓
i_1- ʈ	15.465	2	.000***	3.955	.000*** ↑	1.597	.110	2.210	.027* ↓
i_1- ɖ	16.873	2	.000***	3.844	.000*** ↑	0.872	.383	3.105	.002** ↓
i_1-k	10.121	2	.006**	2.321	.020* ↑	0.724	.469	3.031	.002** ↓
i_1-g	11.463	2	.003**	1.183	.237	2.299	.021* ↓	3.231	.001*** ↓
u_1- t̪	4.580	2	.101	-	-	-	-	-	-
u_1- d̪	15.983	2	.000***	2.439	.015* ↓	3.977	.000*** ↓	1.442	.149
u_1- ʈ	10.030	2	.007**	1.301	.193	1.486	.137	3.341	.001*** ↓
u_1- ɖ	20.748	2	.000***	0.296	.767	3.770	.000*** ↓	4.081	.000*** ↓
u_1-k	9.370	2	.009**	1.412	.158	1.767	.077	2.979	.003** ↓
u_1-g	14.125	2	.001***	0.377	.706	3.253	.001*** ↓	3.223	.001*** ↓
a_2- t̪	15.382	2	.000***	3.482	.000*** ↓	0.399	.690	3.267	.001*** ↑
a_2- d̪	2.582	2	.275	-	-	-	-	-	-
a_2- ʈ	5.837	2	.054	-	-	-	-	-	-
a_2- ɖ	2.013	2	.366	-	-	-	-	-	-
a_2-k	1.530	2	.465	-	-	-	-	-	-
a_2-g	1.680	2	.432	-	-	-	-	-	-
i_2- t̪	2.023	2	.364	-	-	-	-	-	-
i_2- d̪	6.134	2	.047*	1.138	.255	2.513	.012* ↑	1.242	.214
i_2- ʈ	5.916	2	.052	-	-	-	-	-	-
i_2- ɖ	7.595	2	.022*	1.722	.085	2.595	.009** ↑	1.301	.193
i_2-k	1.819	2	.403	-	-	-	-	-	-
i_2-g	0.424	2	.809	-	-	-	-	-	-
u_2- t̪	3.656	2	.161	-	-	-	-	-	-
u_2- d̪	1.857	2	.395	-	-	-	-	-	-
u_2- ʈ	1.548	2	.461	-	-	-	-	-	-
u_2- ɖ	0.649	2	.723	-	-	-	-	-	-
u_2-k	0.929	2	.628	-	-	-	-	-	-
u_2-g	1.784	2	.410	-	-	-	-	-	-

Note: *= p≤ 0.05, **= p≤ 0.01, ***= p≤ 0.001, Upward arrow (↑) shows higher mean EC for the second language mentioned. Conversely, downward arrow (↓) shows lowest mean EC for the second language mentioned. K- Kannada, M-Malayalam, H-Hindi.

4.1.c. Direction of coarticulation across vowels and places of articulation

Comparison of direction of coarticulation was explored across languages based on EC values. As explained earlier, if the EC of the preceding vowel is higher than the following vowel, it indicates anticipatory coarticulation. However, carryover coarticulation is identified when EC of the preceding vowel is less than the following vowel. In Dravidian languages, there was a clear anticipatory coarticulation. This finding was significant across places of articulation except when retroflexes shared neighbourhood with vowel /i/ in VCV syllable of Kannada speakers (Sections 1.1.b and 2.1.b). Indo Aryan language Hindi, also showed similar results to some extent, where majority of the tokens (14/18) exhibited anticipatory coarticulation. Conversely, one token i.e. /iɖi/ showed carryover coarticulation with lesser EC in the preceding vowel context than following. Difference between V_1C and V_2C was not significantly different for /id̪i/, /iʈi/, and /ugu/, though EC of the preceding vowel was higher than the following vowel (Section 3.1.b).

In conclusion, significant anticipatory coarticulation was observed in all three languages though they belonged to two different language families. Carryover coarticulation was significantly present only for one single token in Hindi i.e. /iɖi/.

4.2. Coarticulation resistance (CR)

Across language comparison was implemented to analyse the pattern of coarticulation resistance for the places of articulation and vowels. This was explored for the parameters i.e. coarticulation resistance of consonants, preceding and following vowels.

4.2.a. Comparison of Coarticulation Resistance of Consonants (CRC) across three places of articulation

Coarticulation resistance of consonants was calculated as a comparison of two vowel contexts. Hence, CRC was measured and explained under three vowel pairs, (/a/, /i/), (/a/, /u/), and (/i/, /u/). Mean, median, and standard deviation of CRC across vowel pairs and six consonants considered in each language is given in Table 4.2.a.1. There was no distinct pattern of CRC across languages; it varied across places of articulation rather than language. Highest and lowest CRC was observed for Malayalam speakers; highest was for /k/ in (/a/, /u/) vowel context (Mean = 45.20, Median = 39.36), and lowest was for /t̪/ in (/a/, /i/) vowel pair context.

Kruskal-Wallis H test was adopted to explore the effect of language on CRC and results proved that language had a significant effect, only for CR of few consonants including /k/ in (/a/, /i/) context, /t̪/, /ɖ/, and /g/ in (/a/, /u/) context (Table 4.2.a.2). Pair wise comparisons of languages were performed using Mann Whitney U test for these three tokens. Malayalam speakers had significant high CR for /k/ in (/a/, /i/) context, /ɖ/ and /g/ in (/a/, /u/) context than Hindi speakers. CR for /t̪/ in (/a/, /u/) context was significantly high in Kannada than in Malayalam. Also Kannada speakers had significantly higher CR than Hindi speakers for /ɖ/ in (/a/, /u/) context (Table 4.2.a.2). Effect size was less for all the tokens and ranged from .34 to .43.

Table. 4.2.a.1.

Descriptive statistics of coarticulation resistance of consonant (CRC) across three vowel combinations in three language

CRC	**Language**	**(/a/, /i/)**			**(/a/, /u/)**			**(/i/, /u/)**		
		Mean	**Median**	**SD**	**Mean**	**Median**	**SD**	**Mean**	**Median**	**SD**
/t̪/	K	13.72	13.21	5.80	24.71	23.22	10.29	19.65	15.93	15.2
	M	12.27	11.30	4.88	21.78	20.74	8.60	15.68	13.39	7.56
	H	14.17	12.85	6.17	23.11	23.08	9.02	24.82	20.92	22.6
/d̪/	K	15.51	13.19	8.30	26.08	23.06	12.86	18.86	14.92	11.85
	M	14.02	12.61	6.15	24.72	22.64	10.70	18.67	13.61	13.78
	H	17.65	13.52	10.3	25.98	22.26	15.69	18.93	15.70	12.4
/ʈ/	K	23.50	21.07	13.00	38.18	34.40	24.40	32.98	25.74	19.24
	M	22.52	19.93	11.24	36.01	35.38	21.04	34.33	31.04	17.34
	H	26.00	21.72	16.9	35.11	28.09	18.55	32.46	20.88	24.7
/ɖ/	K	26.55	24.09	13.82	43.63	37.73	31.53	29.40	28.26	13.79
	M	26.97	25.54	12.26	41.51	41.50	13.32	32.71	28.27	14.05
	H	23.97	23.82	9.19	35.44	27.81	34.18	28.48	30.00	16.3
/k/	K	14.43	11.89	10.14	37.77	27.67	22.40	13.47	12.20	7.35
	M	15.42	14.52	5.85	45.20	39.36	24.57	14.78	13.42	7.78
	H	12.05	10.87	6.29	35.00	25.75	22.76	12.35	11.37	5.69
/g/	K	16.18	13.76	7.97	39.32	32.66	21.97	15.96	12.57	10.52
	M	17.48	14.89	7.73	44.74	37.27	20.43	17.06	12.74	12.00
	H	16.53	13.68	10.1	34.22	26.69	22.47	16.37	13.75	11.0

Note: SD- Standard deviation, K- Kannada, M- Malayalam, H- Hindi

Table. 4.2.a.2.

Comparison of Coarticulation Resistance of Consonant (CRC) with vowel combinations across three languages

					K vs M		**K vs H**		**M vs H**	
	CRC	χ^2	**DF**	**P**	**|Z|**	**P**	**|Z|**	**P**	**|Z|**	**P**
	/t̪/	2.644	2	.267	-	-	-	-	-	-
	/d̪/	1.087	2	.581	-	-	-	-	-	-
(a, i)	**/ʈ/**	0.359	2	.836	-	-	-	-	-	-
	/ɖ/	0.417	2	.812	-	-	-	-	-	-
	/k/	6.578	2	.037*	1.212	.225	1.168	.243	2.646	.008** ↓
	/g/	1.716	2	.424	-	-	-	-	-	-
	/t̪/	7.166	2	.028*	2.528	.011* ↓	1.996	.046	0.562	.574
	/d̪/	1.736	2	.420	-	-	-	-	-	-
(a, u)	**/ʈ/**	2.295	2	.317	-	-	-	-	-	-
	/ɖ/	13.27	2	.001***	0.444	.657	2.986	.003** ↓	3.297	.001*** ↓
	/k/	5.004	2	.082	-	-	-	-	-	-
	/g/	6.764	2	.034*	1.360	.174	1.212	.225	2.602	.009** ↓
	/t̪/	4.553	2	.103	-	-	-	-	-	-
	/d̪/	1.282	2	.527	-	-	-	-	-	-
(a, i)	**/ʈ/**	2.211	2	.331	-	-	-	-	-	-
	/ɖ/	2.005	2	.367	-	-	-	-	-	-
	/k/	2.634	2	.268	-	-	-	-	-	-
	/g/	0.633	2	.729	-	-	-	-	-	-

Note: *= $p \leq 0.05$, **= $p \leq 0.01$, ***= $p \leq 0.001$, Upward arrow (↑) shows higher CRC for the second language mentioned. Conversely, downward arrow (↓) shows lowest mean CRC for the second language mentioned. K- Kannada, M-Malayalam, H-Hindi.

4.2.b. Comparison of Coarticulation resistance of preceding vowel (CRPV) and following vowel (CRFV) across three corner vowels

Coarticulation resistance of preceding vowel was studied across languages for the three places of articulation as calculated within each language. The distribution of CRPV and CRFV has been explained as mean, median, and standard deviation in Table 4.2.b.1. CRPV is high for Malayalam speakers in most of the tokens except for /u/ in dental context. Overall CRPV ranged from 16.16 (/u/ in dental context for Hindi) to 79.74 (/i/ in retroflex context for Malayalam).

Similar to CRPV, CRFV varied across languages. Kannada speakers had relatively higher CR for all three vowels in dental context, whereas, for Malayalam speakers in retroflex context. Hindi had relatively less CR for all contexts than Dravidian languages.

Table. 4.2.b.1.

Descriptive statistics of coarticulation resistance of preceding vowel (CRPV) and following vowel (CRFV) across three vowel combinations in three languages

		Dentals			**Retroflexes**			**Velars**		
CRV	**Language**	**Mean**	**Median**	**SD**	**Mean**	**Median**	**SD**	**Mean**	**Median**	**SD**
CRP	**K**	18.57	15.40	12.77	15.39	11.97	12.44	24.83	17.55	20.66
/a/	**M**	23.67	18.34	18.63	30.54	25.35	21.48	35.09	30.30	23.62
	H	15.80	12.42	10.12	16.29	12.47	13.49	20.99	15.89	16.56
CRP	**K**	43.14	30.97	30.64	57.46	46.23	39.54	55.14	32.43	64.65
/i/	**M**	49.17	36.80	39.37	79.74	65.59	81.60	69.59	46.87	56.68
	H	29.18	25.77	18.59	38.08	31.21	38.01	47.29	34.98	65.54
CRP	**K**	51.42	36.10	51.50	52.76	39.56	40.16	35.38	23.12	48.41
/u/	**M**	41.29	24.57	48.55	60.19	53.95	35.43	37.93	31.93	23.15
	L	27.19	21.06	16.94	31.31	21.20	33.59	16.16	12.05	9.33
	K	19.52	18.03	9.43	10.71	8.10	6.66	16.60	12.36	10.53
CRF	**M**	13.87	13.83	6.97	19.05	15.55	12.89	17.16	13.41	13.54
/a/	**H**	12.16	11.17	5.98	16.97	12.56	13.88	11.05	8.46	9.27
	K	24.71	20.25	16.08	14.44	10.71	11.20	20.05	20.02	8.29
CRF	**M**	9.16	9.51	4.67	15.05	12.90	8.47	14.79	12.80	10.07
/i/	**H**	15.36	12.62	8.26	29.05	24.23	24.15	15.50	13.45	8.17
	K	19.34	15.23	14.49	15.85	13.93	12.69	13.75	8.85	11.55
CRF	**M**	15.86	13.02	9.456	19.19	17.24	10.00	14.69	12.40	7.66
/u/	**H**	15.89	14.60	8.15	21.16	17.32	16.49	13.08	11.81	6.21

Note: SD- Standard deviation

Effect of language was tested using Kruskal-Wallis H test, where significant language effect on CRPV was demonstrated for all three vowels in retroflex context, but not for dentals and for vowel /i/ in velar context. Further, pair wise analysis was executed using Mann Whitney U test, (Table 4.2.b.2). CR of /a/ was significantly different across Kannada and Malayalam where the latter had high CR for vowel /a/ in retroflex context. However, Kannada had higher CR than Hindi speakers for vowels /i/ and /u/ in retroflex and for vowel /u/ in velar contexts. Malayalam speakers had marginally significant CR for vowels /a, i, u/ in retroflex context and vowels /a, u/ in velar context than Hindi speakers. Effect size was ranging from .34 to .57 for CRPV in three languages.

Kruskal-Wallis H test findings showed significant language effect on CRFV, specifically for /a/ in all consonant contexts (Table 4.2.b.2). Vowel /i/ was significantly different across languages when it followed dentals and retroflexes in VCV syllable. Mann Whitney U test was administered to establish pair wise comparison of languages. Dravidian languages were significantly different for CR of vowel /a/ in both retroflex and dental contexts where Malayalam speakers exhibited higher CR than Kannada speakers. Also, there was significant difference when two of these Dravidian languages were compared with Hindi an Indo Aryan language. Hindi was significantly different from Malayalam for /a/ in all the three consonant contexts and /i/ for dental and retroflex contexts. The trend was different across tokens where Hindi had higher CR for vowels /a/ and /i/ in retroflex context. However, CR was low for Hindi than Malayalam speakers for vowel /a/ in dental and velar contexts and vowel /i/ in dental context.

Table. 4.2.b.2.

