STUDY OF CO-ARTICULATION USING F2 LOCUS EQUATION AS A METRIC

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CHAPTER 1

INTRODUCTION

Running speech is a continuous stream that can be divided into a string of phones or speech segments. Each phone is representative of a phoneme of the language and involves a set of speech articulators to articulate the target phone. Each phone is said to have its own specific set of acoustic properties. However it has been demonstrated (Ohman, 1967) that phonemes are considerably influenced by their neighbouring phonemes. The rapidity with which we produce speech results in the phenomenon of coarticulation.

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, 1999). For instance, the English phoneme /k/, will be produced with the tongue in a relatively forward position when accompanied with front vowels ([ki] *key*) and comparatively backward in the context of a back vowel ([ka] *caw*). Variations such as this have been traditionally thought of as allophonic variation. Coarticulation also refers to events in speech where the vocal tract shows immediate changes which approximate for the production of different sounds at a given time.

1.1. Definitions of coarticulation

A strict definition of coarticulation is that "two articulators are moving at the same time for different phonemes" (Borden and Harris, 1980).

"Coarticulation refers to the articulatory modification of a speech sound under the influence of adjacent segments" (Daniloff & Hammarberg, 1973; Kent & Minifie, 1977).

"Coarticulation has often been assumed to be an automatic consequence of speech physiology"(Chomsky & Halle, 1968; Sweet, 1877).

Ohde and Sharf (1981) describe coarticulation as-

- In the physiological sense, it refers to combination of neural impulses to the speech motor system and contributing aerodynamic forces that results in spreading of features among different sounds
- Acoustically, it refers to the influence in sound perception due to modifications by contextual cues for consonants and vowels.
- Perceptually, it refers to the listening effects of the contextual cues for consonants and vowels, in the perception of sounds."

Coarticulatory effects are commonly discussed as anticipatory or forward and perseveratory or backward coarticulation. Anticipatory coarticulation refers to the influence of given sound segment on a preceding sound (Daniloff & Moll 1968; Maren & Lieberman, 1987). Perseveratory coarticulation refers to the influence of a given sound segment on a following segment (Fowler, 1981 & Sereno et al, 1987). Coarticulation has both language-universal and language specific components. Universal properties of a language can be attributed to the fact that all humans tend to have similar limitations on configuration of the vocal tract and exhibit similar neuromotor control. Language specific traits require higher-level cognitive and linguistic mechanisms. Based on Ohman (1966) coarticulatory patterns were different in Russian, Swedish and English. Sole (1992, 1995) supported the language specificity of coarticulatory effect.

1.2 Development of Coarticulation

Children at different stages of their speech and language development tend to employ coarticulation in different ways. From babbling to learning complex patterns of connected speech, the child skilfully articulates, an endless number of sound combinations, using necessary co-articulatory adjustments to accommodate neighbouring sounds. Of late, children's acquisition of coarticulatory behaviour has been given increasing attention. Variability in coarticulation in children can be explained broadly by segmental and holistic theories.

1.2.1 Segmental Theory

Children show the tendency to produce speech in a more segmental fashion than adults (Kent, 1983; Katz, Kripke & Tallal, 1991). The notion behind this school of thought is that the motor skill responsible for temporal sequencing of sounds is said to be acquired prior to finer details of temporal coordination which are developed later on. Thus, speech of young children is characteristic of less coarticulation. This is the **segmental theory**. The segmental theory predicts that children initially produce phonetic segments with less coarticulation than an adult's production of the same segment, suggesting children learn patterns of individual components of the CV segment. In this case, the vowel of the CV sequence has less influence on the articulatory movements of the preceding consonant. Later, children modify their articulatory patterns because of the interdependencies of adjacent sounds. Thus, as children master the canonical articulatory patterns of the segments, coarticulation increases and their speech becomes more efficient or adult like (Kent, 1983).

1.2.2 Holistic Theory

Conflicting with the segmental theory, Nittrouer & Whalen (1989) put forth the holistic theory which states that speech of children could be characteristic of more coarticulation as compared to that of adults. This would mean that children are more likely to produce syllable-based speech production units on a larger extent and would thereby move on to narrow down their domain of articulatory organization. Thus, the articulatory gestures involved in speech production at early stages tend to overlap. During the later stages, the magnitude of such an overlap significantly declines by a process known as ‘differentiation’. It predicts that anticipatory coarticulation in children's speech is greater than adults' coarticulation patterns as reflected in their babbling (Nittrouer et al., 1996). Nittrouer et al. (1996) proposed that babbling patterns of reduplicated and variegated syllables and syllable strings are holistic, undifferentiated gestures of consonants and vowels and that the holistic patterns continue during early word productions. Later, the holistic gestures of early word productions are narrowed to a smaller phonetic unit (Goodell & Studdert-Kennedy, 1993). As the holistic gesture narrows to smaller phonetic units, consonant and vowel interdependencies weaken and thus coarticulation decreases with age and motor practice (Nittrouer et al., 1996).

1.3 Locus Equations as a measure of coarticulation

Before the advent of experimental techniques to study coarticulation, the mode of assessment was largely perceptual. Phonetics began to move towards experimental research during the final years of 1800s. One of the earliest instruments used was a kymograph. It recorded time varying signals such as the acoustic signal, air flow (using bulbs in the mouth that are pressure sensitive) and tongue movements. Thus technical procedures provided means to measure data objectively which hitherto was measured through direct observation. Ever since 1960s, with complimentary use of instrumental, acoustic and perceptual means, non linear nature of speech was quite apparent. In particular, studies of anticipatory labial coarticulation in back vowel contexts such as /u/, lip rounding occurred 4-5 speech segments prior to the target vowel (Sussman & Westbury, 1981).

One way to describe the characteristic patterns of anticipatory co articulation is through locus equations. The concept of locus equations were first introduced by Lindblom (1963) and have been most studied extensively by Sussman (1994) and colleagues (Sussman, McCaffrey, and Matthews 1991). According to Sussman (1997), "locus equations are linear regressions of the frequency of the second formant transition sampled at its onset (F2 onset) on the frequency of the second formant sampled in the middle of the following vowel (F2 vowel) for a single consonant co articulated with a range of vowels." The F2 onset is plotted on the *y* axis and the F2 vowel on the *x* axis. Thus, locus equations are linear regression lines of the form $y=mx+b$. Locus equations represent the F2 onset of a given vowel as a function of the F2 of corresponding mid-vowel nucleus. That is, the F2 onset value associated with the release of a preceding stop varies as per the target F2 of the subsequent vowel. For this reason, locus equations are useful in revealing the extent to which the place of articulation of particular stops is influenced by the positioning of the tongue during the production of following vowels. Thus, Sussman (1997) observed that for a given stop place category, for e.g., [dV] as in ''deet, dit, debt, date, dat, dot, dut, doot, daught, dote,'' data points closely cluster in a positively correlated distribution. This scatter plot obtained is fit with a linear regression line, that is, the 'locus equation' of the form

$$F2_{onset} = k \text{ X } F2_{vowel\ +}\ c$$

Where *k* and *c* are the constants, slope and y-intercept, respectively.

