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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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