Comparison of coarticulation resistance of preceding vowel (CRPV) and following vowel (CRFV) across three vowel combinations in three languages

					K vs M		K vs H		M vs H	
	CRV	χ^2	**DF**	**P**	**|Z|**	**P**	**|Z|**	**p**	**|Z|**	**P**
Dental	CRP /a/	2.717	2	.257	-	-	-	-	-	-
	CRP /i/	5.794	2	.055	-	-	-	-	-	-
	CRP /u/	5.463	2	.065	-	-	-	-	-	-
Retroflex	CRP /a/	18.248	2	.000***	3.755	.000***↑	0.503	.615	3.593	.000***↓
	CRP /i/	9.814	2	.007**	0.872	.383	2.040	.041*↓	3.120	.002**↓
	CRP /u/	16.732	2	.000***	1.198	.231	3.223	.001***↓	3.652	.000***↓
Velar	CRP /a/	7.267	2	.026*	1.870	.061	0.532	.595	2.661	.008**↓
	CRP /i/	5.423	2	.066	-	-	-	-	-	-
	CRP /u/	17.941	2	.000***	1.648	.099	2.099	.036*↓	4.450	.000***↓
Dental	CRF /a/	23.563	2	.000***	4.568	.000***↑	3.282	.001***↓	1.907	.056
	CRF /i/	6.048	2	.049***	1.789	.074	2.336	.019*↓	0.606	.544
	CRF /u/	0.039	2	.981	-	-	-	-	-	-
Retroflex	CRF /a/	8.273	2	.016**	2.646	.008**↑	2.321	.020*↑	0.237	.813
	CRF /i/	14.006	2	.001***	1.952	.051	3.445	.001***↑	2.336	.019**↑
	CRF /u/	0.855	2	.652	-	-	-	-	-	-
Velar	CRF /a/	9.977	2	.007**	1.552	.121	3.105	.002**↓	1.685	.092
	CRF /i/	0.111	2	.946	-	-	-	-	-	-
	CRF /u/	2.374	2	.305	-	-	-	-	-	-

Note: *= $p \leq 0.05$, **= $p \leq 0.01$, ***= $p \leq 0.001$, Upward arrow (↑) shows higher CRC for the second language mentioned. Conversely, downward arrow (↓) shows lowest mean CRC for the second language mentioned. K- Kannada, M-Malayalam, H-Hindi.

Effect of language was studied under extent of coarticulation, direction of coarticulation, coarticulation resistance of consonant, preceding vowel, and following vowel. There were more similarities across languages rather than differences with considerably less effect size. General trend of coarticulation was similar though there were variations within tokens. Dravidian languages behaved moreover similarly across the coarticulation parameters. On comparison of Dravidian languages with Hindi, Kannada was closer to Hindi than Malayalam. The hypothesis of language that there is no significant difference of coarticulation across language is rejected for most of the tokens.

CHAPTER V- DISCUSSION

The results obtained from the present study are discussed under the following headings:

I. Effect of places of articulation and vowels on coarticulation

II. Effect of voicing on coarticulation

III. Effect of gender on coarticulation

IV. Effect of language on coarticulation

I. Effect of places of articulation and vowels on coarticulation

Findings showed different patterns of EC in each language, both in preceding and following vowel contexts. As clearly seen in the findings, the coarticulatory effect of consonants varies based on the syllabic position. For example, when a consonant is considered in vowel preceding the consonant (VC) condition, the coarticulatory effect varies across consonants.

Kannada speakers showed significant difference across consonants in the context of vowel /i/ and /u/. Retroflexes had reduced EC when it occurred with vowel /i/, whereas velars were noticed to have minimal EC in the neighboured of vowel /u/. This indicates that retroflexes and velars had greater coarticulation in /i-C/ and /u-C/ contexts respectively. This can be explained based on the figure 1.1.b.1 (under results section), where the active articulators are the same i.e. tongue tip/blade and dorsum for the production of both vowel /i/ and retroflex (/i-Retroflexes-i/), and tongue root for both vowel /u/ and velars (/u- Velars-u/). Hence, it was easy to move from one phoneme to other (V to C) and influence each other.

In Malayalam, dentals had lowest EC in vowel /a/ context, velars in /i/, and retroflexes in /u/ context when the vowels were in the preceding position. This denotes that dentals, velars, and retroflexes had higher coarticulation in these respective contexts. As seen in figure 2.1.b.1., tongue height was increased for /a/ and moreover mimics the pattern of dentals. Tongue contour of all the consonants were more towards the tongue contour of vowel /i/ when they were proximal. Retroflexes were strong enough to make the tongue dorsum movement instead of tongue root for the production of /u/.

Hindi speakers had different pattern of EC, where dental /t̪/ had greater coarticulation, but velars and retroflexes had medium coarticulation in vowel /a/ context. Tongue contour of /a/ slightly altered towards the tongue contour of /t̪/, specifically the area of tongue tip/ blade along with tongue height which was not obvious in other places of articulation (Figure 3.1.b.1). In the vowel /u/ context, dentals had greater EC and low coarticulation than other two places of articulation. Here, the articulatory gestures of dentals and vowel /u/ are entirely different. Coupling of these gestures was partial resulting in lack of impact. For other places of articulation especially velars, the gestures were similar and was easy to couple the gestures.

Similar to consonant coda position, there was significant difference across consonants in onset or consonants preceding a vowel position (CV). Malayalam speakers showed significant difference for dentals compared to other places of articulation with greater coarticulation in /a/ context and lesser in /i/ context. It is apparent in figure 2.1.b.1., that the tongue contour of following vowel /a/ impersonates dentals. However, this imitation of articulatory synergy is lacking in /i-dental/ context compared to retroflexes and velars. In Hindi, only the following vowel /a/ had significant effect on retroflexes with highest EC and reduced coarticulation compared to other two places of articulation. On the other hand, there was no EC difference across consonants in

Kannada speakers. Tongue contours of each phoneme in VCV in three languages explained a common feature of greater change in the following vowel context. This reduced variability of EC in the following vowel context was common across places of articulation.

Lack of invariance in coarticulation with respect to syllabic position are partially in agreement with Lindblom (1963) and Sussman et al. (1997), where the slope values were different across bilabial, alveolar, and velars both in preceding and following vowel contexts. Krull (1988) explored the locus equation slopes and *y* intercepts in a single Swedish speaker and reported a clear pattern of decreased y-intercept values from velar > dental > labial in VC context. Gibson and Ohde (2007) found the same pattern of coarticulation, i.e. /g/>/b/>/d/, even in young children below 2 years of age. Contrastingly in the present study, there was no specific pattern observed in any of the three languages both in VC and CV contexts. This can be an attribute of language specific nature of coarticulation or the subjects considered for the study. Krull (1988) had considered a single subject, whereas the present study included 30 participants in each language. So, the inter subject variability reduces the chances to obtain a single pattern as observed in previous studies.

Findings that explain the variation of coarticulation based on the surrounding vowels in concurrence with previous studies (Blumstein & Stevens, 1979; Fowler & Brancazio, 2000; Gibson & Ohde, 2007; Haris, 1984; Hawkins & Slater, 1994; Hillenbrand & Clark, 2000; Magen, 1997; Ohala, 1993; Ohman, 1965; Recasens, 1984, 1985, 1987, 2012; Recasens et al, 1997; Rossato, Badin & Bouaouni, 2003; Sereno & Lieberman, 1987; Zharkova, 2007, 2008; Zharkova & Hewlett, 2008; Zharkova et al, 2011, 2012). Zharkova (2007) reported that there was variation in the articulatory posture for the production of alveolar consonant /t/ in the context of vowels /a/ and /i/. The tongue root was more retracted in the /a/ context than in the /i/

context. The dorsum was lower in /a/ than in the /i/ context. The only portion in the two /t/ contours that overlapped was the front region of the tongue.

There are other reports of difference in coarticulation across consonants (Fort et al, 2015; Repp & Mann, 1980; West, 1999). Slope value of locus equation for velar and bilabial places of articulation was higher than coronal consonants in Yindjibarndi and Yanyuwa (Tabain & Butcher, 1999). Findings are in consonance with the results of Tabain and Butcher (1999) who reported that velar fronting was observed when they preceded front vowels (CV). This was the rationale for extremely high F_2 onset value in spite of no perceptual similarity with alveopalatal stops. Conversely, Repp and Mann (1980) reported that velar had higher coarticulation than alveolar consonant in the context of /u/ with higher F_4 onset. Fowler and Brancazio (2000), Fletcher (2004) agreed with greater coarticulation of velars even in /i/ context in English. Sussman et al. (1993) reported based on F_2 locus equation data that dento-alveolar had higher coarticulation than retroflex consonants in Urdu which is deviant from the present results. There is an assumption of similarity in coarticulatory pattern since both Hindi and Urdu are from the same language family. Discrepancy can be accounted to difference in methodology.

Coarticulation resistance was measured with the consideration of two vowel pair contexts. Findings were interesting in each language and vowel pair. **Retroflexes were found to have significantly higher coarticulation resistance compared to dentals and velars in Kannada for all the vowel pair contexts.** Voiced velar consonant evidenced significantly higher CR than dentals in /a/ and /u/ vowel contexts. However, CRC was lowest for dentals than retroflexes and velars in vowel /i/ and /u/ contexts. **Similar to Kannada, Malayalam speakers showed greater CRC for retroflexes both in (/a/, /i/) and (/i/, /u/) contexts.** However, in (/a/, /u/) category, both retroflexes and velars were found to have similar resistance of coarticulation than dentals, with lowest CRC for dentals. **Hindi speakers followed the same pattern of CRC as Dravidian languages: retroflexes had higher CR in all the three vowel pairs.** There was indistinct difference between dentals and velars. Over all, CRC was noticed to be greater in retroflex context in the three languages.

Tongue contour of retroflexes varied slightly across vowel contexts in all the languages indicating that they were strong enough to block the influence of neighbouring vowels. Moreover, the articulatory posture of vowels varied marginally, especially for vowel /a/ and /u/. This is in agreement with reports of Dixit (1990), Dixit and Flege (1991) Krull and Lindblom (1996) and Tabain (2002). Hence, CR of retroflexes was relatively high when compared within /a/ and /u/ contexts than /i/. Since /i/ is one of the highly coarticulation resistant vowel (Scobbie et al, 2013; Irfana & Sreedevi, 2016), it is not easy for retroflex to influence vowel /i/, rather there is a mutual influence by each other. Similar result was reported in another study in Kannada (Kochetov & Sreedevi, 2013; Kochetov et al, 2014, Sreedevi et al, 2014). According to previous experiment (Sindusha, et al, 2013) reports, Malayalam retroflexes have more complicated tongue movement than dental and velars consonants. Also, the angle between the slope of the surface of the anterior tongue body and the tongue blade is reduced, indicating a greater degree of tongue curling typical of a sub-apical post alveolar retroflex articulation in Malayalam.

Tongue contours indicated anterior movement of tongue tip to make constriction with lowering of tongue back during retroflex production. Tongue blade was high with tongue tip, but there was dip in between these two structural points. Similar findings were reported in Kannada (Bhat, 1974; Hamann, 2003; Kochetov et al, 2012) that are also compatible with earlier X-ray and MRI results for Tamil (Švarný & Zvelebil, 1955; Narayanan *et al.,* 1999), which reported greater anterior tongue body movement during retroflex than for dentals. In a way, it is possible to make a comment that the tongue body lowering/backing is an obligation of retroflexion. In fact, this is a dependent articulatory gesture along with other gestures of retroflection (Best et al. 2010; Narayanan et al. 1999).

Subjectively, variations of tongue contours were evident in Hindi than the two Dravidian languages. Tongue curling was seldom visible in all the tokens, as ultrasound is not competent enough to get all the tongue tip information (Stone, 2005). This was noticed in all the three languages. However, individual data depicted better image of tongue curling than averaged images showing variation across subjects in their production. This can be considered as motor equivalence of speech production system to compliment the output goal as perceptually acceptable retroflex production in respective languages. Though tongue contours of both preceding and following vowels were influenced by the retroflex, the effect was more on following than on the preceding vowel (Dixit, 1990). This may be because of tongue constraint posture during the production of retroflex, which continues in the same posture for the following vowel also.

Similarly, velar consonants highly resisted the coarticulatory influence in (/a/, /u/) contexts and CR was lowest for dentals especially in Dravidian languages. This can be attributed to the presence of wider tongue dorsum contact area during the production of velars than dentals (Graetzer, 2007). Tongue dorsum constriction is very minimal in dental consonants where the tip of the tongue touches the teeth to make obstruction rather than the entire tongue body constriction. Moreover, dental consonants were able to influence vowel /a/ to some extent. However there is a possibility of conflict of influence of /u/, since the articulatory gestures are different for dentals and vowel /u/.

However, Dutta and Redmon (2013) explained that alveolars have stronger coarticulation resistance than retroflex followed by dental consonant in Malayalam. Since in the present study alveolars are not considered, it is not possible to make a comment on the pattern of coarticulation in alveolars, rather will consider this as a future direction. Dentals had lesser resistance than retroflex in Malayalam which is in congruent with the above results. In Standard Chinese, the pattern was different where velars had weak coarticulation resistance. Dental and retroflex consonants strongly resisted the influence of neighbouring vowels not only in monosyllables even in symmetrical V1#C2/#C2V2 and V1#C2V2 sequences (Li et al., 2012). This disparity can be explained as an articulatory gesture difference in different languages. Fowler and Brancazio (2000) also reported similar report where velars had low resistance and they reasoned that "it is because their tongue position in English can shift across vowel environments without perceptual damage" and attributed this to the shift in the tongue position in English across vowel environment without perceptual damage. Zharkova (2007) reported that the tongue position changes for /k/ across the two vowel environments, but it is not far more than alveolar consonants which is in partial agreement with the findings and reported that the tongue position changes for /k/ across the two vowel environments, but it is not far more than alveolar consonants.

Two Australian languages followed the same trend where in the alveolar consonant had fairly higher coarticulation than labial and dental sounds (Graetzer, 2007). Also, the author explains the variation of CR for palatal and velar consonant based on the fact that the production of palatal and velar consonants requires use of the tongue body in conflict with the production of vowels, thereby restricting coarticulation by adjacent vowels. This was observed even in children of 3 years, 5 years and adult speakers of English (Karen et al. 1985). Lin et al (2014) agreed that dentals have weak coarticulation with low tongue height and displacement than palatals in ‘Kaytetype’, another Australian language.

Results showed that vowel /i/ had lowest EC and higher coarticulation than /a/ and /u/ in all the three languages both in preceding and following contexts. In Kannada, /a/ and /u/ were moreover similar except for few contexts where these vowels followed /d̪/ and /g/. However in Malayalam, /u/ had greater coarticulation similar to vowel /i/ in preceding context except during retroflexes and voiced dental /d̪/ contexts. Vowel /a/ had significantly high EC than /u/ in the following vowel context especially in combination with velars and voiced retroflex /ɖ/. In Hindi, coarticulation of /u/ was significantly greater than /a/ in preceding context with velar consonants, but it was converse in unvoiced dental context. **In general, pattern of EC varied from /a/ > /u/ > /i/, demonstrating that coarticulation decreases in the order of /i/ > /u/ > /a/.**

Since vowels behaved differently in the preceding and following contexts specifically for /a/ and /u/, it is possible to deem the importance of phonetic place of a phoneme in a segment (Fowler & Brancazio, 2000; Iskarous et al. 2010; Ohman, 1965). The question of stability of vowel /i/ across both preceding and following contexts to exert the influence is no longer continue, as tongue gestures of vowel /i/ had least variability across consonants in all the three languages. Compared to other two vowels i.e. /a/ and /u/, vowel /i/ was produced with greater tongue height. This distinction makes /i/ a vowel with greater coarticulation (Hillenbrand et al, 2010; Recasens, 1987; Zharkova, 2007; Zharkova & Hewlett, 2008). These results are also in agreement with Scobbie et al’s (2013) study, where /i/ is in symmetrical context influenced liquids in Malayalam. Hence, the findings can be extended to other classes of consonants rather than restricting to only stops.

Also, the results indicated better coarticulatory effect for high back vowel /u/ than low central vowel /a/. This is in congruence with previous studies (Perkell & Nelson, 1985; Recasens & Espinosa, 2009; Zharkova, 2007). This discrepancy can be explained as a property of vowel production, where both /a, u/ are considered as back vowels in English, whereas in Dravidian languages and Hindi, /a/ is a low central vowel. This can be attributed to the possibility of variance across /a/ and /u/. Also, /a/ had high possibility of getting influenced since it is a less constraint low central vowel (Glassman, 2014).