Considerable research has proved the fact that F2 onset values serve as strong cues to identify place of articulation of stop consonants preceding the sampled vowel (Liberman et al. 1954). Locus equations were deemed to quantify the extent to which an upcoming vowel could influence F2 onset of a preceding stop. The locus equation slopes were shown to range from 0 to 1, with 0 indicating that the particular stop consonant is least influenced the following vowel and 1 indicating maximum influence or coarticulation (Krull, 1987)

1.4 Need for the study

F2 locus equation is considered as a quantifying metric of coarticulation in different studies both developmental and in disordered population especially in English and Swedish. The development of coordinated articulatory movements indicates the sequence of speech motor control and it is known that coarticulation varies across place of articulation as the maturation of each articulator occurs at different periods of age. A review of literature on studies pertaining to coarticulation indicates that the phenomenon arises both due to language-specific and language universal attributes. There are limited number of attempts which use locus equation to explore the nature and extent of articulatory overlap in Indian languages and more so in Kannada. Hence the present study attempts to delineate trends of coarticulation in children across various places of articulation.

1.5 Objectives of the study

The study sought to address the following objectives:

- Can locus equations capture age-related developmental changes in CV coarticulation of place of articulation across different vowel contexts?
- Are locus equation parameters sensitive enough to capture coarticulatory effects as a function of place category (/b, d̪, d̟, g/) and vowels /a, i, u/ in children and adults?

1.5 Brief method of the study

Participants: Fluent native speakers of Kannada, children and adults, were selected for the study. Children in the age range of 3-7 years were divided into four groups (3-4; 4-5; 5-6; 6-7 years). Adult group belonged to an age range of 20-30 years. Each group consisted of 15 males and 15 females (a total of 120 children and 30 adults). It was ensured that participants were devoid of speech, language, hearing or any neurological impediments.

Material: The test stimuli were of the form $C_1V_1C_2V_2$ sequences where C and C2 corresponded to voiced bilabial stop /b/ or dental /d̪ / or retroflex /d̢ /or velar /g/. Vowels V1 and V2 were either the high front vowel /i/, low central vowel /a/ or high back vowel /u/. A digital recorder (LS 100 Olympus Multi track linear PCM recorder) with sampling frequency of 44000 Hz will be used for recording the samples.

Procedure: All the participants were selected from native Kannada speaking background with their consent. Participants were made to sit comfortably and the recorder was kept at 10 cm distance from the participant's mouth. Stimuli were elicited from each participant using "repeat after me" procedure. Three repetitions of each CVCV sequence were recorded from the participants with an inter stimulus interval of 30 seconds. Thus, a total of 12*3=36 utterances were recorded from each participant. 1080 CVCV sequences (36 * 30) were collected from each age group thus yielding total of 5400 utterances (1080*5=5400).

1.6 Implications of the study

- The result provides insight about the pattern of coarticulation in typically developing children and adults in an Indian language.
- Helps document important aspect in speech production which is in turn an aspect of speech perception.

- Helpful in understanding the developmental trends of coarticulation across places of articulation which could indicate the maturational pattern of articulators. It will be useful in therapy directions for speech disordered population
- Has applications in the area of linguistics.
- Possible to make an attempt to describe a model of coarticulation.

CHAPTER 2

REVIEW OF LITERATURE

Coarticulation can be generally described as the obvious variation of speech sound fragments due to the influence of adjacent speech segments. It 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). For instance, the English phoneme /k/, will be produced with the tongue in a relatively forward position when accompanied with front vowels ([ki] *key*) and comparatively backward in the context of a back vowel ([ka] *caw*). Variations such as this have been traditionally thought of as allophonic variation. Coarticulation also refers to events in speech where the vocal tract shows immediate changes which account for the production of different sounds at a given time.

There have been a number of explanations to account for the phenomenon of coarticulation. It might be convenient to think of phonemes as independent, invariant units that are simply linked together to produce speech. However, this simplistic approach does not really explain the act of speech production. For instance, if the mentally stored representation of the word ‘key’ were a detailed articulatory plan, then, when the word was actually uttered, it would only match up to a set of instructions for the corresponding articulators and therefore, there would be no coarticulation. However, from storing and accessing the mental lexicon standpoint, this hypothesis would be seemingly implausible as it would be less efficient if every word were stored as a set of articulatory (or auditory) properties. It would also not explain, for instance, the apparent difference in lip rounding while producing words such as ‘caw’ and ‘caught’ or extent of velar fronting in words like ‘key’ and ‘keen’.

To understand coarticulation more clearly, one must realise that we do not have a separate vocal tract for each phoneme. Instead, a single vocal tract must be accommodating enough to satisfy the requirements of all the target sounds in a stipulated sequence. The vocal tract works by the law of physics and is restricted by its physiology. It cannot move instantaneously from one target configuration to the next. Rather than following a separate and tedious process of allowing one phoneme an invariant articulation and so on, it navigates though a smooth course through the sequence, the result being coarticulation.

2.1 Coarticulation: A Historical Perspective

The term "coarticulation" was used as early as 1930s when Menzerath and De Lacerda, (1933) published *Koarticulation, Lautabgrenzung und Steuerung* (1933). During these times, coarticulation was principally studied through direct observation and introspection. The general notion was that every sound had a steady state and that these sounds are interconnected by short transitional glides. Sievers (1876) stated that speech sounded continuous because of the role the transitional glides played. As the phenomenon of coarticulation became more clear, Sievers (1876) himself admitted the possibility of articulators not involved in the current speech sound production anticipating their upcoming configuration. For eg., lip rounding of /k/ in the production of /ku/.

During the late 19th century, with the advent of instruments, phonetics moved towards experimental research. These instruments were employed to find objective measurements of individual speech events. 'Kymography', allowed the mechanical recording of time varying signals, including the acoustic signal, air flow, and (via rubber pressure-sensitive bulbs in the mouth) tongue movements. Through the use of kymograms including air flow measurements, Menzerath & De Lacerda (1933) investigated the production of a series of German labial consonant and vowel sequences and conclude that articulation is ruled by two major principles:

- ‘Koarticulation’ (Synkinese) indicates that articulators already prepare for the following sound during the production of preceding sound segment, e.g. in segments /ma/ and /pu/, the articulatory movement for vowels began at the same time as the movement of initial consonant.
- ‘Steuerung’ on other hand meant movement of an articulator away from its trajectory of one sound due to the presence of a different target in another sound.

Thus, Menzareth and de Lacerda (1933) introduced the concept of coarticulation in phonetic research. Likewise, Stetson (1951) laid the groundwork for providing a theoretical basis for coproduction. His work proved to be a foundation for several theories such as Action Theory (Fowler et al, 1980), Articulatory Phonology (Browman and Goldstein, 1986, 1989) and Task Dynamics (Saltzman and Munhall, 1989).

Stetson opined that phonetic modification such as changes in rate and stress influenced the coordination of articulatory movements in speech production. Moreover, he considered syllable to be the primary unit of speech production. His data revealed that if a syllable is rapidly repeated, such as /tas tas tas/, its structure will at one point, result in /sta sta sta/. Jumps in syllable composition such as this were considered to be evidence for existence of coordinative structures in speech.

Also, Stetson contemplated that articulatory movements can be present although acoustically they might be obscured completely. For example, in fast productions of the nonsense syllable /ispda/, it was observed that the two tongue movements merged into one, and the lip movement for /p/, though visible in the kymogram, was completely taken over by the tongue movement for alveolar. There was no proof of closure phase of the bilabial acoustically. Presence of hidden gestures of this kind was central to Browman and Goldstein's Articulatory Phonology (1990) for the discussion about relationship between coarticulation and coproduction. The use of instruments thus reaffirmed the assumptions that speech sounds influenced each other and varied and that they cannot be divided into separate segments of 'sounds' or 'letters'.

2.2 Description of Coarticulation

Coarticulation can be described in terms of

1. The main articulators involved
2. Some of the muscles considered to be primarily responsible for articulatory movements
3. Movements spreading over adjoining segments
4. Major acoustic consequences of such overlap (Refer Table 2.1)

Table 2.1

Effects of various articulators on coarticulation

Articulators	**Muscles**	**Articulatory activity**	**Acoustic consequences**
LIPS	Orbicularis oris/Risorius	Lip rounding/spreading	Formant changes
TONGUE	Genioglossus, and other extrinsic and intrinsic lingual muscles	Tongue front/back and high/low displacement	Formant changes
VELUM	Levator palatini	Velum lowering	Nasal formants and changes in oral formant structure
LARYNX	Posterior cricoarytenoid/Lateral cricoarytenoid, Interarytenoid	Vocal fold abduction/adduction	Signal (a)periodicity

As for lingual co-articulation, the tongue tip/blade and the tongue body can act as two separate articulators, such that their activity in the production of adjacent segments can overlap in time. Jaw movements are not included in Table 2.1 since the jaw plays a role in both lip and to tongue positioning as a part of labial and lingual subsystems respectively. (Bernthal, Bankson & Flipsen , 2009)

2.2.1 Types of coarticulation

Coarticulation can be described in terms of:

- Anticipatory
- Retentive

Anticipatory Coarticulation

For example,

a) He sneezed

b) He snoozed

c) He asked

d) He answered

The only phonemic difference between the first two items is the appearance of the unrounded vowel /i/ in ‘sneezed’ and the appearance of the rounded vowel /u/ in ‘snoozed’. The lip rounding for /u/ in ‘He snoozed’ usually begins to form during the articulation of the /s/. The contrast between ‘sneeze’ and ‘snooze’ shows that the /sn/ cluster acquires lip rounding only if it is followed by a rounded vowel.

Retentive Coarticulation

It applies to situations where an articulatory feature is retained after its required appearance. For eg., in the production of the word ‘me’, the vowel /i/ tends to be nasalized because of a carry-over velopharyngeal opening from the nasal consonant /m/.

2.2.2 Overlapping of articulators in consonant clusters

Cluster is a tightly organized sequence of articulatory gestures. During its production the articulation for the second consonant is made before the release of the first consonant in any two-consonant cluster. For example in the word /spai/, the bilabial closure for /p/ is accomplished shortly (about 10-20 msec) before the release of the constriction for /s/. This overlapping of consonant articulation makes the overall duration of the cluster shorter than the sum of individual consonant duration. By eliminating interruptions, the overlapping of consonant articulations contributes to smooth flow in speech.

The temporal structure of the word ‘spray’ is shown schematically in Figure 2.1. It can be noted that the constrictions for /s/ and /p/ overlap between by 10 to 20 milliseconds and the closure for /p/ overlaps with the tongue position for /r/ by a similar amount.

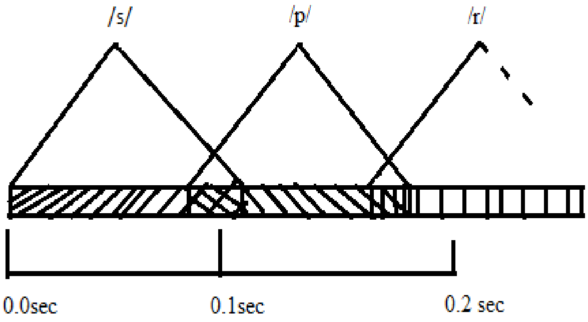


Figure 2.1., Schematic drawing of the articulatory organisation of a /spr/ consonant cluster (in the word ‘spray’, showing overlap of consonantal clusters (*Source: Bernthal, Bankson & Flipsen , 2009*).

2.2.3 Context dependent articulatory modification

The examples of context-dependent articulatory modifications show the variety of influences that sounds exert on adjacent sounds (Refer Table 2.2). For a given sound, place of articulation, duration, voicing, nasalization and rounding may vary with phonetic context. (Bernthal, Bankson & Flipsen, 2009).

Table 2.2

Examples of context-dependent modifications of phonetic segments

Modification	**Context Description**
1) Nasalization of vowel	Vowel is preceded or followed by a nasal, e.g. [mæn] – man. ,[hʌṇṇu] (“fruit” in Kannada)
2) Rounding of consonant	Consonant precedes a rounded sound, e.g. [k^{w}win] – queen & [t^{w}ru] – true, ko:l̟I] (‘hen’ in Kannada)
3) Palatalization of consonant	Consonant precedes a palatal sound, e.g. [mis] – miss
4) Devoicing of obstruent	Word-final position of voiced consonant, e.g. [dɔg] – dog and [liv] – leave
5) Devoicing of liquid	Liquid follows word-initial voiceless sound, e.g. [pleI] – play and [tri] – tree
6) Dentalization of coronal	Normally alveolar sound precedes a dental sound, e.g. [widɵ] – width & [nainɵ] – ninth, [nind̪u] (‘your’ in Kannada)
7) Retro flexion of fricative	Fricative occurs in context of retroflex sounds, e.g. [harsor] – harsher.
8) Devoicing of sound	Consonant / vowel in voiceless context, e.g. [sist∂r] – sister, [bid̟t̪u] (‘left’ in Kannada), [sigt̪u] (‘got’ in kannada)
9) Lengthening of vowel	Vowel preceding voiced sound, especially in stressed syllable e.g. [ni:d] – need
10) Reduction of vowel	Vowel in unstressed (weak) syllable e.g. [tæbjuleit]– tabulate
11) Voicing of sound	Voiceless in voiced context, e.g. [æbsɅrd] – absurd.
12) Deaspiration of stop	Stop follows /s/, e.g. [spai] – spy vs. [p^{h}ai] - pie , [st̪a:pane] (‘establish’ in Knnada)

2.2.4 Co-articulation Matrix

Some aspects of co-articulation can be understood by knowing the extent to which individual sounds restrict the positions of the various articulators. Table 2.3 summarizes degrees of restriction on lips, jaw and parts of the tongue for different places of consonant articulation. A strong restriction is indicated by an X, a slight to moderate restriction by a -, and a minimal restriction by an O. Because, this table shows which parts of the vocal tract are free to vary during articulation of a given consonant; it can be used to predict certain aspects of co-articulation. For example, the Bilabials /b/, /p/, and /m/ strongly restrict the lips, moderately restrict the jaw, and leave the tongue essentially free to vary. Hence, Os are indicated for all parts of the tongue. Jaw position is shown as (-) moderately restricted for most places of articulation because some degree of jaw closing usually aids consonant formation (*Source: Bernthal, Bankson & Flipsen, 2009*).