As seen in EC, highest CR was for /i/ and lowest for /a/ in all the three languages across three places of articulation in both preceding and following contexts. CR varied across vowels where /u/ had greater CR along with /i/ than /a/ in the preceding context of dentals and retroflexes in Dravidian languages, but only in the preceding context of dentals in Hindi. However, CR of /u/ was weaker and similar to /a/ than vowel /i/ in velar context in Dravidian languages. There was no change of CR across vowels in Hindi in the following context for retroflexes and velars.

Similar to EC, CR was greater for vowel /i/ in all the three places of articulation than /a/ and /u/ in both syllabic contexts. This exemplifies that the high front vowel /i/ has the capacity to resist the influence of consonant in both preceding and following contexts. Physiologically, vowel /i/ was distinctive from other two vowels /a/ and /u/, since the tongue was higher with more constraint against palate. These results are in agreement with some of the previous studies where the vowel /i/ showed maximum coarticulation resistance in English (Stevens & House, 1963), Dutch (Pols, 1977), Catalan (Recasens, 1987, Recasens & Rodriguez, 2016) and Scottish English (Zharkova, 2007).

Along with vowel /i/, /u/ had greater CR than /a/ particularly in dental context. This might be because of the gestural difference across the phoneme. Per se, articulatory gesture of vowel /u/ is entirely different especially for dentals in all the three languages. Hence, /u/ is not influenced easily by these consonants, rather it influences them. Converse to this, /u/ had weaker CR than /i/ which was similar to vowel /a/ in velar context in Dravidian languages. This also explains as an out turn of sharing same articulatory gesture for both vowel /u/ and velars where the tongue root plays a major role. Hence, it is difficult for vowel /u/ to resist and rather is influenced by. These variations can be an effect of synergy of independent gestures for speech, especially for a syllable (Sussman et al., 1998). However, this property of distinction of CR across vowels was observed in the preceding context, whereas all the three vowels exerted resistance similarly in the following context. Contrary to this, Recasens and Rodriguez (2016) reported that CR was high for /a/ than /u/ in Catalan language even though both followed similar characteristics of vowels which are considered in the present study. Consonants considered for the measurement of coarticulation resistance were more of non-stop consonant, where coarticulation properties are different for stop consonants from other categories (Ohman, 1965).

However, Yun (2005) explained that /a/ and /u/ had similar coarticulation resistance than front vowel /i/ in Korean language. This disparity was caused because of the difference in the vowel system of Korean and Indian languages.

To correlate, DAC model explains that the degree of coarticulation should vary with the constraints exerted upon the kinematics of different tongue constrictions. Thus, for instance, concluded that the place categories especially, retroflex consonants impose restrictions upon tongue activity to almost prevent V-to-V coarticulation from occurring. From this study, it is evident that there is a general trend of coarticulation resistance which decreases progressively in the order retroflex > velar > dental. Though the production of retroflexes occurs as apical constriction rather than tongue dorsum constriction as discussed in DAC model, the degree of constriction is more influential and the tongue tip constriction is more precise to make accurate angle of retroflection. Hence, this specific articulatory gesture opposes the influence of other adjacent segments. Similarly, better coarticulation resistance of velars than dentals provides reason to believe the notion of tongue dorsum constriction against palate. Among vowels, there was general pattern of reduction of coarticulation resistance in the order /i/ > /u/ > /a/. As per the vowel system of Dravidian languages and Hindi, tongue height and constriction also follow the trend of coarticulation resistance. Hence, it is possible to state that CR of Kannada, Malayalam, and Hindi also follow the DAC model.

Many studies have explored the same in different languages and their results are in congruence. Recasens et al. (1997) explained DAC in Catalan, whereas Pastatter and Pouplier (2015) concurred with them based on the findings in English. Most resistant consonants were /s, ʃ/, less resistant consonants were /m, p, k/ and /n, l/ showed intermediate resistance (Pastatter & Pouplier, 2015). In Catalan, the pattern was /ʃ, ɲ, k/ > /s/ > /p, n, l/ since the tongue body height is greater for the lamino-dorsal and dorsal consonants / ʃ, J, k/ than for /s/, and lowest for the bilabial /p/ and the non-fricative alveolars /n, l/ (Recasens & Espinosa, 2009). Similar to this, Recasens and Clara Rodríguez (2016) reported that coarticulation resistance vary in the progression /ʎ, ɲ, ʃ > /s, r/> /t, n, ɾ, l/ > /d/ for consonants and /i, e/ > /a/ > /o, u/ for vowels. Three Australian languages including Burarra, Gupapuyngu and Warlpiri also showed the same trend (Graetzer, 2007).

2. Effect of place of articulation and vowel on the direction of coarticulation

Anticipatory coarticulation was evident for almost all token across languages, places of articulation and vowels except /iɖɖi/ in Hindi. Even though /iʈʈi/ did not show significant difference between EC in the preceding and following contexts in Kannada, there was a greater coarticulation in the following context which indicates anticipatory coarticulation. However, mean EC of /iʈ/ and /ʈi/ was same in Hindi, explained as balanced coarticulation.

This drift of greater anticipatory coarticulation than carryover coarticulation has been reported in in other languages also (German- Butcher & Weiher, 1976; French and Mandarian- Ma et al. 2006; Ndebele and Shona- Manuel, 1990; Swedish, American, and Russia- Ohman, 1966; Kannada- Kochetov et al. 2014; Sreedevi et al, 2014; French- Ushijima & Hirose, 1974; Chinese- Wang & Huang, 2013; Scottish English - Zharkova & Hewlett, 2008). Similarly anticipatory coarticulation was observed in long term coarticulation (Kochetov & Neufeld, 2013; Recasens, 2002). However there are reports which disagree with this directionality of coarticulation (Bell-Berti & Harris, 1982; Fowler, 1981; Flege, 1987; Gay, 1977; Recasens, 1985; Rossato et al. 2003). This discrepancy can be explained as a language effect which was stated by Sharf and Ohde (1981) where they reviewed 31 studies, 14 reported of anticipatory effects, 8 were more towards carryover coarticulation and 9 of them had symmetrical effects.

As seen in the findings, tongue contour of second vowel mimicked the pattern of consonant. The distance between the consonant and the following vowel was lesser than the distance between consonant and the preceding vowel. Similar findings were reported in the previous studies which claimed stronger CV coarticulation than VC, even though they considered syllable boundary between VC and CV, (Browman & Goldstein, 1988; Byrd, 1996; Gay, 1977; Kozhevnikov & Chistovich, 1965; Lindblom et al. 2002; Perkell, 1986; Zharkova & Hewlett, 2008).

This notion of pre-programmed influence in anticipatory coarticulation happens at the level of motor planning (Van der Merwe, 1997). Based on Van der Merwe's model of speech motor control, motor planning is articulator specific and motor goal specific. There are different movements which are necessary to produce each sound and it is planned as a motor goal. Similarly inter-articulatory synchronization is planned based on the articulator required to generate a particular motor goal. As seen in the results, tongue movement of the following vowel was planned along with the consonant as single motor goal where the articulatory gesture of the following vowel was flexible enough to adapt within the spatial temporal limit.

The output or the end effector was perceptually same, even though there were individual variation and variation across repetition of a particular token. This is because of the motor planning at the level of central nervous system which leads to motor equivalence (Hansen et al. 2015), through adaptability and articulatory adjustment (Van der Merwe, 1997).

However, retroflex in the context of high front vowel /i/ was different in the present study. As found in the results, there is a possibility of conflict of influence since both of these phonemes had higher coarticulation resistance. Also the tongue dorsum constraints are observed to be higher compared to other phonemes. Hence, it is possible to obtain a "different" pattern of directionality in these contexts and it is very well in agreement with DAC model where there is greater coarticulation resistance for alveolar (Recasens, 1985, 1987, 1989, 2002). Phoneme /r/ (Recasens & Pallares, 2001) had similar trend in Catalan. Other languages such as American English (Modarresiet et al, 2004; Modarresiet al. 2004) and Chinese (Ma et al. 2006) also showed similar pattern of directionality in the context of higher tongue dorsum constraint phoneme.

This explanation can be questioned by the functionality of speech production model, specifically Van der Merwe's model (1997) as explained in the present study. However, discontinuous coarticulatory effect explains that anticipatory coarticulation can be discontinuous and interrupted for a brief period of time based on the intervocalic consonant (Fowler, 1993; Fowler & Brancazio, 2000). Based on the contour obtained in the present study, retroflex had greater articulatory constraint in all the contexts compared to dental and velar consonants. Though selection and sequencing of motor programs occurred for the movement of each articulatory gesture at the level of motor planning, the articulatory constraint of /ʈ/ was overcome momentarily and suspended the influence. This was in congruence with other studies where the phonemes were noncontiguous (Bell-Berti & Harris, 1982; Perkell, 1986). However, based on the finding, discontinuous coarticulatory effect can occur even in the context of contiguous phoneme as is seen for /i/ and /ʈ/, where both showed higher lingual trajectory with strong constraint against the palate.

II. Effect of voicing on coarticulation

As per the findings there was no voicing effect in Kannada either for EC or for CRC. However, there was a difference across voicing counterparts of dentals for EC when /a/ was in the following context in Malayalam and /a/, /u/ were in the following context in Hindi. Furthermore, significant difference was obtained for CRC across retroflex voicing counterparts both in (/a/, /i/) and (/a/, /u/) vowel pair contexts in Malayalam, whereas in Hindi, it was across velars in (/a/, /i/) context.

Even though there were disparities across tongue contours of voicing counterparts, in general, the effect of voicing is quite less explicit across places of articulation and languages

(Zharkova, 2007). The major distinctive feature of voicing counterparts within each place of articulation is the difference in the voice onset time, physiologically the “voicing gesture” of the larynx. It is attained as results of abduction of vocal folds leading to lengthening and stiffening of vocal folds. Variation of this voicing gesture diverse for voiced and unvoiced stop consonants where the gesture is very brief for unvoiced compared to voiced consonant (Fowler, 1995). Though gestural variation at the level of vocal folds is not coming under the purview of this study, the articulatory end or speech output had not shown much contrast across voicing counterparts for both the parameters including EC and CRC.

Considering the few tokens that showed significant difference, which were mostly dentals in the context of /a/, can be explained as unstable nature of the vowel. However, voicing effect of velars can occur since voiced velar consonant has higher peak velocity and larger amplitude (Lofquist & Gracco, 1994). Some of the previous studies agree upon the effect of voicing, which were explained as tongue trough variation in Swedish (Engstrand, 1988; McAllister & Engstrand 1991; McAllister & Engstrand 1992; Modarresi et al. 2004) and magnitude of tongue displacement difference in English (Svirsky et al. 1997) both across /p/ and /b/. However, the significant voicing effect was observed across even dentals and velars in the context of /a/, /i/ and /u/ based on the acoustical measures (Hillenbrand et al. 2000). Australian English also showed similar trend of voicing effect based on the locus equation data, conversely no effect was reported in EPG data (Tabain, 2002). It is possible to have discrepancies across voicing counterparts in the acoustical measures since it can tackle the gestural changes at the vocal folds level. Since ultrasound and EPG are restricted only to tongue movements, it is better to have both acoustical and physiological methods to study effect of voicing. Indeed, this shed light on the need for future studies on correlation between acoustical and physiological manifestations of voicing contrast.

III. Effect of gender on coarticulation

Gender comparison was administered in each language for all the parameters including extent of coarticulation, CRC, CRPV and CRFV. Findings were interesting since the null hypothesis of gender was partially accepted in all the three languages. In Kannada, gender effect was seen in EC for 3 out of 36 tokens (/a1d̪/, /i2d̪/, and /i2ɖ/), CRC [/d̪/ in (/a/, /i/) context] and CRPV (/u/ in retroflexes context). However, null hypothesis was completely accepted for CRFV, where there was no significant difference across gender. Females had higher value of EC and CRC than males, while it was opposite for CRPV.

There were three tokens of EC and CRPV which were significantly different across male and female speakers in both Malayalam and Hindi languages. Though there were three tokens in both languages which were different in each language group (/a_1t̪/, /a_1ʈ/ and /u_2t̪/ were the tokens in Malayalam whereas /i_1ɖ/, /i_2t̪/ and /u_2ʈ/), the significant difference across gender was observed only in Hindi. Gender effect of CRPV was observed for /a/ in retroflexes context, which was same in both languages. As observed in Malayalam and Hindi, EC was greater for females and CRPV for males. Gender effect was not evident for CRC and CRFV in both language groups.

Overall, the effect of gender on coarticulatory parameters was inconsistent (Oh, 2008), especially for EC, CRC and CRPV where the statistical significance across gender varied from token to token in each language. Both males and females supposedly show similar pattern of articulatory gestures for each token, it seems the discrepancy can be because of the execution of the gestures had different degrees of stiffness (Hazan & Simpson, 2000).

CRFV was less in all subjects even across vowels since EC was reduced in the following vowel context as it was indicated anticipatory coarticulation. EC was always greater for females which are enough to compose greater articulatory accuracy rather than demanding faster movement to makes less temporal extent (Hazan & Simpson, 2000).

Production of velars were moreover similar in both males and females compared to other two places of articulation (Seaver & Kuehn, 1980).In the case of velars, bulkiness of the articulator played a role rather than the stiffness which leads to reduced speed of articulatory gesture (Saltzman,1986). Retroflexes and dentals are reported to show variation across gender in Kannada where the opening interval and plateau interval were different among them (Kochetov et al. 2014).

IV. Effect of language on coarticulation

In this experiment, the aim was to explain the nature of coarticulation as language universality and/or language specificity. The output of the data analysis proposed something interesting where it is not opposing anyone of these viewpoints rather it is leading towards the concept of coarticulation as a composite of both.

There were more similarities except for few disparities across languages. Extent of coarticulation showed there is a partial acceptance of null hypothesis for language effect. **Few tokens of EC including both preceding and following contexts exhibited discrepancies. This comprised of difference between Dravidian languages with high EC in Malayalam for tokens such as /a-ʈ/, /i-d̪/, /i-ʈ/, /i-ɖ/ and /i-k/, whereas lowest EC in Malayalam for /u-d̪/.** When compared across language families, Hindi had lowest EC than Kannada for /a-t̪/, /i-g/, /u-d̪/, /u-ɖ/ and /u-g/. Similarly, EC of Hindi speakers was significantly lesser than Malayalam speakers except when

/a/ preceded unvoiced dental consonant /t̪/ and /u/ preceded voiced dental consonant /d̪/. Hindi had significantly lowest EC in /i/ in the following context than Kannada. However, EC of /a/ in the following context was significantly less for Malayalam than Kannada and Hindi. Though there were variations across languages concerning the tokens, a common trend of reduced EC and greater coarticulation for low front vowel /i/ than vowel /a/ and /u/ in both languages was observed. Similar reports were observed in Catalan language (Recasens, 2002) and Kannada (Irfana & Sreedevi, 2016). This can be a supportive statement which is useful to generalize the notion of language specificity of coarticulation (Manuel & Krakow 1984).

Direction of coarticulation was found to have significant anticipatory coarticulation in all three languages. Carryover coarticulation was observed only for a single token in Hindi. As explained previously, anticipatory coarticulation was observed in most of the studies reported (German- Butcher & Weiher, 1976; French and Mandarian- Ma et al. 2006; Ndebele and Shona- Manuel, 1990; Swedish, American, and Russia- Ohman, 1965; Kannada- Kochetov et al. 2014; French- Ushijima & Hirose, 1974; Chinese- Wang & Huang, 2013; Scottish English - Zharkova & Hewlett, 2008). But there can be constrains based on language (Sharf & Ohde, 1981).