Table 2.3

Coarticulation Matrix shown for each place of articulation

Place	**Lip**	**Jaw**	**Tip**	**Blade**	**Dorsum**	**Body**
1) Bilabial /bpm/	X	-	O	O	O	O
2) Labiodental /v, f/	X	-	O	O	O	O
3) Interdental /r, 0/	0	-	X	X	-	-
4) Alveolar /d, t, z, s, l, n/	0	-	X	X	-	-
5) Palatal /s, z, dz, t , j, r/	0	-	-	X	X	X
6) Velar /g, k, y/	0	0	0	-	X	X
7) Glottal /h/	0	0	0	0	0	0

The ability of jaw movement to aid tongue movement declines as place of articulation moves back in the mouth, so a velar consonant may not restrict jaw position as much as more frontal articulation (Kent and Moll, 1972). The only sound that allows essentially unrestricted co-articulation is the glottal /h/. Thus, /h/ usually is made with a vocal-tract configuration adjusted to an adjacent sound, such as the following vowel in the words he /hi/, who /hu/, ham /hæm/, and hop /hap/.

2.2.5 Coarticulation and rate of utterance

Speed of speaking is another important aspect of the flow of speech. Speed of articulation can vary greatly depending on different styles and dialects of different speakers. These variations in rate of articulation cause appropriate compression or expansion in time of the sound patterns. It is expected that, since consonant movements must often attain a specific occlusion or narrow constriction, increase in rate of utterance would tend to be absorbed more by the vowels than the consonants.

2.3 Coarticulation: Theories and Experiments

2.3.1 Joos' s overlapping Innervation Theory

Joos (1948) conducted an acoustic analysis of American English vowels and revealed that vowels vary according to the characteristics of neighbouring consonants not only during the transitional periods but also during their steady state. With reference to the occurrence of the second formant, Joos opined that "the effect of each consonant extends pasts the middle of the vowel, so that at middle the two effects overlap. In his theoretical account, he explains the 'glide' hypothesis, which explains coarticulation as the consequence of inertia of vocal organs and muscles. He contests that as there cannot be a shift from one articulatory position to the other instantaneously, there occurs a transition which merges the two successive phones. Hence, he proposes the "overlapping innervation wave theory", wherein each phonetic segment is an “invariant wave” that “waxes and wanes smoothly” and “waves for successive phones overlap in time”.

2.3.2 Coarticulation as a component of Grammar

2.3.2 (a). The theory of feature spreading (Daniloff & Hammarberg, 1973)

Considering coarticulation as a pure physiological process due to mechano-inertial constraints of the speech apparatus, requires a sharp distinction between intent and execution. It implies that articulators are unable to carry out commands as required. In order to overcome the distinction, one must assume that coarticulation itself is a part of the phonological component. The arguments in support of this assumption are: (1) phonology is prior to phonetics, i.e., phonology component underlies the phonetic implementation of speech sounds. (2) phonological segments are abstract entities which cannot be altered by physical speech mechanism (3) speech mechanism can execute only higher level commands. Hence the variations attributed to coarticulation should be the input to speech mechanism. Speech sound segments are thought of as having inherent and derived properties. The derived properties are a result of coarticulation. Phonological rules define which segments should be modified, and, the phonetic representation which forms the input to the speech mechanism specifies the details of articulation and coarticulation.

According to this theory, anticipatory coarticulation is deliberate in nature as the speaker tends to minimise the transition between adjacent sound segments. However, carryover coarticulation is in part the effect of inertia and in part a feedback assisted strategy that accommodates speech segments to each other.

2.3.2 (b). Henke’s articulatory model (Henke, 1966)

This model explains experimental data on the extent of coarticulation. It contrasts the "articulator syllable" model, proposed by Kozhenikov and Christovich (1965). This model is based on information on anticipatory labial coarticulation in Russian, where segments appear to coarticulate, within but not across C_nV sequences. Henke's model does not impose top-down boundaries on anticipatory coarticulation, instead input segments are assigned specific binary phonological features (+ or -), unspecified features are given the value of 0. These binary features are assigned by means of a look ahead scanning mechanism. The spread of features is blocked by a specified feature: for example the feature [+nasal] will be anticipated to all preceding segments unspecified for nasality.

2.3.3. Coarticulation as speech economy

2.3.3 (a) Adaptive variability in speech

As per Lindblom's theory of speech variability, the main aim of phonetics is not to explain how linguistic forms are produced in speech but to explain and derive the linguistic forms from "substance-based principles pertaining to use of spoken language and its biological, sociological and communicative aspects'' (Lilijencrants & Lindblom, 1972). In his theory of "Adaptive variability" and "Hyper-/hypo- speech" (Lindblom, 1983, 1990), phonetic variation is professed to be the result of continuous adaptation of speech mechanism to the demands of the communicative situation.

Variations arise as production strategies change as a result of interaction between system oriented and output oriented motor control. Some situations will require an output with a high degree of perceptual contrast; others will require less perceptual contrast and will allow more variability. Thus, the acoustic characteristics of the same target utterances will vary depending on its over- to under-articulation, or hyper-to-hypo speech.

2.3.3. (b) Natural speech as a low-cost strategy

Lindblom et al. (1975) showed that normal speech is always a result of low cost strategy. The authors studied apical consonants in VCV utterances. Using a numerical model of apical stop production, they showed that, the best match between the output of the model and spectrographic data of naturally occurring VCV realisations in isolation is a tongue configuration that is always compatible with apical closure but characterised by a minimal displacement from the preceding vowel. Thus, the tongue body always tends to take a shape such that it requires the least amount of movement to achieve the articulatory configuration of the adjoining vowels. Lindblom's hypothesis that the more speech style shifts towards the hypo speech continuum, the greater will be the extent of coarticulation is supported by various other studies on connected speech- Krull (1987) for Swedish; Duez (1991) for French.

2.3.4 Other models of Coarticulation

2.3.4. a The Window Model of Coarticulation (Keating, 1985)

Keating (1985) formulated an articulatory model which can account for variations in space and time in speech as well as for inter-language differences in coarticulation. Keating argues that even though phonological rules cannot explain the graded nature of coarticulation, such variations are imperative to the speech production mechanism. She proposes that all graded spatial and temporal contextual variations can be accounted for by the phonetic rules of grammar.

Windows

Input to the window model is the phonological representation in terms of binary features. For a given articulatory or acoustic dimension, a feature value is associated with a range of values called a window. Specified features that permit little contextual variation are called narrow windows and wide windows allow for larger contextual variation. Windows are connected by interpolation functions called 'paths' or contours which represent articulatory or acoustic changes over time in a specific context.

Cross – language differences

According to Keating, inter-language differences in coarticulation may be phonologic or phonetic in nature. Phonologic differences arise when phonological assimilatory rules are seen in one language but not in another. Phonetic differences occur due to different phonetic interpretation of a feature left unspecified. Speech analysis will help in determining if the differences are phonetic or phonological.

Manuel (1987) disagrees with Keating's perspective that all phonetic changes have to be solely accounted for by grammatical rules simply because they are not universal. With reference to inter language differences in V-to-V coarticulation, Manuel proposes that language particular behaviour can be attributed to interaction between universal characteristics of the motor system and language specific phonologic facts such as the inventory and distribution of vowel phonemes. She hypothesises that V-to-V coarticulation is regulated in languages such that the perceptual contrast among vowels be preserved. Therefore more coarticulatory variations can be seen in languages which have a smaller inventory of vowel phonemes where there can be lesser confusion in perception of vowels, than in languages that have more number of vowels. This hypothesis was tested across languages with varying vowel inventories (Manuel &Krakow, 1984). Results support her hypothesis, stating that if output constraints of a given language are related to its inventory size and to the distribution of vowels in articulatory/ acoustic space, then no specific language rules are required since degrees of coarticulation across languages can be predicted to some extent.

2.3.4. b. The DAC model of coarticulation (Recasens, 1997)

The degree of articulatory constraint or DAC model of coarticulation has been proposed by Recasens, with studies being done in Catalan language to study lingual coarticulation. (Recasens et al., 1997; Recasens, 2002). It claims that the size, temporal extent and direction of lingual coarticulation are largely influenced by the productional requirements imposed on tongue for vowels and consonants.

According to this model, vowels and consonants are entrusted with specific DAC values. Thus, front vowels are more constrained than low and back rounded vowels in accordance with biomechanical properties associated with upward and forward tongue dorsum movement and the least constrained vowel is schwa since it does not have any clear articulatory target.

Differences in degree of coarticulation have been observed in consonants as well. DAC values are higher for consonants that require a high degree of articulatory precision, say, production of frication for ligual fricatives, trilling for alveolar trill, tongue predorsum lowering and tongue predorsum retraction for dark /l/. Labials have the least DAC value as tongue body hardly participates their production.

Increased DAC value in consonants indicates increased coarticulatory resistance and coarticulatory dominance, i.e., in the strength of coarticulatory effects from and onto adjacent segments respectively. Thus, as compared to the alveolar /n/ which is less constrained, the alveopalatal /ɲ/ is less coarticulation- sensitive to tongue dorsum lowering effects in the context of /a/ and exerts more prominent tongue-dorsum raising effects on this vowel.

Another characteristic feature of this model is the ability to explain coarticulatory direction. This theory postulates that vowels and consonants usually favour a particular coarticulatory direction over another; i.e. anticipatory or carry over coarticulation based on spatio-temporal features of the lingual gestures involved. Thus, dark /l/ favours anticipation (the tongue lowers and backs in anticipation of the tongue-tip raising gesture for this consonant) while alveopalatals such as /ɲ/ may favour carryover coarticulation.

There have been several studies that have supported the DAC model of coarticulation. Zharkova, Lickley and Hardcastle (2014) used ultrasound imaging to investigate lingual coarticulatory patterns in 13 year old adolescents and 5 year old children, using two consonants that considerably differ with respect to DAC properties. To quantify lingual coarticulation, Tongue Constraint Position Index (TCPI) (Zharkova, 2013a) was used. TCPI represents the location of the most "bunched" part of the tongue. Negative values are associated with backward excursion of the tongue along the tongue contour whereas positive values are associated with forward excursion of the tongue. CV syllables with the consonants /p/ and /ʃ/ and the vowels /a/ and /i/ were produced in the carrier phrase. Results revealed that for both 13-year-old adolescents and 5-year-old children, contrasting vowels /a/ and /i/ had an effect on the tongue shape at mid-consonant. The difference for the adolescents and 5-year olds between the two consonants in the amount of tongue shape adaptation to the following vowel, whether /a/ or /i/ was consistent with the DAC model predictions, with the bilabial stop /p/ being significantly more affected than the postalveolar fricative /ʃ/. Hence, as far as difference in articulatory constraint on the tongue between bilabials and postalveolars is concerned, the model could very well predict lingual coarticulatory behavior in 5-year-old children which is consistent with the premise of the DAC model.

Recasens and Pallares (1997) studied the magnitude and temporal extent of coarticulation in VCV sequences with two vowels (/i/, /a/) and seven consonants (/p/, /n/, dark /l/, /s/, /ʃ/, /ɲ/, /k/ in five speakers of Catalan language. Predictions based on the DAC value for consonants and vowels accounted satisfactorily for the C-to-V effects, especially for /ɲa/ which are more prominent that those for /pi/. Moreover, vowel-dependent effects were negatively correlated with the DAC value for the consonant, e.g., DAC values were more prominent when the intervocalic consonant is /p/ than when it is dark /l/. V-to-C effects were also determined by the tongue-dorsum position for the consonantal gesture. Coarticulatory directionality trends revealed that the extent to which the vowel-dependent tongue-dorsum activity may be anticipated is closely linked to the mechano-inertial constraints associated with the tongue dorsum during consonantal production.

2.4 Development of Coarticulation

Of late, increased attention has been given to acquisition of coarticulated speech in children. Considerable research has been carried out to track various routes of development of coarticulation. It is also possible that the pattern could be purely unique and distinctive, with each individual free to develop his/her own pattern to integrate successive speech segments. These patterns would later on persist into adulthood.

2.4.1 Segmental theory

Many previous investigations (Kent & Forner, 1980) have shown that children are much more variable in their phonetic pattern than adults. Two differing accounts have been postulated in order to explain coarticulatory patterns in children. One school of thought posits that children show the tendency to produce speech more segmentally than adults (Kent, 1983; Katz et al; 1991). This is thought to reflect an acquisition process wherein motor skill of the temporal sound develops first followed by acquisition of finer details of temporal coordination of articulators develop. As a result, coarticulation is supposed to be less pronounced in children. (Kuhnert & Nolan, 1999).

2.4.2 Holistic Theory

In contrast to Kent's Segmental theory, an alternative approach to speech development suggests that children's productions might be characterised by more coarticulation. (Nittroueur et al; 1989; Nittrouer and Whalen, 1989). This view is consistent with the gestural approach of Browman and Goldstein (1986), which says children tend to produce syllable based speech units and then narrow their minimal domain of articulatory organisation. Thus, the spatiotemporal overlap of gestures is more pronounced during the early years which then subside by the process of differentiation. (Kuhnert & Nolan, 1997)

2.4.3 Idiosyncratic routes of development of coarticulation

Studies concerning developmental routes of coarticulation have so far not yielded any clear picture. This could be because of the nature of the dynamic articulatory subsystem under consideration, methodological differences across studies and the various vowel contexts studied. (Sussman et al; 1999). The most divided picture arises with respect to anticipatory lingual coarticulation. For example, Nittrouer et al. (1989) conducted a study on production of fricatives /s/ and /ʃ/ with eight adults and eight children at ages 3, 4, 5 and 7 years and showed that children preferred to organise their speech over a wider temporal domain. F2 estimates and centroid frequencies showed a gradual age-related reduction of the influence of vowels /i/ and /u/ on the preceding /s/ or /ʃ/. In an attempt to replicate this study with ten adults and ten 3-, 5- and 8- year olds, however, no age-dependent differences could be detected by Katz et al (1991).