Coarticulation resistance of consonants (CRC) was different across language families especially for retroflex. Malayalam speakers had significant CR for /ɖ/ and /g/ in (/a/, /u/) context, /k/ in (/a/, /i/) context than Hindi speakers. However, CR for /t̪/ in (/a/, /u/) context was significantly high for Kannada than Malayalam, while Kannada speakers had significantly higher CR than Hindi speakers for /ɖ/ in (/a/, /u/) context.

Coarticulation resistance of vowel (CRV) showed discrepancies across language especially in retroflex context. CR of /a/ was significantly different across Dravidian languages where

Malayalam speakers had high CR of /a/ in retroflex both in preceding and following context than Kannada. However, Kannada had higher CR than Hindi speakers for /i/ and /u/ in retroflex and only /u/ in velar in the preceding context. Similarly, Malayalam speakers had marginal significant CR for /a, i, u/ in retroflex context and /a, u/ in velar context than Hindi speakers. However, the trend was different in the following context, where Hindi had higher CR for /a/ and /i/ in retroflex context. However, CR was lowest for Hindi speakers than Malayalam for /a/ in dental and velar contexts and /i/ in dental context.

Across-language comparison proves that Dravidian languages exhibited higher coarticulation resistance of consonants than Indo-Aryan language and retroflexes constituted to have greater coarticulation. This is congruent with previous reports that explain the sub-apicality of retroflexes in Dravidian languages and apical production in Hindi (Bakst, 2012; Dart & Nihalani, 1999; Kochetov et al, 2015; Ladefoged & Bhaskararao, 1983; Sindusha et al, 2014; Švarný & Zvelebil, 1955). This complex articulatory constriction resists the influence of nearby phonemes and exerts strong influence on them. Dravidian languages were found apart only for single token of CR of /t̪/ in (/a/, /u/) context. As seen in the previous section regarding the CRC, /t̪/ itself is the lowest CR consonant. This feature may be the reason for the viable changes across Dravidian languages. Similarly the disparities of CRV were obvious across language families especially in retroflex context. This is in agreement with Choi and Keating (1991) who reported of coarticulatory difference across Slavic languages and English where Slavic languages (Russian, Polish and Bulgarian) showed similarity among them. Some of the reports showed contrasting results with different dialects as reported by Embarki et al (2007) where coarticulation was different for Dialect of Arabic from Modern Standard Arabic. As explained previously, ability of coarticulation of retroflexes varies across languages due to the articulatory gestural differences. This can be attributed for the variation of CRV in retroflex context.

In general, few tokens of each parameter showed differences besides having similarities. Major difference was regarding CR especially for retroflex which also leads to divergent pattern of CRV across languages. This can be considered as language specific aspect. This is in agreement with previous studies where authors reported of articulatory gestural difference which can be the reason for the language specificity of coarticulation (Bladon & Al- Bamerni, 1976; Lindblom et al. 2002; McAllister & Engstrand, 1992; Perkell, 1986). Urdu retroflexes were different with lesser slope of F_2 from Australian languages (Yanyuwa and Yindjibarndi) (Sussman et al. 1993). Crosslinguistic differences observed even for velar consonants across German and Hungarian (Geng et al, 2010).

However, few studies explain that coarticulatory difference is possible if the vowel system differs (Manuel & Krakow, 1984). Ndebele and Shona were different from Sotho since Sotho languages are reported to have higher number of vowels (Manuel, 1990). Shona and English also differed with the same reason (Beddor et al. 2002). There were coarticulatory differences between Romanian and Italian languages and reported that it is not only with vowel space, rather more to do with the articulatory variability of vowel (Renwick, 2013).

It is not always vowel system which direct to language specific nature, rather articulatory gestures of consonants can also contribute towards it (Renwick, 2013). Another reported study explains coarticulatory similarity between Gupapuyngu and Warlpiri (Australian languages) which have different consonant inventories (Graetzer, 2007).

Nevertheless, the pattern of coarticulation was interestingly similar across languages, which includes greater coarticulation of retroflex and high front vowel /i/, greater EC in CV than VC (Browman & Goldstein, 1988; Byrd, 1996; Gay, 1977; Kozhevnikov & Chistovich, 1965; Lindblom et al. 2002; Perkell, 1986; Zharkova & Hewlett, 2008) indicating anticipatory coarticulation. Regardless of the amount of contrast in coarticulation parameters, there are some points which shed light towards the universality of coarticulation (Fowler, 1981; Lindblom & MacNeilage, 2011; Tabain & Butcher, 1999). Findings exhibited similarity across languages and implicated articulatory trajectory as explanation of the variation of extent of coarticulation across the phonemes based on the tongue contours, there are some characters which are homogeneous to each language (Maddieson, 1995). Hence, findings are in partially agreement with both language universality and language specificity of coarticulation.

Summary

Speech is complex because of its lack of invariance itself. Though there were constraints regarding the quantitative measures, this lack of invariance has a pattern to some extent. Moreover, the articulatory system adaptable enough through the adjustment of articulatory gesture motor equivalence without affecting the motor goal or speech output. Each part of the tongue can move independently based on the motor commands (Ohman, 1965) which are planned at the level of motor programming (Van der Merwe, 1997). Sequential motor commands from the central nervous system work based on the phonetic distinction and complexity of the syllable (Kent & Minifie, 1977). Spatial extent of influence is adjusted related to the articulatory gestures involved. In instant, phonological system can be distinct both in the case of vowel and consonant inventory which makes the difference in articulatory contours and evolve language specific nature of coarticulation.

Articulatory characteristics of each phoneme have an impact on coarticulation along with the language effect. This individuality of phoneme varies or shade to some extent based on the phonetic context and the neighbouring phoneme. Based on the DAC model (Recasens et al, 1997), magnitude of this influence varies based on the articulatory constraint of the phoneme. If there are two equally constraint phonemes, then phonemes mutually influence. In other words, one phoneme has greater constraint than the neighbouring phoneme, then the greater constraint phoneme over shade on the other.

CHAPTER VI- SUMMARY AND CONCLUSIONS

Communication rarely involves production of one sound in isolation, but rather is a continuous, dynamic sequencing of vocal tract movements produced in rapid succession. When sounds are put together to form syllables, words, phrases, and sentences, they interact in complex ways and sometimes appear to lose their separate identity. The influence that sounds exert on one another is called Coarticulation, which means that the articulation of any one sound is influenced by a preceding or following sound. Coarticulation is measured using several methods including perceptual, acoustic and physiological procedures. Among these physiological studies are less explored, particularly in the Indian context. Hence the current study aimed to investigate some of the parameters of coarticulation in few Indian languages.

Parameters of coarticulation investigated in this study are extent of coarticulation (EC), direction of coarticulation and coarticulation resistance (CR) in Kannada, Malayalam (Dravidian languages) and Hindi (Indo-Aryan) and compared across these three languages. A total of 90 subjects including 30 adult native speakers each in Kannada, Malayalam and Hindi groups comprising equal number of males and females in the age range of 20-30 years served as participants in the study.

The test material consisted of VCV non-word symmetrical sequences with C corresponding to geminate forms of voiced and unvoiced counterparts of dental (/t̪/, /d̪/), retroflex (/ʈ/, /ɖ/) and velar stops (/k/, /g/). Likewise, the vowels in the VCV stimulus form were in symmetrical environment: high front vowel /i/, low central vowel /a/, or high back vowel /u/. The target VCV sequences were embedded in a short carrier phrase in the respective languages (Now I will say "VCV").

The instrument Mindray Ultrasound 6600 was used to obtain the ultrasound tongue images and the software Articulate Assistant Advanced (AAA) ultrasound module Version 2.14 (Articulate Instrument, Wrench & Scobbie, 2011) with 60 frames per second for the analysis. The instrument was synchronized to the audio input with a sample rate of 22,050 Hz. The transducer, a long-handled microconvex probe, operating at 6.5 MHz, was placed beneath the chin of the participant with the support of stabilization headset (Articulate instrument, Scobbie, Wrench & van der Linden, 2008). Each ultrasound frame is stored in AAA system as a set of raw echo-pulse with a depth of 7 mm, facilitating a standard two dimensional image.

To record the speech samples, the individual participants were made to sit comfortably on a high back chair. They were briefed on the test procedure and were asked to sip water before the recording to moisturize the oral cavity for better ultrasound images. The transducer probe placed beneath the chin was smeared with ultrasound transmission gel *(Aquasonic 100)* for superior tongue imaging. The probe was fastened by stabilization headset *(Articulate Assistant Advanced)* to reduce the artifacts caused by head movements. For recording the speech sample, a multimedia microphone *(iball i 333)* was used. Stimuli were presented visually on the computer screen to one participant at a time and 10 repetitions of each prompt were recorded for further analysis. A total of 180 utterances were recorded for each participant in each of the three languages considered.

The ultrasound image analysis was carried out using the software AAA with a technique 'fan spline' which had 42 axes or points. Plotted contours were exported to the workspace to measure the following parameters including EC, direction of coarticulation, coarticulation resistance of consonant (CRC), coarticulation resistance of preceding vowel (CRPV) and coarticulation resistance of following vowel (CRFV).

Extent of coarticulation is measured as a difference between the averaged tongue contour of vowel and consonant which is represented as Root Mean Square (RMS) distance in AAA software. This RMS distance value or EC is indirectly proportional to the magnitude of coarticulation. Increased RMS distance between two phonemes is more, it indicates less coarticulation and, on the contrary, reduced RMS distance signifies greater coarticulation. Also, the direction of coarticulation is inferred based on the RMS value of preceding and following vowels. If the EC of preceding vowel to consonant is greater than for that of consonant to following vowel, it is considered as anticipatory coarticulation. Conversely, carryover coarticulation was stated when the EC of preceding vowel to consonant is lesser than consonant to the following vowel.

Coarticulation resistance of consonants is the ability of the consonant to resist the influence of neighboured vowels in a VCV syllable. Coarticulation resistance of preceding vowel is the ability of the preceding vowel to maintain its identity and resist the influence of the following consonant. Coarticulation resistance of the following vowel is its ability to maintain its own identity and resist the influence of the preceding consonants. CRC, CRPV and CRFV were calculated using the formulae proposed by Zharkova (2007).

I. Effect of places of articulation and vowel position on coarticulation

With reference to vowel, findings showed different patterns of EC in each language, both in the preceding and following vowel contexts. In general, dentals had lowest EC or maximum coarticulation in vowel /a/ context, retroflexes in /i/ and velars in /u/ when the vowels were preceding the target consonant in all the three languages. Tongue contour of /a/ fairly changed towards the tongue contour of dentals, specifically the area of tongue tip/ blade moved anteriorly and vertically. This was not seen in retroflexes and velars. Active articulators were the same for other tokens i.e. tongue tip/blade and dorsum for the production of both vowel /i/ and retroflex (/i-Retroflexes-i/), and tongue root for both vowel /u/ and velars (/u- Velars-u/). Hence it was easy to move from one phoneme to another (V to C) and influence each other.

Similar to the preceding context, there was significant difference across consonants in the following vowel context. Malayalam speakers showed significant difference for dentals from other places of articulation where coarticulation was greater in /a/ context and it was reduced in vowel /i/ context. Tongue contour of following vowel /a/ mimics dentals. However, this imitation of articulatory synergy is lacking in /i-dental/ context compared to retroflexes and velars. In Hindi, only vowel /a/ had significant effect in following vowel context where retroflexes had highest EC and reduced coarticulation than other two places of articulation. But there was no EC difference across consonants in Kannada speakers in the following vowel context. In the findings, it can be stated that there was maximum coarticulation between the consonant and following vowel in all the three languages. This was true for all the three places of articulation also.

With reference to the vowel across languages, results showed that vowel /i/ had lowest EC and higher coarticulation than vowels /a/ and /u/ in all the three languages both in the preceding and following contexts. In Kannada, /a/ and /u/ were moreover similar except for few contexts where these vowels followed /d̪/ and /g/. However, in Malayalam and Hindi, similar to /i/, vowel /u/ had greater coarticulation than vowel /a/ in the preceding context. In general, pattern of EC reduced in the order of /a/ > /u/ > /i/, indicating that coarticulation was minimum for vowel /a/ followed by /u/ and /i/ respectively

Coarticulation resistance was measured considering two vowel pair contexts. Findings were interesting in each language and vowel pair. Retroflexes were found to have significantly highest coarticulation resistance compared to dentals and velars in Kannada for all the vowel pair contexts. Similar to Kannada, Malayalam speakers also showed greater CRC for retroflexes in both (/a/, /i/) and (/i/, /u/) contexts. However, in (/a/, /u/) category, both retroflexes and velars were found to have similar resistance of coarticulation than dentals, where dentals had lowest CRC. Hindi speakers followed the same pattern of CRC as Dravidian languages, where retroflexes had higher CR in all the three vowel pairs. But there was unclear difference between dentals and velars. Over all, CRC was noticed to be greater in retroflex context in all the three languages.

Among vowels, highest coarticulation resistance (CR) was for /i/ and lowest for /a/ in all the three languages across three places of articulation in both preceding and following contexts. CR of vowel /u/ was greater as /i/ than vowel /a/ in preceding context with dentals and retroflexes in Dravidian languages. Same trend of CR for vowels was observed for dentals in Hindi.

Similar to EC, CR was greater for vowel /i/ in all the three places of articulation than for /a/ and /u/ in both preceding and following syllabic contexts. This exemplifies that the high front vowel /i/ has the capacity to resist the influence of consonant in both preceding and following contexts. Physiologically, vowel /i/ was distinct from other two vowels /a/ and /u/, since the tongue was higher with more constraint against the palate. Following vowel /i/, /u/ had greater CR than /a/ particularly in the dental context. This might be because of the gestural difference across the phonemes. Per se, articulatory gesture of vowel /u/ is entirely different especially from dentals which are observed commonly in all the three languages. Hence, it is easy for /u/ to get away from being influenced by dental consonants. Converse to this, /u/ had weaker CR than /i/ which was similar to vowel /a/ in velar context in Dravidian languages. This is explained as an output of sharing same articulatory gesture for both vowel /u/ and velars where the tongue root plays a major role. Hence, it is difficult for vowel /u/ to resist the impact.

Anticipatory coarticulation was evident for almost all tokens across languages, places of articulation and vowels except /iɖɖi/ in Hindi. Though /iʈʈi/ did not show significant difference between EC in the preceding and following contexts in Kannada, there was greater coarticulation in the following context resulting in anticipatory coarticulation. However, equal mean EC of /iʈ/ and /ʈi/ in Hindi is explained as balanced coarticulation.

II. Effect of voicing on coarticulation

As per the findings there was no voicing effect in Kannada either for EC or for CRC. However, there was a difference across voicing counterparts of dentals for EC when /a/ was in the following context in Malayalam and /a/, /u/ were in the following contexts in Hindi. Furthermore, significant difference was obtained for CRC across retroflex voicing counterparts both in (/a/, /i/) and (/a/, /u/) vowel pair contexts in Malayalam, whereas in Hindi it was across velars in (/a/, /i/) context.