On the other hand, greater coarticulation for adults was observed by Kent (1983), who studied the influence of a following consonant on a preceding vowel. Also, Sereno and

Lieberman (1987), looking at the influence on a velar stop by a subsequent vowel in /ki/ and /ka/ syllables of five adults and 14 children between the ages of 3 and 7, found consistent coarticulatory effects for adults in the form of different predominant spectral peaks in the consonant. However, their measurements varied greatly between individual children, with some of them displaying adult-like patterns while others did not show any trace of lingual coarticulation. Significantly, the differences among the child speakers did not correlate with age.

Abelin, Landberg & Persson (1980) studied coarticulation in 6 children (2-10 years old, 3-8 years old and 1-7 years) of Swedish speaking population. Their meaningful and non meaningful word productions were compared with the productions of one adult male speaker. Results revealed lesser extent of coarticulation in children as compared to adults because of increased consonant duration. Duration from the onset of labial EMG activity to the acoustic onset of V2 was also increased in children which was characteristic of lesser coarticulatory effects.

Studies have also shown variations in coarticulatory patterns, especially labial coarticulation in children and adults owing to the ambient nature of the spoken language. Coarticulation in the speech of English children is said to be somewhat similar to that of adult subjects. Conversely, for Swedish which has more lip rounding than English, Abelin (1980) reported that adults adopt a look ahead strategy while the children’s labial coarticulation increased with age. Thus, variations in coarticulatory pattern such as that can be attributed to language specific factors.

Similarly, Thompson and Hixon’s (1979) study on nasal airflow measurements in /ini/ showed a greater extent of anticipatory nasalisation with increasing age. However, when Flege (1988) the time of velopharyngeal opening and closing during the vowel in /dVn/ and

/nVd/ sequences in adults and children aged 5 and 10 years, he found out that both groups produced nasalised vowels with almost similar extent.

Turnbaugh et al. (1985) investigated within syllable CV coarticulation in three 3- and 5- year old children and three adult males who were made to produce three repetitions of CVC nonsense syllables. They found out that the degree and pattern of coarticulation in children and adults remained essentially the same and thereby suggested the need to study coarticulation in children younger than 3 years for a meticulous study of development of within syllable coarticulation.

Sussman, Duder and Dalston (1999) examined a single child from seven to 40 months for the production of stop consonants and vowels by measuring the second formant at the onset and vocalic center. Labial, alveolar and velar CV productions followed distinct articulatory paths toward adult like patterns of coarticulation. Most stable slope values were obtained for velars relative to the adult norm

Hodge (1989) conducted a study on subjects aged 3-. 5-, 9- years by making them repeat monosyllables such as [di], [dæ] and [du]. Although results reported of variation in F2 onset values with respect to following vowel, the difference was not statistically significant.

In light of several studies stating near-equal difference in degree and coarticulatory pattern in young children adults, Goodell & Studdert-Kennedy (1993), experimented longitudinally, coarticulation and gestural coordination in a much younger population, i.e., children aged 22-32 months old. Twelve subjects (6 girls of age 20-27 months old at the start of the study and 6 adult females) were recruited for the study. Results demonstrated clear differences in duration and gestural coordination between children and adults and a marked shift toward adult patterns in the third year of life.

Speaker-specific coarticulation behaviour has been observed not only during the phase of speech acquisition but also in adult speakers. Lubker and Gay (1980) investigated upper lip movement and EMG activity of four labial muscles in English and Swedish speakers. Apart from language-specific differences, variations in coarticulation patterns were seen among speakers of the same language. Among the five Swedish speakers, three were reported to employ look-ahead mechanism thereby adjusting the onset of labial movement to the time available while the two others kept the onset of lip rounding constant until the articulation of the target vowel.

Thus, in view of such contrasting results, it is not possible to arrive at any clear picture regearding the acquisition process of coarticulation. Thus, Repp (1966) concluded that "The various patterns of results suggest that phenomena commonly lumped together under the heading of "coarticulation" may have diverse origins and hence different roles in speech development. Some forms of coarticulation are an indication of advanced speech production skills, whereas others may be a sign of articulatory immaturity, and yet others are neither because they simply cannot be avoided. Therefore it is probably not wise to draw conclusions about a general process called coarticulation from the study of a single effect. Indeed, such a general process may not exist."

Thus, it could be inferred that speakers are indeed free to employ any coarticulatory behaviour that is beyond the purview of their anatomical differences. Such individual differences have not been taken into consideration in the formulation of theories. So, truly quantitative statements about coarticulatory effects are yet difficult to derive. Hence more studies on development of coarticulation in children are warranted for a better understanding of the process of speech production.

2.5 Measures of coarticulation

Instruments have been used to measure coarticulation. There are direct and indirect forms of measurement. Indirect measurement comes from instruments that are remote from the structures of interest such as Imaging Techniques. Direct measurements come from instruments that contact the structures of interest such as point tracking devices and electropalatography etc.

Coarticulation can be measured at – articulatory, velopharyngeal and laryngeal levels. It can also be measured by acoustic analysis.

2.5.1 Articulatory Level

A. Electropalatography

B. Imaging techniques such as X-rays, CT Scan, MRI and Ultrasound

C. Point tracking measurements like EMMA, optotrack, x-ray micro beam and strain gauges.

D. Electromyography

Following are some of the techniques that have been used to study coarticulation.

2.5.1. a Electropalatography

- It directly measures tongue–palate contact in real time during speech and swallowing. Small metal electrodes (about 0.5–1.5 mm diameter) are embedded into an acrylic pseudopalate and are activated when contacted by the tongue; this contact completes an electric circuit in the body (Figure 2.2)

- The electrodes measure on/off contact, and though the activation threshold can be changed, subtle changes in pressure are not recorded.
- Thin wires (approx. 42 gauge) attached to each electrode, exit the palate by winding behind the back molars bilaterally, and running forward along the outer surface of the teeth and out through the corners of the lips. A ground electrode completes the circuit.
- The pseudopalate is electrically isolated from the computer that drives it, and the wires are driven by an AC current of less than five micro amps. When the tongue contacts an electrode, the circuit is completed and the contact registered.
- EPG is high-dimensional as it dynamically records multiple contact points between two structures (tongue and palate) from the entire palate surface.
- A recent system, WinEPG (Articulate Instruments, Edinburgh), uses 62 electrodes embedded into a very thin (0.5 mm) acrylic pseudo-palate, which is molded to fit the palate of the speaker
- Coarticulation is observed well in EPG because of its high spatial resolution and fast sampling rates. EPG records details of the tongue's contact with the hard palate and registers characteristic patterns for lingual obstruents, approximants, laterals, nasals etc. Close vowels and diphthongs show measurable degrees of contact, and this has allowed researchers to investigate the influence of vowel context on consonant production.
- However, it would be better if this method of measurement is coupled with other modes such as acoustic analysis because electropalatography can only register sounds which involve tongue-palate contact. For eg., during the production of the lateral approximant /l/ in the context of back vowels such as /ɒ, ɔ:, ʊ, u:/ and relatively open vowels such as /a:, ə, Λ/, generally there is hardly any contact, although in certain cases contact with the posterior part of the palate is seen for /u:/. Moreover, it is not possible to obtain

information regarding the part of the tongue (whether tongue tip or tongue blade) that makes contact with the palate during a speech sound production