III. Effect of gender on coarticulation

Gender comparison was carried out in each language for all the parameters including extent of coarticulation, Coarticulation Resistance of Consonants (CRC), Coarticulation Resistance of Preceding Vowel (CRPV) and Coarticulation Resistance of Following Vowel (CRFV). Findings were interesting since the null hypothesis of gender was accepted in all the three languages for major number of tokens. In Kannada, it was observed that EC was significantly different across gender for 3 out of 36 tokens (/a_1d̪/, /i_2d̪/, and /i_2ɖ/), CRC [/d̪/ in (/a/, /i/) context] and CRPV (/u/ in retroflexes context). Null hypothesis was completely accepted for CRFV, as there was no significant difference across gender for any of the tokens. However females had higher value of EC and CRC than males, and it was opposite for CRPV.

There were three tokens of EC and CRPV which were significantly different across male and female speakers in both Malayalam and Hindi languages. Hence, EC was greater for females and CRPV for males in both these languages. Gender effect was not evident for CRC and CRFV in both Malayalam and Hindi speakers.

IV. Effect of language on coarticulation

Extent of coarticulation (EC) showed that the null hypothesis is accepted for a number of tokens for language effect. Few tokens of EC including both preceding and following contexts exhibited differences. This included difference between Dravidian languages with high EC in Malayalam for tokens such as /a-ʈ/, /i-d̪/, /i-ʈ/, /i-ɖ/ and /i-k/, and lowest EC in Malayalam for /u-d̪/. When compared across language families, Hindi had lowest EC than Kannada for /a-t̪/, /i-g/, /u-d̪/, /u-ɖ/ and /u-g/. Similarly, EC of Hindi speakers for these tokens was significantly reduced than Malayalam speakers. Hindi had significantly low EC for vowel /i/ in the following context than in Kannada. However, EC of vowel /a/ in the following context was significantly reduced for Malayalam than in Kannada and Hindi. Though there were variations across languages for same tokens, a common trend of reduced EC and greater coarticulation for high front vowel /i/ than vowel /a/ and /u/ were observed in all the three languages. Direction of coarticulation was found to be significantly anticipatory in all the three languages.

CRC was different across language families especially for retroflex. Malayalam speakers had significantly higher CR for /ɖ/ and /g/ in (/a/, /u/) context, for /k/ in (/a/, /i/) context than Hindi speakers. However, CR for /t̪/ in (/a/, /u/) context was significantly high for Kannada than Malayalam, also Kannada speakers had significantly higher CR than Hindi speakers for /ɖ/ in (/a/, /u/) context.

Coarticulation resistance of vowels (CRV) exhibited differences across languages especially in the retroflex context. CR of /a/ was significantly different across Dravidian languages. Malayalam speakers had higher CR of vowel /a/ both in preceding and following contexts than in Kannada. However, Kannada had higher CR than Hindi speakers for vowels /i/ and /u/ in retroflex context and for vowel /u/ in velar context. Similarly, Malayalam speakers had significant CR for /a, i, u/ in retroflex context and /a, u/ in velar context than Hindi speakers. Conversely, the trend was different in the following vowel context, where Hindi had higher CR for /a/ and /i/ in retroflex context. However, CR was lowest for Hindi speakers than Malayalam for /a/ in dental and velar contexts and /i/ in dental context. Across language comparison revealed that Dravidian languages exhibited higher coarticulation resistance than Hindi and retroflexes seemed to have greater coarticulation resistance.

In general, the study highlights the effect of vowel and places of articulation of stop consonants on coarticulation across languages. Similarly, findings revealed that there was variation of effect of vowel in the preceding and following contexts on the coarticulation parameters including EC and CR. Even though tongue tip information was missing in some tokens, averaged tongue contour well correlated with quantitative values of coarticulation effect specifically parameters including EC, CRC, CRPV and CRFV. Direction of coarticulation was evidently anticipatory across languages. Effect of voicing and gender did not seem to impact coarticulation. But, language effect was present as there were variations of EC and CR for some tokens. The findings supported a combinations of two theories of language on coarticulation i.e. language specificity and language universality.

Implications of the study

Findings provide better understanding on the articulatory gestures in three places of articulation i.e. dentals, retroflexes and velars and vowels including /a/, /i/ and /u/ in three Indian languages. Since the study used ultrasound as the physiological method, it is possible to draw comparisons between the current data with many previous studies using acoustical and perceptual methods. The results provide an insight into the pattern of coarticulation resistance and extent of coarticulation in three key languages of India. It is possible to add information to the existing theories of coarticulation and state that coarticulation is a consequence of articulatory gestures with few language effects. Findings also provide facts that Indian languages also followed the DAC model which has been explored in many other worlds' languages. Results explain typical speech production in an improved way; the study has applications in the area of linguistics since it focuses on the coarticulation patterns across places of articulation in different vowel contexts.

Limitations and Future directions of the study

Tongue tip information was missing for few tokens. Though averaging of 10 repetitions take care of this, it is better to include other physiological methods such as EMA with ultrasound for better understanding of coarticulation. Temporal information of coarticulation could not be measured using the selected parameters for the study but the same can be explored using frame variation of the same token. Present study explored only lingual coarticulation. Coarticulation effect can be studied as an involvement of other articulators such as jaw and lips. Also it is possible to verify the concordance of ultrasound parameters with acoustical analysis. Similarly long term coarticulation effect can be studied across languages.

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APPENDIX I

ORO MOTOR SENSORY EXAMINATION

Structure

Tongue size

Lingual frenulum length

Tongue tip shape

Tongue surface texture

Overall tongue shape

Motor

Protrusion

Elevation

Lateralization

Wiggle to the left and to the right side

Rotation

DDK- AMR: SMR:

Tongue resistance

- Front
- Side

Sensory

Sensation of:

- Presence of an object
- Size and shape of an object
- Hot
- Cold
- Taste

APPENDIX II

Table 1

Extent of coarticulation (EC) across gender in Kannada

EC	/a/		/i/		/u/	
	|Z|	p	|Z|	P	|Z|	p
/V_1t̪/	.726	.468	.124	.901	.249	.803
/t̪V_2/	.353	.724	.270	.787	.560	.576
/V_1d̪/	2.157	.031*	2.240	.025*	.892	.373
/d̪V_2/	1.950	.051	.933	.351	.767	.443
/V_1ʈ/	.518	.604	.622	.534	.850	.395
/ʈV_2/	1.099	.272	.996	.319	.249	.803
/V_1ɖ/	.913	.361	.394	.693	.518	.604
/ɖV_2/	.933	.351	2.033	.042*	1.079	.281
/V_1k/	.124	.901	1.016	.310	.104	.917
/kV_2/	.104	.917	.228	.820	1.535	.125
/V_1g/	.726	.468	1.058	.290	.602	.547
/gV_2/	1.224	.221	.913	.361	.394	.694

Note: *= $p \leq 0.05$

Table 2

Extent of coarticulation (EC) across gender in Malayalam

EC	/a/		/i/		/u/	
	|Z|	P	|Z|	p	|Z|	p
/V_1t̪/	2.012	.044*	.436	.663	.988	.217
/t̪V_2/	1.555	.120	.104	.917	2.219	.026*
/V_1d̪/	.767	.443	.581	.561	.436	.633
/d̪V_2/	.581	.561	.954	.340	.062	.950
/V_1ʈ/	2.261	.024*	.560	.575	1.079	.281
/ʈV_2/	.830	.407	1.950	.051	.477	.633
/V_1ɖ/	.995	.263	1.804	.071	1.095	.236
/ɖV_2/	.021	.983	.477	.633	.726	.468
/V_1k/	.850	.395	.684	.494	1.764	.078
/kV_2/	.394	.694	1.058	.290	1.390	.165
/V_1g/	.145	.885	.892	.372	.436	.663
/gV_2/	.975	.330	.436	.663	1.472	.141

Note: *= $p \leq 0.05$

Table 3

Extent of coarticulation (EC) across gender in Hindi

EC	**|Z|**	**p**	**|Z|**	**P**	**|Z|**	**p**
	/a/		**/i/**		**/u/**	
/V_1t̪/	.270	.787	1.493	.135	.684	.494
/t̪V_2/	.353	.724	2.800	.005*	.083	.934
/V_1d̪/	.145	.885	1.763	.078	.145	.885
/d̪V_2/	.830	.407	.643	.520	.373	.709
/V_1ʈ/	1.369	.171	.145	.885	.498	.619
/ʈV_2/	1.079	.281	.850	.395	2.841	.004*
/V_1ɖ/	.353	.724	3.007	.003*	1.348	.178
/ɖV_2/	1.804	.071	1.095	.236	.726	.468
/V_1k/	.353	.724	.353	.724	.518	.604
/kV_2/	1.162	.245	.477	.633	.518	.604
/V_1g/	.290	.772	1.556	.120	1.722	.085
/gV_2/	1.286	.198	.187	.852	1.224	.221

Note: *= $p \leq 0.05$

APPENDIX III

Table 1

Coarticulation resistance of coarticulation (CRC) across gender in Kannada

CRC	|Z|	p	|Z|	P	|Z|	p
	(/a/, /i/)		(/a/, /u/)		(/i/, /u/)	
/t̪/	1.141	.254	.145	.885	.883	.394
/d̪/	2.883	.004*	1.472	.141	2.426	.015*
/ʈ/	.850	.395	.394	.694	1.182	.237
/ɖ/	.270	.787	.892	.373	.021	.983
/k/	.767	.443	.518	.604	1.348	.178
/g/	.187	.852	1.597	.110	.187	.852

Note: *= p≤ 0.05

Table 2

Coarticulation resistance of coarticulation (CRC) across gender in Malayalam

CRC	|Z|	p	|Z|	P	|Z|	p
	(/a/, /i/)		(/a/, /u/)		(/i/, /u/)	
/t̪/	1.759	.079	1.738	.082	1.656	.098
/d̪/	1.162	.245	1.016	.310	.504	.614
/ʈ/	1.141	.254	.560	.576	1.925	.054
/ɖ/	1.409	.159	1.058	.290	1.876	.057
/k/	1.265	.206	.809	.419	1.929	.054
/g/	.021	.983	1.265	.206	.436	.663

Table 3

Coarticulation resistance of coarticulation (CRC) across gender in Hindi

CRC	|Z|	p	|Z|	P	|Z|	p
	(/a/, /i/)		(/a/, /u/)		(/i/, /u/)	
/t̪/	.353	.724	.643	.520	.104	.917
/d̪/	1.390	.165	.062	.950	.518	.604
/ʈ/	1.680	.093	.062	.950	1.265	.206
/ɖ/	.436	.663	.353	.724	.518	.604
/k/	1.141	.254	1.763	.078	.477	.633
/g/	.062	.950	.270	.787	.477	.633

APPENDIX IV

Table 1

Coarticulation resistance of preceding vowel (CRPV) across gender in Kannada

CRPV	|Z|	P	|Z|	p	|Z|	p
	Dentals		Retroflexes		Velars	
/a/	1.141	.254	.104	.917	.684	.494
/i/	1.099	.272	1.016	.310	1.555	.120
/u/	.021	.983	2.592	.010*	.228	.820

Note: *= p≤ 0.05

Table 2

Coarticulation resistance of preceding vowel (CRPV) across gender in Malayalam

CRPV	|Z|	P	|Z|	p	|Z|	p
	Dentals		Retroflexes		Velars	
/a/	.270	.787	2.178	.029*	.270	.787
/i/	.145	.885	1.141	.254	.228	.820
/u/	.518	.604	1.594	.111	.684	.494

Note: *= p≤ 0.05

Table 3

Coarticulation resistance of preceding vowel (CRPV) across gender in Hindi

CRPV	|Z|	P	|Z|	p	|Z|	p
	Dentals		Retroflexes		Velars	
/a/	.021	.983	2.012	.044*	.270	.787
/i/	.560	.576	.104	.917	.353	.724
/u/	.021	.983	1.514	.130	.145	.885

Note: *= p≤ 0.05

APPENDIX V

Table 1

Coarticulation resistance of following vowel (CRFV) across gender in Kannada

CRFV	|Z|	p	|Z|	p	|Z|	p
	Dentals		Retroflexes		Velars	
/a/	1.597	.110	.477	.633	1.348	.178
/i/	.311	.756	.477	.633	1.680	.093
/u/	.021	.983	1.555	.120	1.141	.254

Table 2

Coarticulation resistance of following vowel (CRFV) across gender in Malayalam

CRFV	|Z|	p	|Z|	p	|Z|	p
	Dentals		Retroflexes		Velars	
/a/	.228	.820	1.846	.065	.560	.576
/i/	.726	.468	.477	.633	.560	.576
/u/	.850	.395	.311	.756	.643	.520

Table 3

Coarticulation resistance of following vowel (CRFV) across gender in Hindi

CRFV	|Z|	P	|Z|	p	|Z|	p
	Dentals		Retroflexes		Velars	
/a/	.187	.852	.228	.820	1.016	.310
/i/	.809	.419	.436	.663	.933	.351
/u/	.767	.443	1.680	.093	.477	.633

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An Ultrasound Study of Coarticulatory Resistance and Coarticulatory Aggression

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ABSTRACT

The term 'coarticulatory resistance' refers to the degree to which a given segment, a consonant or a vowel, resists potential interference of neighbouring segments. The phoneme with coarticulatory resistance exert stronger influence on neighbouring phoneme and exhibit less contextual variation, this characteristic termed as 'coarticulatory aggression'. The present study aimed to analyse the coarticulatory resistance and coarticulatory aggression based on ultrasound imaging technique . Thirty adult Malayalam speakers participated as subjects . The stimuli consisted of VCV sequences , with C corresponding to voiced /voiceless counterparts of dental stops (/t̪/, /d̪/) or retroflex stops (/ʈ/, /ɖ/) or velar stops (/k/, /g/), in the context of vowels /a, i, u/. Measurements of coarticulation resistance of consonants, preceding vowels and following vowels were carried out based on Root Mean Square (RMS) distance between the tongue contours of vowels and consonants. Results showed that coarticulatory resistance of consonants were decreased in the order from retroflex followed by velars and dentals. High front vowel /i/ resisted coarticulation of preceding consonant more than other vowels considered. It highlights the trend of Degree of Articulatory Constraint (DAC) model for both consonant and vowel system.

Key words: *Coarticulatory resistance, Coarticulatory aggression, Ultrasound, Malayalam, Stops.*

1. Introduction

Coarticulation in a broad manner refers to the fact that a phonological segment is not realized identically in all environments, but often apparently varies to become more like an adjacent or nearby segment (Kuhnert & Nolan, 2000). Lingual coarticulation is important since the tongue is a complex, mobile organ which plays a major role in the production of all vowels and majority of the consonants. The term coarticulatory resistance refers to the degree to which a given segment resists the potential interference of neighbouring segments. The sounds with coarticulatory resistance also exert strong influence on their neighbouring vowels; they exhibit the least contextual variation and induce the greatest. In VCV syllable, if coarticulatory resistance of the consonant is higher, it indicates that the consonant has higher resistance against the influence of preceding and following vowel.

Coarticulation varies as a property of tongue dynamics of each phoneme in a particular language. Previous studies especially Recasens (1984a, 1984b, 1985, 1989, 1993) suggested that variation of coarticulatory resistance is consequence of gestures of phonemes place on the tongue dorsum. He had studied different consonants including palatal consonant /j/, alveopalatals /ɲ/ and /ʎ/, alveolar /n/ in VCV syllable context. Their extended studies revealed that constraint of the tongue dorsum is the major factor for lack of invariance in the coarticulatory resistance. In subsequent studies, Recasen, Pallarès and Fontdevila (1997) proposed a “Degree of Articulatory Constraint (DAC) model” to explain this property of speech production. According to this model coarticulatory resistance should increase with the degree of articulatory constraint, i.e., with the mechano-inertial properties of the articulators and their involvement in the formation of a closure or constriction. Fowler and Brancazio (2000) explored this trend using locus equation and suggested that magnitude of resistance is determined by the mutual incompatibility of their gestures with those of sequentially adjacent or nearby segments.

The phoneme having higher coarticulatory resistance exert stronger influence on their neighbouring vowels, but, exhibit the least contextual variation. This characteristic has been termed, coarticulatory aggression (Fowler & Saltzman, 1993). It is the characteristic of a phoneme or segment with high coarticulatory resistance to exert high influence on the adjacent phonetic segments. When the segment is aggressive, the influence extends well beyond the boundary. It also indirectly indicates how the phoneme resists the influence of neighbouring segment and exhibits its own identity. Based on DAC model, coarticulatory aggression is more related to the tongue dorsum constraint and it can be dependent on the phonetic characteristics of the sound segment. According to this model, coarticulatory sensitivity of the consonants in VCV sequences (V-to-C effect) varies inversely with the strength of the consonantal effects (C-to-V effects) and with the degree of articulatory constraint of the intervocalic consonant. Recasens and Espinosa (2009) revealed that coarticulatory aggressiveness scale decreases in the progression from lingual fricatives, alveolopalatals, velars, labials, /n/, to a lesser extent, /l/ for consonants, high /i, u/ > low /a/ for vowels in Catalan. Based on tongue height, high vowels are more aggressive than low vowels (Recasens, 2012).

The present study intend to explore the coarticulatory resistance and aggression in Malayalam, a less explored language, across three places of articulation specifically voiced and unvoiced counterparts of dentals, retroflexes and velars with three cardinal vowels. Malayalam is one of the major Dravidian languages that is spoken in the south Indian state of Kerala. Like other languages of the sub-continent, it has complex set of place contrasts involving labials, alveolar, velars, dentals, palatals, and retroflexes (Asher & Kumari, 1997).

Articulatory dynamics are different across these consonants and vowels. Production of retroflex consonant got particular interest because of its articulatory complexity and rarity across languages (Ladefoged & Maddieson, 1996). It produces with higher articulatory constraint with sub-apical contact than other Dravidian language retroflexes (Sindusha, Irfana & Sreedevi, 2014). The contact for the dental consonant is made with the moderately raised blade of the tongue, presumably at the alveolar ridge and the upper teeth. The shape of the tongue is overall lowered, and flat, with the posterior tongue body somewhat backed. The point of contact for the velar stop is presumably at the velum and the tongue body is strongly convex (Kochetov, Sreedevi, Kasim & Manjula, 2014). The present study considered phonemes with different articulatory placement including phonemes more towards front i.e /i/ and dentals, back vowel (/u/) and velars and phonemes more central position including vowel /a/ and retroflexes with the intention to explore the relation of coarticulation resistance and aggression with articulatory dynamics.

2. Method

Thirty native adult speakers of Malayalam served as subjects for this study. All of them were considered after oro motor examination and were excluded if identified with speech, language, hearing, or any cognitive deficits. The test material consisted of non-meaningful V1CV2 sequences with C corresponding to voiced and unvoiced counterparts of dental stops (/t̪/, /d̪ /) or retroflex stops (/ʈ/, /ɖ/) or velar stops (/k/, /g/) in the context of vowel V1 and V2, these were high front vowel /i/ or low central vowel /a/ or high back vowel /u/. Table 2.1 shows the test items. VCV were sequences embedded in a short carrier phrase (Now I will say CVCV).

Table 2.1: Stimuli list of V1CV2 sequences with consonant in 3 places of articulation in the context of vowel V1 and V2 (/a, i, u/).

Vowels	**Places of articulation**					
	Dental		**Retroflex**		**Velar**	
	Voiced	**Unvoiced**	**Voiced**	**Unvoiced**	**Voiced**	**Unvoiced**
Low central	/ad̪d̪a/	/at̪t̪a/	/aɖɖa/	/aʈʈa/	/agga/	/akka/
High front	/id̪d̪i/	/it̪t̪i/	/iɖɖi/	/iʈʈi/	/iggi/	/ikki/
High back	/ud̪d̪u/	/ut̪t̪u/	/uɖɖu/	/uʈʈu/	/uggu/	/ukku/

In the present study, articulatory movement data were obtained using the instrument Mindray ultrasound 6600. This system was connected to a PC installed with the software Articulate Assistant Advanced (AAA) ultrasound module Version 2.14 (Articulate Instrument, Wrench & Scobbie, 2011) for the analysis with 60 frames per second. It was synchronized to the audio input with a sample rate of 22050 Hz. Hardware pulse generated a tone frequency of 1000 Hz with beep length of 50 millisecond to accurate the synchronization. The transducer, a long-handled microconvex probe operating at 6.5 MHz, was placed beneath the chin of the participant with the support of stabilization headset (Articulate instrument, Scobbie, Wrench & van der Linden, 2008). Each ultrasound frame stored by AAA system as a set of raw echo-pulse with a depth of 7mm from which a standard two dimensional image was created. Figure 2.1 depicts the midsagittal ultrasound image of vowel /a/.

Figure 2.1. Midsagittal image of vowel /a/. The anterior tongue is towards the right side. (Note. Tongue image in Articulate Assistant Advanced, Phonology lab, Department of Speech Language Sciences, All India Institute of Speech and Hearing, Mysore).

2.1. Data collection: Participants were made to sit comfortably in a high back chair and the transducer probe was placed beneath the chin smeared with ultrasound transmission gel (*Aquasonic 100*) for better tongue imaging. The probe was fastened by stabilization headset (*Articulate Assistant Advanced*) to reduce the artifacts because of head movements. A headphone *iball i 333 was used* for recording the audio speech sample. Stimulus list was presented visually in grapheme mode to individual participant and 10 repetitions of each prompt were considered for further analysis. A total of 270 utterances were recorded from each participant including 10 repetitions of 9 target samples (3 same vowel contexts (V1CV1) * 9 consonants including both voiced and unvoiced counterparts= 27*10 repetitions=270). A grand total of 810 utterances (30*270=8100) were recorded for the study.

2.2. Data Analysis: For analysis, semiautomatic contour plotting was considered in this study. Individual token splines for each consonant and vowel were used to create mean splines, based on means at 42 fan lines. Plotted contours were exported to workspace to find following parameters.

2.2.1. Coarticulation resistance

In VCV syllable, it is possible to find coarticulation resistance of consonants (CRC) and coarticulatory resistance of vowel (CRV). CRC is the ability of consonant to restrict the coarticulatory effect of preceding and/or following vowel. CRV is the vowel capacity to maintain its own characteristics. The formula used in the study was adapted from Zharkova (2007) to find the coarticulatory resistance.

2.2.1.a) Coarticulation resistance of consonants (CRC)

CRC was calculated in relation to both vowels from a VCV sequence where the calculations can also be performed in relation to V1 and V2 separately. CRC was found by using the formula:

$$CRC_{C\,(V1\text{-}V2)} = \frac{(C-V)}{(C_{V1}-C_{V2})} \times 10$$

In the above equation, the numerator "C-V" indicates the averaged value of RMS of both V1 and V2 contexts. The denominator ($C_{V1} - C_{V2}$) was obtained as RMS distance between tongue contours of C in different vowel contexts.

2.2.1.b) Coarticulation resistance of preceding vowel (CRPV)

CRPV was calculated in relation to different consonants from preceding vowel in VCV sequence. The RMS distances from the vowel to neighbouring consonant (V1-C and V2-C) are proportionate to the degree of CR of the vowel, i.e., the degree to which V retains its identity in a VCV sequence. The V1-C and the V2-C, RMS distances were computed within token, separately for each of the tokens and for each of the 10 repetitions also. CRPV was found by using the formula:

$$CRPV_{V\,(C1\text{-}C2)} = \frac{(V\text{-}C)}{(V_{C1}\text{-}V_{C2})} \times 10$$

The numerator of the above equation, "V-C" indicates the averaged value of RMS of both contexts. The denominator (V_{C1}-V_{C2}) was obtained as RMS distance between the mean tongue contours of V in different consonant contexts.

2.2.1.c) Coarticulation resistance of following vowel (CRFV)

CRFV was calculated in relation to different consonants from following vowel in VCV sequence. The analysis was similar as above described format. In this section following vowel was considered instead of preceding vowel to find the CRFV.

3. Results

3.1. Tongue dynamics across places of articulation

Figure 3.1-3.3 shows the average tongue contours of 30 subjects for each phoneme in VCV syllable. There was difference across tongue contours though the vowels were same in preceding and following context. General trend of fronting was observed when consonants neighboured with front vowel /i/. Both voiced and unvoiced counterparts of each place of articulation are discussed together since there is much variation across them in the tongue dynamics as seen from the images.

As seen figure 3.1, dental consonants were vulnerable and changed based on the vowels occurred with. It was evident that backing of posterior tongue body when they nearby with back vowel /u/ and centralization of anterior tongue body when occurred with vowel /a/.

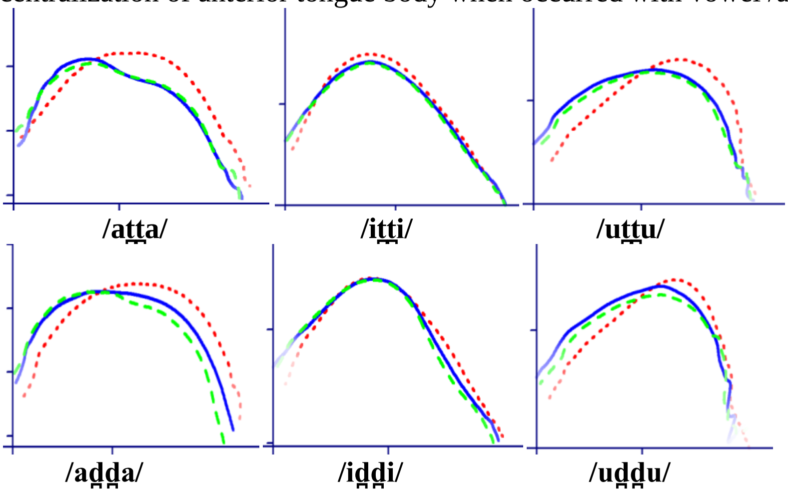

Figure 3.1. Average tongue contours of 30 subjects- preceding vowel (red dotted line), consonant (blue solid line) and following vowel (green dashed line) for voiced and unvoiced counterparts of dental consonants across three vowel contexts.

Contrast to dentals, retroflexes were influenced the vowels and changed the articulatory dynamics as observed in figure 3.2. Though there is some information loss of tongue tip curling, overall tongue shape of vowels were more as retroflexes especially back vowel /u/ and low central vowel /a/.

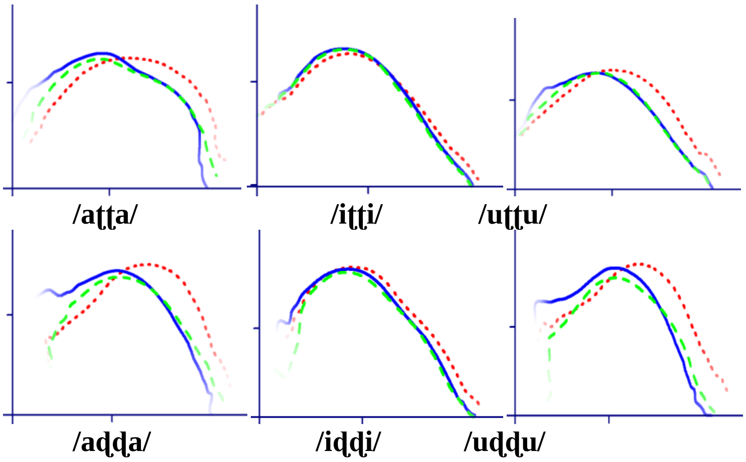

Figure 3.2. Average tongue contours of 30 subjects- preceding vowel (red dotted line), consonant (blue filled line) and following vowel (green dashed line) for voiced and unvoiced counterparts of retroflex consonants across three vowel contexts.

There were slight variations in articulatory position of vowels and velars. Velars were not always raise towards posterior with posterior tongue body. It was more of in between the articulatory position of velars and vowels. Especially when it occurred with front vowel /i/, there the tongue contour of velar consonant moved towards anterior position.

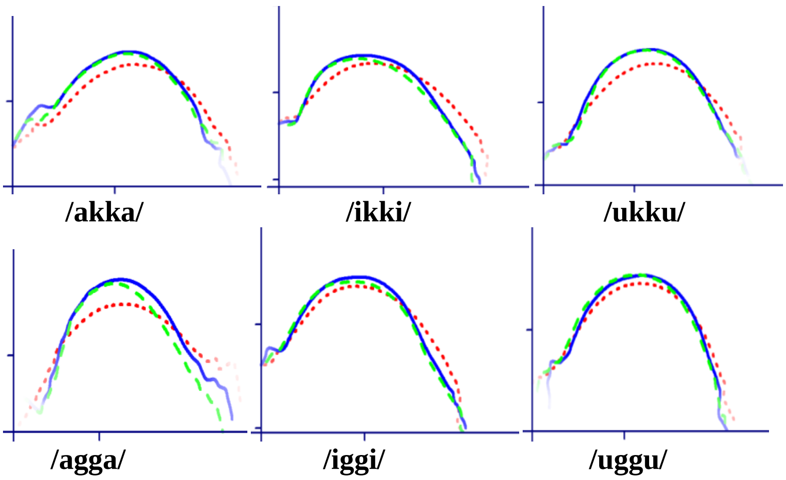

Figure 3.3. Average tongue contours of 30 subjects- preceding vowel (red dotted line), consonant (blue filled line) and following vowel (green dashed line) for voiced and unvoiced counterparts of velar consonants across three vowel contexts.

3.2. Coarticulatory resistance of consonants

Based on the equation, CRC calculated for each subject and mean and standard deviation of 30 subject depicted in Table 3.2. It is evident that the coarticulatory resistance is relatively higher when sequentially adjacent to vowels /a/ and /u/ than other contexts. Interestingly, all the places of articulation including dental, retroflex, and velar stop consonants followed the same trend.

Friedman non-parametric tests were administered across consonants to analyse the coarticulatory resistance in each vowel context. Results showed that there was significant difference between the coarticulatory resistances of consonants in all the three vowel contexts (χ^2 (5) = 15.80, p< .001).

Table 3.2: Mean and standard deviation of coarticulatory resistance of consonants of 30 subjects

CRC	Mean	SD	CRC	Mean	SD	CRC	Mean	SD
CRCt̪(a, i)	12.27	4.88	**CRCʈ(a, i)**	22.52	11.24	**CRCk(a, i)**	15.42	5.85
CRCt̪(a, u)	21.78	8.60	**CRCʈ(a, u)**	36.01	21.04	**CRCk(a, u)**	45.20	24.57
CRCt̪(i, u)	15.68	7.56	**CRCʈ(i, u)**	34.33	17.34	**CRCk(i, u)**	14.78	7.78
CRCd̪(a, i)	14.02	6.15	**CRCɖ(a, i)**	26.97	12.26	**CRCg(a, i)**	17.48	7.73
CRCd̪(a, u)	24.72	10.70	**CRCɖ(a, u)**	41.51	13.32	**CRCg(a, u)**	44.74	20.4
CRCd̪(i, u)	18.67	13.78	**CRCɖ(i, u)**	32.71	14.05	**CRCg(i, u)**	17.06	12.00

Further, Wilcoxon Sign Rank test revealed similar pattern of coarticulatory resistance when the consonant was near to vowels /a/ and /i/ (|Z|=4.271, p= .010); /u/ and /i/ (|Z|=2.098, p= .036). Here, dental and velar consonants were significantly more influenced by adjacent vowels than retroflex consonants which were not different for both voiced and unvoiced counterparts. Particularly retroflex consonants set strong constraints on the tongue dorsum that limit the variation exerted by both preceding and following vowels, whereas, other consonants were influenced by adjacent segments.