Figure 2. 2, A pseudopalate containing 64 electrodes that record tongue palate

- Figure 2.3 shows code number for electrodes for each side of the electro palate, starting from the backmost electrode to the frontmost. Also, the number of electrodes decreases as the rows become more central. Thus, as in Figure 3, there are 8 electrodes on row 1, 7 on row 2 and so on. Rows are numbered from 1 through 5, from periphery to midline.

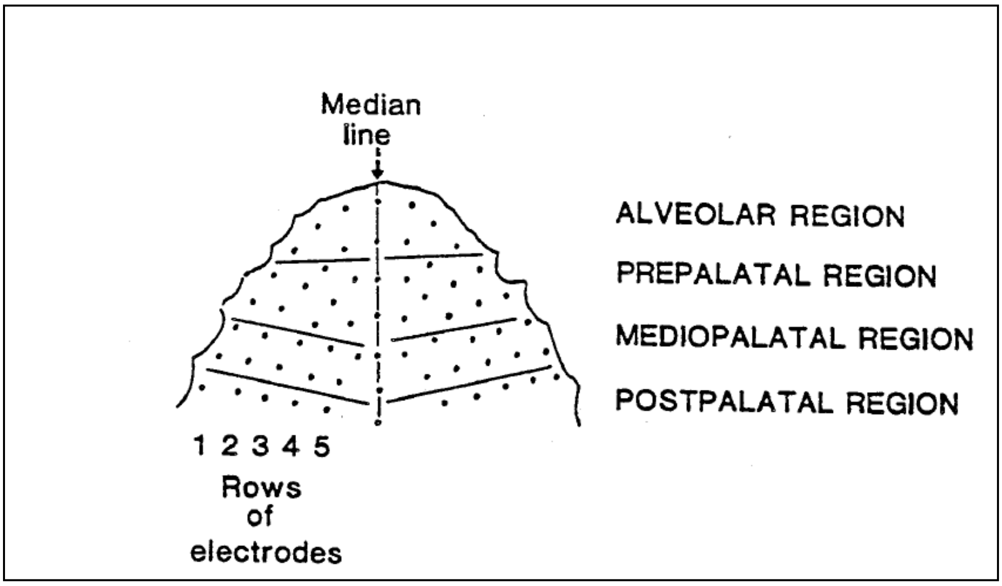


Figure 2. 3. Arrangement of electrodes in an Electropalate (*Source: Recasens, 1980)*

- Figure 2.4 shows selected EPG frames durng production of /k/ in various phonetic contexts. Six phases have been selected to give a picture of transition of tongue movement during the word production. Phase 1 ‘C’ refers to the beginning of closure for the velar region for /k/, C-1 refers to the frame prior to C, C-4 refers to the fourth frame before C ; MAX refers to the maximum number of contacts during the velar closure for /k/, R= refers to the beginning of release of closure and R+4 being the fourth frame after release.

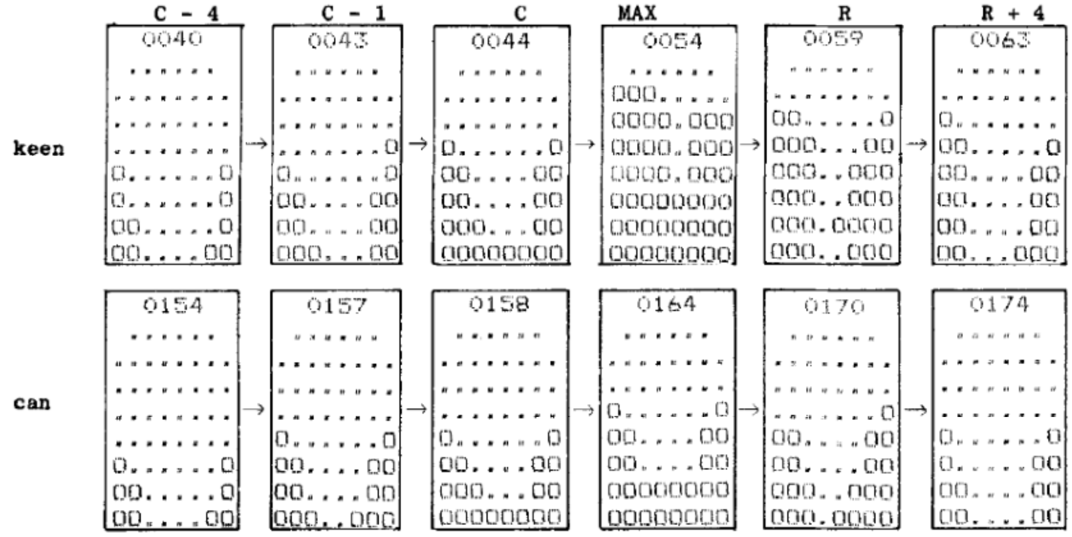


Figure 2.4, Selected EPG frames during production of /k/ (*Source: Hardcastle, W. et al. ,1989)*

The EPG frames shown in the above illustration depict production of sounds at different stages in their articulation. Influence of the following vowel on tongue movement can be clearly understood when MAX frames are compared. In case of the word ‘keen’, the tongue contact is as forward upto the alveolar ridge. The contact is generally far greater for /i:/ than for /æ/ (as in ‘can’).

Electropalatographic studies for coarticulation

Several studies have been carried out to study coarticulation using electropalatograph. Butcher (1987) attempted to quantify the variability of tongue contact patterns at certain stages during the production of VCV utterances by a normal speaker using contact totals derived from an electropalatograph system. VCV sequences (810 tokens) where V was /a/, /i/or /u/ and C was /p/, /t/ or /k/ were read out by three adult native speakers of English. Results showed that vowel-to-vowel coarticulation appeared to be very similar for /p/ and /t/ tokens, and was mainly 'right-to-left' or anticipatory in nature. In general the vowel /i/ in the second syllable influenced both /u/ and /a/ in initial position, in as much as these latter sounds were produced with a greater area of contact than in the VI = V2 context. Similarly, initial /i/ was in turn influenced by following /u/ and /a/, in that these tokens tended to show less contact than for /ipi/ and /iti/. The vowels /a/ and /u/ did not appear to influence each other in terms of palatal contact. Some 'left-to-right' or perseverative effects were noted, where final /i/ preceded by initial /a/ or /u/ has less contact than in /iCi/ contexts.