Dental consonants were weak to exert coarticulation even when the vowels were /a/ and /u/, while velars and retroflexes showed significantly higher magnitude of resistance ($p \leq 0.001$). Also, dentals permitted influence of all the three vowels when they preceded and followed in VCV segment, whereas, retroflex opposed the influence and maintained their own identity. Velars were flexible purely based on the context of vowel that were mutually compatible.

3.3. Coarticulatory resistance of preceding vowel

Table 3.2 depicts that the mean of coarticulatory resistance of preceding vowel was more for vowels /i/ and /u/ followed by /a/. Variability noticed was high for /a/ and relatively less for vowel /i/ indicating robust articulatory gesture.

Table 3.3: Mean and standard deviation of coarticulatory resistance of preceding vowel

	t̪ & d̪		ʈ & ɖ		k & g	
Tokens	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
CRPV	23.67	39.37	30.54	81.60	35.09	56.68
CRPV	49.17	18.63	79.74	21.48	69.59	23.62
CRPV	41.29	48.55	60.19	35.43	37.93	23.15

Coarticulatory resistance by preceding vowels was analysed using Friedman test. Results showed significant difference of coarticulation resistance only in dental consonant contexts (χ^2 (2) = 20.89, p= .001). Wilcoxon Sign Rank test revealed that vowel /a/ was having significantly less coarticulation resistance than /i/ and /u/ (|Z|=2.887= 15.23, p= .004). This indicates that vowel /i/ and /u/ resisted the influence of voiced and voiceless counterparts of dentals moreover similarly, whereas, vowel /a/ could not influence neighbouring consonants.

3.4. Coarticulatory resistance of the following vowel

Coarticulation resistance of following vowel /i/ was higher than /a/ and /u/ vowels. This was common across all the stop consonants considered in this study. Table 3.3 illustrates the mean and standard deviation of coarticulatory resistance of /a/, /i/, and /u/ in the following context.

Table 3.4: Mean and standard deviation of coarticulatory resistance of following vowel

	t̪ & d̪		ʈ & ɖ		k & g	
Tokens	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
CRPV	9.16	6.97	15.05	12.89	14.79	13.54
CRPV	13.87	4.67	19.05	8.47	17.16	10.07
CRṖV	15.86	9.45	19.19	10.00	14.69	7.66

The ability to retain the characteristics of following vowel was analysed using Friedman's test. There was significant effect in consonant context including dental (χ^2 (2) = 15.23, p= .009) retroflex, and velar (χ^2 (2) = 27.78, p= .000). Wilcoxon Sign Rank test was used to do pair wise comparison and the results showed the presence of stronger coarticulatory resistance of /i/ than /a/ (|Z| = 2.859, p=.004) across three different places of articulation.

4. Discussion

The present study results revealed that the retroflex consonants /ɖ/ and /ʈ/ resisted coarticulatory effect significantly than other consonants especially in the context of /aCa/, /iCi/, and /uCu/ respectively. Similar result was reported in another Dravidian language, Kannada study (Kochetov & Sreedevi, 2013). A previous experiment (Sindusha, Irfana & Sreedevi, 2013), reports that Malayalam retroflexes have more complicated tongue movement. Also, the angle between the slope of the surface of the anterior tongue body and the tongue blade is reduced indicating a greater degree of the tongue curling typical of a sub-apical post alveolar retroflex articulation.

Similarly, velar consonants highly resisted the influence when occurred in /a-a/ and /u-u/ contexts. This can be attributed to the presence of wider tongue dorsum contact area during the production of velars than dentals. Tongue dorsum constriction is very minimal in dental consonants where the tip of tongue touches the teeth to make obstruction rather than entire tongue body constriction.

To correlate, DAC model explains that the degree of coarticulation should vary with the constraints exerted upon the kinematics of different tongue constrictions. Thus, for instance, concluded that the place categories especially, retroflex consonants impose restrictions upon tongue activity to almost prevent V-to-V coarticulation from occurring. From this study, it is evident that coarticulatory resistance decreases progressively from retroflex > velar > dental. Though the production of retroflexes occurs as apical constriction rather than tongue dorsum constriction discussed in DAC model, the degree of constriction is more influential and this tongue tip constriction is more precise to make accurate angle of retroflection. Hence, this specific articulatory dynamics oppose the influence of other adjacent segments. Similarly, better coarticulatory resistance of velars than dentals provides reason to believe the notion of tongue dorsum constriction against palate. This suggests that the coarticulatory resistance scale is a valid criterion for consonant classification and also provides valuable information on spatio-temporal planning mechanisms underlying speaker's speech production.

Furthermore, results showed that there is significant difference in the coarticulatory resistance of vowels in preceding (V1) and following vowel (V2) contexts. Resistance declined progressively from high front vowel /i/ to high back vowel /u/ followed by low central vowel /a/. For coarticulatory resistance of preceding vowel, this pattern was seen only in the context of dental consonants. This might be because of the property of high coarticulatory resistance of the retroflex and velar consonants. However, resistance of vowel /i/ was obvious in all the three considered places of articulation than /u/ and /a/ in the following vowel context. This exemplifies that the high front vowel /i/ has the capacity to resist the influence of consonant in both preceding and following contexts. These results are in agreement with some of the previous studies where the vowel /i/ showed maximum coarticulatory resistance in English (Stevens & House, 1963), Dutch (Pols, 1977), and Catalan (Recasens, 1985).

Since the vowels behaved differently in preceding and following context, it is possible to deem the importance of phonetic place of a phoneme in a segment (Fowler & Brancazio, 2000). Also, the present study indicated strong coarticulatory effect for high back vowel /u/ than low central vowel /a/. This is incongruent with previous studies (Perkell & Nelson, 1985; Recasens & Espinosa, 2009). This can be explained based on the property of vowel production, where both /a, u/ are considered as back vowels in English, whereas, in Malayalam /a/ is low central vowel and possibility of variance is more compared to high back vowel /u/.

Coarticulatory aggressiveness is directly related to the resistance of the phoneme. Hence, it follows the same trend as explained in DAC model. Phonemes have raised tongue dorsum position and more constriction that show sheer antagonism against influence. Results reveal that the retroflexes in consonants and high front /i/ in vowel category spectacled maximum aggressiveness. Tongue dynamics of vowels were customized based on the neighbouring consonant. This was more evident when retroflexes were adjacent to vowels /a/ and /u/ (/aʈʈa/, /aɖɖa/, /uʈʈu/, /uɖɖu/). Retroflexes neighboured to other higher aggressive phoneme /i/ was interesting aspect of the study. Though direct parametric comparison is not applicable here, tongue contour of vowel /i/ was modified when it occurred in both preceding and following contexts. Tongue tip curling with wide angle of retroflection was observed during the production of /i/. Hence, the statement of opinion is that, coarticulatory aggressiveness is more for lingual consonants than vowels. Perhaps, tongue body constriction explains the same.

Articulatory dynamic properties of speech production categorise phonemes differently. Hence, it is not always possible to conclude coarticulation as language independent aspect. It is better to explain as combination of articulatory and language property. More crosslinguistic studies are required along this line to validate this notion.

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Coarticulatory Aggression and Direction of Coarticulation: An Ultrasound Study

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Abstract:
Coarticulatory pattern can be varied based on the articulatory dynamics of the sound produced. The present study aims to analyze some of the coarticulatory patterns such as coarticulatory aggression and direction of coarticulation based on ultrasound imaging technique. Ten adult Kannada speakers participated as subjects. The stimuli consisted of V1CV2 sequences, with C corresponding to voiced/voiceless counterparts of dental stops (/t̪/, /d̪/) or retroflex stops (/ʈ/, /ɖ/) or velar stops (/k/, /g/), in the context of vowels /a, i, u/. Measurements of coarticulation resistance of consonants were carried out based on Root Mean Square (RMS) distance between the tongue contours of consonant and vowel. Results showed that there was a clear pattern of minimum extent of coarticulation from intervocalic consonant to following vowel in VCV syllable structure. Significant coarticulatory aggressive was noticed in high front vowel /i/ at all three places of articulation considered. Anticipatory coarticulation was evident across dental, retroflex, and velar stop consonants. Overall, the study agreed that the pattern of coarticulation explained using Degree of Articulatory Constriction (DAC) model and the duration of phoneme planning varied as a property of articulatory dynamics.

Keywords: *Coarticulation, aggression, Direction of coarticulation, Kannada, Stops*

1. Introduction

Speech rarely involves production of one sound in isolation, but rather is a continuous, dynamic sequencing of vocal tract movements produced in rapid succession. Though it might be convenient to consider phonemes as independent, invariant units that are simply linked together to produce speech, this simplistic approach does not really adhere to the facts. When sounds are put together to form syllables, words, phrases, or sentences, they interact in complex ways and sometimes appear to lose their separate identity. The influence that sounds exert on one another is called coarticulation*,* that is, the articulation of any one sound segment is influenced by a preceding or following sound. Kühnert and Nolan (1999) defined coarticulation as a fact that a phonological segment is not realized identically in all environments, but apparently varies to become more like an adjacent or nearby segment. It refers to the events in speech in which the vocal tract shows immediate changes that are appropriate for the production of different sounds at a given time.

Coarticulatory influences often extend well beyond the boundaries of a particular segment and appear to be the influence of both spatial and temporal linking of articulatory gestures. It arises for different reasons, like, the phonology of a particular language; the basic mechanical or physiological constraints of the speech apparatus. Quantification of coarticulation can explain the factors that influence phonemes and their direction of coarticulation.

1.1. Extent of Coarticulation and Direction of Coarticulation

Literature on lingual coarticulation has shown that the extent of coarticulation differs based on the phonetic context of consonants and vowels. Quantity of coarticulatory effects for different articulators is strongly related to the patterns of interarticulatory coordination and intravocalic consonant (Recasens, 2002a). Extent of coarticulation can be changed based on the vocalic position. Recasens (2002b) reported that the extent of coarticulationis generally longer in the context of back vowels /a/ and /u/ compared to front vowel /i/. However, dorsal consonants may cause long tongue dorsum effects even in the context of front vowel /i/.

Based on the directionality, coarticulation is majorly divided into two types, that is, anticipatory (Right to left) and carryover (Left to right). Anticipatory coarticulation refers to the influence of given sound segment on a preceding sound (Daniloff & Moll, 1968; Sereno & Lieberman, 1987). Physiologically, it is an adjustment of the vocal tract posture in anticipation of the next phoneme. It is envisaged as cognitively controlled, intentional, large scale and it is often viewed as reflecting preprogramming strategies. The carryover coarticulation refers to the influence of a given sound segment on a following segment (Fowler, 1981). Here, the vocal tract posture adjustment happens because of the sound that immediately precedes the phoneme. It is a small scale effect of mechanical and inertial force acting on the articulators. Bi-directionality has been studied physiologically, acoustically, and perceptually (Sharf & Ohde, 1981) that have revealed varied results. Some of the studies supported more of anticipatory coarticulation than carry over whereas others believed in carryover beyond anticipatory effect. Further, reports showed that directionality changes over place of articulation. Literature reports that bilabials (Bell-Berti & Harris, 1976; Recasens, 1985); dento-alveolar stops (Bell-Berti & Harris, 1976; Farnetani, 1990); dorso-alveolar palatals (Recasens, 1985; Farnetani, 1990), and dorso-velars (Bell-Berti & Harris, 1976) exhibited high carryover effect. On the other hand, labials (Hoole, Gfroerer & Tillmann, 1990) and dento-alveolars (Magen, 1997) had higher anticipatory effect.

Hence, the present study aimed to pursue the notion of directionality across different stop consonants. Also, hypothesized that anticipatory coarticulation is associated with phonemic planning, and carryover coarticulation is strongly dependent on the ongoing articulatory requirements for the production of the contextual segments.

1.2. Coarticulatory Aggression

Coarticulatory aggression is the characteristic of a phoneme/segment with high coarticulatory resistance to exert high influence on the adjacent phonetic segments. When the segment is aggressive, the influence extends well beyond the boundary. It also indirectly indicates how the phoneme resists the influence of neighboring segment and exhibits its own identity. Based on Recasens, Pallare and Fontdevila's (1997) Degree of Articulatory Constriction (DAC) model, coarticulatory aggression is more related to the tongue dorsum constraint and it can be varied dependent on the phonetic characteristics of the sound segment. According to this model, coarticulatory sensitivity of the consonants to the influence of the adjacent vowels in VCV sequences (V-to-C effect) varies inversely with the strength of the consonantal effects (C-to-V effects) and with the degree of articulatory constraint of the intervocalic consonant. Recasens and Espinosa (2009) revealed that greater coarticulatory aggression is observed for consonants /p, n/ in the vowel contexts /i, a, u/ than alveolo-palatals in Catalan. Based on tongue height, high vowels are more aggressive than low vowels (Recasens, 2012).

Reviewing the literature, there are reports regarding coarticulatory aggressiveness across place of articulation using imaging techniques like Electromagnetic articulography (EMA) and Electropalatography (EPG). The present study aimed to improve our understanding on stop consonants' aggressive patterns in VCV sequences across three corner vowels using ultrasound imaging in Kannada.

2. Method

2.1. Participants

A total of 10 native Kannada speakers in the age range of 20-30 years with equal number of males and females served as participants of the study. All the subjects had a normal oro-motor mechanism and were free of speech, language, hearing, neurological, and cognitive impediments.

2.2. Material

The test material consisted of VCV sequences with C corresponding to geminate forms of voiced and unvoiced counterparts of dental, (/t̪/,/d̪ /), retroflex (/ʈ/,/ɖ/),and velar stops (/k/,/g/). Likewise, the vowels in the VCV stimulus form were high front vowel /i/, low central vowel /a/ or high back vowel /u/. Table 1 depicts the test items.

	Places of articulation					
	Dental		**Retroflex**		**Velar**	
Vowels	**Voiced**	**Unvoiced**	**Voiced**	**Unvoiced**	**Voiced**	**Unvoiced**
Low central	/ad̪d̪a/	/at̪t̪a/	/aɖɖa/	/aʈʈa/	/agga/	/akka/
High front	/id̪d̪i/	/it̪t̪i/	/iɖɖi/	/iʈʈi/	/iggi/	/ikki/
High back	/ud̪d̪u/	/ut̪t̪u/	/uɖɖu/	/uʈʈu/	/uggu/	/ukku/

Table 1: Stimuli list of V1CV2 sequences with consonants in 3 places of articulation in the context of vowels V1 and V2 (/a, i, u/).

Three different places of articulation were also included to identify the coarticulatory effects on them. The test VCV sequences were embedded in a short carrier phrase in the respective language (Now I will say "VCV").

2.3. Principle and Instrumentation

The instrument Mindray Ultrasound 6600 connected to a computer and installed with the software Articulate Assistant Advanced (AAA) ultrasound module Version 2.14 (Articulate Instrument, Wrench & Scobbie, 2011) was used for the analysis with 60 frames per second. It was synchronized to the audio input with a sample rate of 22050 Hz. Hardware pulse generated a tone frequency of 1000 Hz with a beep length of 50 ms for an accurate synchronisation. Mindray ultrasound 6600 was set as edge enhancement of 3 with noise restriction of zero. Both smooth function and softening of image function was set as 2 that helped to suppress the tongue image noise. The transducer, a long-handled microconvex probe, operating at 6.5 MHz, was placed beneath the chin of the participant with the support of a stabilization headset (Articulate instrument, Scobbie, Wrench & van der Linden, 2008). Each ultrasound frame was stored by AAA system as a set of raw echo-pulse with depth of 7mm, from which a standard two dimensional image was created.

The ultrasound image is usually displayed as a brightness scan (B-mode) with automatic gain of 1. The borders between different structures and layers of tissue are displayed as grey values. The interface between the tongue and the air are visible as a bright white band. The midsagittal plane is preferentially used in ultrasound imaging as the image is most intuitive and can be compared between different speakers.

2.4. Data Collection

Participants were made to sit comfortably on a high back chair. They were briefed about the test procedure before the recording and were asked to drink a sip of water before the recording to moisten the oral cavity to obtain better ultrasound images. The transducer probe was placed beneath the chin smeared with ultrasound transmission gel (*Aquasonic 100*) for superior tongue imaging. The probe was fastened to stabilization headset (*Articulate Assistant Advanced*) to reduce the artifacts caused by head movements. For recording the speech sample, a headphone (*iball i 333)*was used. Stimuli list were presented visually in a grapheme mode on the computer screen to one participant at a time and 10 repetitions of each prompt was recorded for further analysis. A total of 180 utterances were recorded for each participant that included ten repetitions of 18 target samples (3 same vowel contexts (V1CV1) x 6 consonants including voiced and unvoiced counterparts of 3 places of articulation =18 x 10 repetitions=180). A grand total of 1800 utterances (10 x 180 =1800) were analyzed and subjected to analysis.

2.5. Data Analysis

For analysis, the software AAA having the technique 'fan spline' which has 42 axes or points was used. Splines are curves defined by a mathematical function that are constrained to pass through specified points. Fan spline setups were decided for each place of articulation and were used respectively. For dental and retroflex sound, the fan spline was set more anteriorly, and for velars, more towards the posterior region. Semiautomatic contour plotting of midsagittal view was used for the analysis. Individual token splines for each consonant and vowel were used to create mean splines, based on means at 42 fan splines. Plotted contours were exported to the workspace to measure Root Mean Square (RMS) distance.

Extent of coarticulation (EC) is the magnitude of influence of one phoneme on a neighboring phoneme. To find the EC, the 10tongue contour frames of each utterance were averaged in workspace to minimize the variation. Averaged C spline and V1/V2 spline were considered as analysis pair. These pairs of mean and standard deviation splines were further evaluated using the function "Diff". The function compared the two splines by means of a 2 tailed t-test using the Welch- Satterthwaite equation for each CV and provided Root Mean Square (RMS). The resulting RMS distance values were weighted by 95% confidence considered as EC since it is the distance between the analysis pair. This value is indirectly proportional to the magnitude of coarticulation. Also, the direction of coarticulation and coarticulatory aggression was speculated on the RMS value in comparison with preceding and following phonemes.

3. Results

3.1. Extent and Direction of Coarticulation

The measurements of influence ofvowels on consonants were analyzed using RMS method. Findings revealed that RMS distance was lesserbetween consonant and the following vowel compared to the preceding vowel. This indicates that there is considerable influence of following vowel on consonant than preceding vowel. It was evident in both voiced and unvoiced stop counterparts across all vowels including /a, I, u/. Hence,it is possible to make a comment that the extent of coarticulation of vowel on consonants varies based on the phonetic position of the vowel in a syllable. The mean RMS values are given in Table 2-3.

V1 to Unvoiced stops	Mean RMS distance	V2 to Unvoiced stops	Mean RMS distance	V1 to Voiced stops	Mean RMS Distance	V2 to Voiced stops	Mean RMS distance
a1-t̪	0.63*	**a2-t̪**	0.35	**a1-d̪**	0.51*	**a2-d̪**	0.30
a1-ʈ	0.39	**a2-ʈ**	0.29	**a1-ɖ**	0.63*	**a2-ɖ**	0.32
a1-k	0.73*	**a2-k**	0.32	**a1-g**	0.79	**a2-g**	0.55

Table 2: Mean RMS distance between consonants and low central vowel /a/ both in preceding and following contexts
**Significance at the level of 0.05*

Though the distance between preceding vowel and the consonant was more compared to the consonant and the following vowel in all phonetic contexts, the statistical test showed significant difference only for /t̪/, /d̪, /ɖ/, and /k/ in the context of /a/. As seen in table 2, the distance between consonant (/t̪/, /d̪, /ɖ/, /k/) and the following vowel /a/ was lesser than preceding vowel /a/. Also the extent of coarticulation of a consonant to the following vowel was less than 0.5 nearing zero. It is possible to contemplate that the direction of coarticulation is anticipatory since there is a high influence of the following vowel on consonant than the preceding vowel.

V1 to Unvoiced stops	Mean RMS distance	V2 to Unvoiced stops	Mean RMS distance	V1 to Voiced stops	Mean RMS Distance	V2 to Voiced stops	Mean RMS distance
i1-t̪	0.34	**i2-t̪**	0.31	**i1-d̪**	0.31*	**i2-d̪**	0.20
i1-ʈ	0.19	**i2-ʈ**	0.18	**i1-ɖ**	0.18	**i2-ɖ**	0.1
i1-k	0.43*	**i2-k**	0.31	**i1-g**	0.48	**i2-g**	0.40

Table 3: Mean RMS distance between consonants and high front vowel /i/ both in preceding and following contexts
**Significance at the level of 0.05*

Mann-Whitney U test depicted that the RMS distance was significant / for consonants /d̪/ and /k/ when they were either preceded for followed by vowel /i/. In the Table 3, it is observed that the distance between average tongue contour of the preceding /i/ and the consonants (/d̪/ and /k/) are more than the average tongue contour of the consonants to the following vowel /i/. Thus, vowel /i/ also showed similar directionality of coarticulation as vowel /a/. Speculation of anticipatory coarticulation can be made, but the effect of preceding vowel on consonant was not negligible.
Similar to the other two vowels, /u/ also showed significant difference for consonants /ʈ/ and /k/. The mean tongue contour of vowel /u/ was distant when it is the preceding context than following especially in the context of consonants /ʈ/ and /k/ (Table 4). Anticipatory coarticulation was predominant than carry over as observed in other vowels.

V1 to Unvoiced stops	Mean RMS distance	V2 to Unvoiced stops	Mean RMS distance	V1 to Voiced stops	Mean RMS Distance	V2 to Voiced stops	Mean RMS distance
u1-t̪	0.81	**u2-t̪**	0.39	**u1-d̪**	0.87	**u2-d̪**	0.3
u1-ʈ	0.55*	**u2-ʈ**	0.34	**u1-ɖ**	0.53	**u2-ɖ**	0.24
u1-k	0.56*	**u2-k**	0.38	**u1-g**	0.61	**u2-g**	0.32

Table 4: Mean RMS distance between consonants and high back vowel /u/ both in preceding and following contexts
**Significance at the level of 0.05*

3.2. Coarticulatory Aggression of Vowels
Coarticulatory aggression reflects the capacity to resist the influence and induce effect onneighboring phonemes. This was analyzed for each vowel within the context of the entire six consonants. Friedman test was administered to evaluate the coarticulatory aggression of vowel, both in preceding and following contexts. Dental unvoiced stop /t̪/ showed significant RMS distance in the preceding vowel context, but not in the following vowel context. Further Wilcoxon pair wise analysis was administered and findings were interesting. RMS distance from /t̪/ to /i/ was significantly different from /t̪/ to /a/ and /t̪/ to /u/. Similarly, the mean tongue contour of dental voiced stop /d̪/ was significantly different for preceding vowels /a/, /i/, and /u/. Similar to /t̪/, pair wise comparison showed significance only for /a1/ and /i1/ contexts.
From Table 5, it is evident that RMS distances were less in the context of /i/, both in voiced and unvoiced counterparts of dental stop that indicated more resistance against the influence of the consonant and aggressiveness of /i/ was enough to influence the close proximal phoneme. Though following vowels did not show significant effect, the mean RMS value depicted the same trend of the preceding vowel, that is, high front vowel /i/ had a tendency to influence the preceding consonant.

V1 to Unvoiced stops	Mean RMS distance	V2 to Unvoiced stops	Mean RMS distance	V1 to Voiced stops	Mean RMS Distance	V2 to Voiced stops	Mean RMS distance
a1-t̪	0.63*	**a2-t̪**	0.35	**a1-d̪**	0.51*	**a2-d̪**	0.30
i1-t̪	0.34*	**i2-t̪**	0.31	**i1-d̪**	0.31*	**i2-d̪**	0.20
u1-t̪	0.81*	**u2-t̪**	0.39	**u1-d̪**	0.87*	**u2-d̪**	0.30

Table 5: Mean RMS distance between dental stops and vowels (/a, I, u/) both in preceding and following contexts
**Significance at the level of 0.05*

Similar to dental stop consonants, retroflex unvoiced stop /ʈ/ also showed significant effect of RMS distance across preceding vowels specifically /a/ and /i/; /i/ and /u/ as given in Table 6. but, was not significant in the following vowel context. Voiced retroflex /ɖ/ was significantly distant from preceding and following vowels. Pair wise comparison explained that vowel /a/ to /ɖ/ and /i/ to /ɖ/ were significantly different, but when the vowels followed the voiced retroflex, the significantly different pairs were /a/ to / ɖ/ and /i/ to / ɖ/; /u/ to / ɖ/ and /i/ to / ɖ/. As stated above, the common vowel for consonants /ʈ/ and /ɖ/ was /i/. This high vowel /i/ has more aggressiveness neither it occurs preceding nor following to /ɖ/. But unvoiced retroflex /ʈ/ resists the coarticulatory aggressiveness when it occurs in the following phonetic context.
With respect to velar consonants, there were no significant effects of preceding and following vowels for velar unvoiced stop /k/, but voiced velar stop /g/ showed significant difference only for following vowels. Indeed, it was significant only in the vowel contexts /a/

and /u/, where /g/ to /a/ RMS distance was more (0.55) than /g/ to /u/ (0.32) as given in Table 7. Hence, it shows that /u/ influenced /g/ aggressively than /a/. Also, it is interesting that /i/ did not influence velars extensively as seen in other two places of articulation.

V1 to Unvoiced stops	Mean RMS distance	V2 to Unvoiced stops	Mean RMS distance	V1 to Voiced stops	Mean RMS Distance	V2 to Voiced stops	Mean RMS distance
a1-ʈ	0.39*	**a2-ʈ**	0.29	**a1-ɖ**	0.63*	**a2-ɖ**	0.32*
i1-ʈ	0.19*	**i2-ʈ**	0.18	**i1-ɖ**	0.18*	**i2-ɖ**	0.1*
u1-ʈ	0.55*	**u2-ʈ**	0.34	**u1-ɖ**	0.53	**u2-ɖ**	0.24*

Table 6: Mean RMS distance between retroflex stops and vowels (/a, I, u/) both in preceding and following contexts
**Significance at the level of 0.05*

V1 to Unvoiced stops	Mean RMS distance	V2 to Unvoiced stops	Mean RMS distance	V1 to Voiced stops	Mean RMS Distance	V2 to Voiced stops	Mean RMS distance
a1-k	0.73	**a2-k**	0.32	**a1-g**	0.79	**a2-g**	0.55*
i1-k	0.43	**i2-k**	0.31	**i1-g**	0.48	**i2-g**	0.40
u1-k	0.56	**u2-k**	0.38	**u1-g**	0.61	**u2-g**	0.32*

Table 7: Mean RMS distance between velar stops and vowels (/a, I, u/) both in preceding and following contexts
**Significance at the level of 0.05*

4. Discussion and Conclusion

In the present study, measurements of coarticulation showed that there is a significant influence of following vowels on consonants than preceding vowels. This was evident in both voiced and unvoiced stop counterparts across all vowels including /a, i, u/.It is possible to comment that the extent of coarticulation of vowels on consonants varies depending on the phonetic position of the vowel in a syllable. More specifically, the nature of coarticulation of vowel in the initial position exhibits differentially from the final vowel in a VCV syllable structure. This is in agreement with Sussman, Bessell, Dalston and Majors (1997) whose locus equation data has shown greater degrees of coarticulation in CV units relative to VC across the stops /b, d, g/.As discussed in DAS model V-to-C effect varies inversely with the strength of the consonantal effects and with the degree of articulatory constraint of the intervocalic consonant. This is evident in the present study results, where the interarticulatory consonant resists the influence of the preceding vowel. The extent of coarticulation from preceding vowel to consonant was more than C-to-V. Similar pattern of extent of coarticulation in all the three place of articulation can be explained as a property of speech production rule. Stevens (1972) explained that stop consonants are produced by complete closure in the vocal tract followed by building up pressure in the mouth behind the closure and then releasing the closure. In case of lingual stops, the closure is formed by tongue tip, or tongue body. The extent of coarticulation was longer in the context of back vowels /a/ and /u/ compared to front vowel /i/. However, dorsal consonants especially /k, g/, had long tongue dorsum effects even in the context of front vowel /i/. Similar reports were observed in Catalan language (Recasens, 2002b). This can be a supportive statement which is useful to generalize the notion of 'language independent' coarticulatory pattern.

Similarly, results indicated that anticipatory coarticulation is apparent in all the consonant contexts across vowels. This result is in agreement with some of the previous studies (Ohman, 1966; Ushijima & Hirose, 1974) and simultaneously contradicting with other studies (Bell-Berti & Haris, 1976; Fowler, 1981). Results suggest that there is tongue dorsum involvement for the production of the following vowel immediately after the production of the consonant. Also, velar consonant was predominantly showing anticipatory direction of coarticulation and it was common for all the three vowels. Itis possible to assume that backing of the tongue dorsum act as an articulatory gesture which induces higher coarticulation. Anticipatory coarticulation predominates when the phoneme planning overcomes the inertia of articulatory dynamics. Results depict that dental and retroflex consonants anticipated following vowel with long duration compared to velars since there are distinct articulatory dynamic properties for each consonant.

Coarticulatory aggressiveness was more for vowel /i/ when it preceded /t̪/, /d̪/, /ɖ/ and /ʈ/. Also /i/ was aggressive when it followed /ɖ/ and /ʈ/. Similarly, /u/ showed aggressiveness when it followed velar voiced consonant /g/. Similar reports are noted in literature. As explained in DAC model, coarticulatory aggressiveness increases with the involvement of the tongue body in closure or constriction formation. Similarly tongue height for vowels /i, u/ being greater than for /a/ (Fletcher & Harrington, 1999). Hence, the present study results are in close agreement with Recasens (2012), where the coarticulatory aggressiveness scale decreases in progression from high vowels /i, u/, to low vowel /a/ v. Tongue position restrict any further movement when the tongue dorsum constraints against the palate to produce a phoneme. Also, this constraint position can induce further influence to the neighboring phoneme.

Ultrasound data on tongue dynamics was presented in the study for better understanding of coarticulatory patterns including the extent of coarticulation, direction of coarticulation, and coarticulatory aggression. There was a clear pattern of minimum extent of coarticulation from intervocalic consonant to following vowel in VCV syllable structure. High front vowel /i/ was aggressive enough to resist the coarticulation at all three places of articulation considered. Another trend in coarticulatory direction was anticipatory which was same across dental, retroflex, and velar stop consonants. Overall, the study agreed on the pattern of coarticulation explained using DAC model and the duration of phoneme planning varied as a property of articulatory dynamics. Also, most of the results are incongruent with other language studies; this may be considered as a matter of subject for language independent coarticulation.

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