Recasens (1997) examined coarticulatory effects of consonant with vowels by the combined use of electropalatograph and acoustical analysis. [CVˈCa] sequences served as stimuli where V1 slot is filled with all reduced Catalan vowels, namely [i], [e], [ɛ], [a], [ɔ], [o] and [u]. In all the segments C1 was the same as C2. The consonants used in the stimuli were- bilabial [p], apicodental [t], apico-alveolar [s], lamino-postalveolar [ʃ]; predorso-alveopalatal [ɲ]; dorsopalatal [j]. The EPG data revealed differing degree of coarticulatory influence of consonants on the subsequent vowels. It was noted that coarticulatory effects were found to be larger for back vowels and for [ə]. Back vowels and the schwa showed large positive coarticulatory effects because of raising (typically for [a]) and fronting (typically for rounded vowels) of the tongue dorsum as a function of adjacent dentoalveolar and palatal consonants. These articulatory differences had considerable effect on F2.

Farnetani et al (1985) studied coarticulation in Italian /VtV/ sequences through electropalatography. Patterns of linguopalatal contact during the production of intervocalic /t/ in different vowel contexts were examined. To check for the degree of dependency between tongue tip and tongue body, the relative strength of anticipatory and perseveratory effects were assessed. It was observed that though both carryover and anticipatory effects could extend over a consonant, carryover effects were stronger as compared to anticipatory effects. It was also observed that coarticulation was influenced by suprasegmental aspects such as stress although to a lesser degree.

2.5.1. b. Ultrasound

- Ultrasound produces an image by using the reflective properties of sound waves. A piezoelectric crystal stimulated by an electric current emits an ultra high-frequency sound wave. The crystal both emits a sound wave and receives the reflected echo. The sound wave travels through the soft tissue and reflects back when it reaches an interface with tissue of a different density, like bone, or when it reaches air. The best reflections are perpendicular to the beam. In order to see a section of tissue rather than a single point, one needs an array transducer. In an array transducer, up to 128 crystals fire sequentially, imaging a section of tissue that is rectangular or wedge-shaped.
- The image size is proportional to the size of the transducer and frequency of the crystals, the wedge angle may be up to 140 degrees. The returning echoes are processed by an internal computer and displayed as a video image.
- Figure 2.5 shows a sagittal image of the tongue in a 90-degree wedge-shaped scan. Such an image is created when the transducer placed below the chin sends a beam of

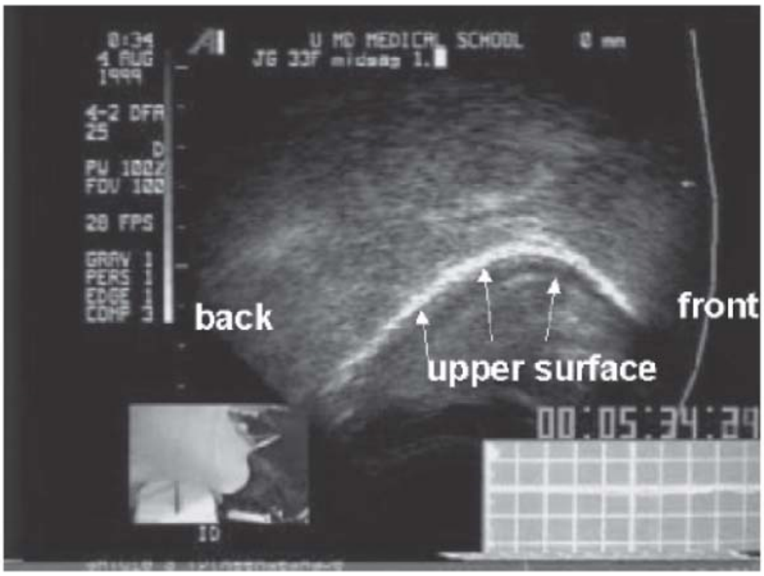


Figure 2.5, An ultrasound image of the sagittal (lengthwise) tongue. The white line is the upper surface of the tongue.

- However, there are certain demerits associated with the use of ultrasound. Firstly, the tongue tip may not be captured in the image, because the ultrasound beam is reflected at the floor of the mouth and the sound wave doesn't enter the tongue tip. The tongue tip can only be imaged when there is sufficient saliva on it or when the tongue is resting against the floor, or if the transducer is posterior and angled forward (Stone, 2005). Secondly, it is not possible to see beyond a tissue-air or tissue-bone interface because, as the tissue-air interface at the tongue reflects the sound wave, the structures that are relatively further away, such as the palate and pharyngeal wall cannot be imaged. Similarly, when

Studies on ultrasound and coarticulation

Several studies on coarticulation using ultrasound have been cited in literature. Zharkova, Hewlett and Hardcastle (2011) compared lingual coarticulation in children and adults speech using ultrasound tongue imaging. The participants were speakers of Standard Scottish English, ten adults and ten children aged 6–9 years. The consonant /ʃ/ followed by vowels /a, i, u/ in consonant -vowel syllables served as stimuli. These sequences were presented in a carrier phrase. Distances between tongue curves were used to quantify coarticulation. Results showed that in both adults and children, vowel pairs /a/-/i/ and /a/-/u/ significantly affected the consonant, and the vowel pair /i/-/u/ did not. Extent of coarticulation was significantly greater in the children than in the adults, providing support for the notion that children's speech production operates with larger units than adults'. Similar findings have also been seen in other ultrasound based studies on coarticulation. (Zharkova et al. 2008a; 2008b). A greater extent of within-speaker variability was seen in children than in adults as evidenced by their varying tongue positions.

2.5.1.c. Point-Tracking Measurements of the Vocal Tract

Point-tracking systems measure relative distances between individual structures of interest by placing pellets on them and tracking their movement with time. By this procedure, multiple articulators are measured simultaneously and tracking speed is so fast that the inter-articulatory timing can be measured reliably. Well-known tracking systems can be external to the oral cavity, such as Optotrak or Vicon, or both external and internal, such as the articulometer and the X-ray microbeam.

Electromagnetic Articulometer (EMA)

- It's also known as Electromagnetic Midsagittal Articulometer (EMMA), Electromagnetic Articulometer (EMA), and Articulograph. These instruments keep a note of movements occurring in and around the oral cavity by virtue of receiver coils through alternating magnetic fields.
- In the 2D EMA systems, three transmitter coils which form an equilateral triangle are suspended over the subject's head by means of a big plastic assembly. Each of these transmitter coils are set at different sinusoidal frequencies which generate alternating magnetic field. Small receiver coils are placed on oral and facial structures which are of interest, by means of an adhesive. The alternating magnetic fields induced by the transmitter coils now generate alternating signals of different frequencies. The voltage of this signal is inversely related to the distance between the transmitter and the receiver coil. A computer algorithm uses these distances to calculate the location of the receiver coil as it moves in *x–y* space over time. The best resolution in the field space is found in the center, i.e., in the oropharyngeal region, where measurement resolution is calculated at less than 1 mm.
- A 3D EMA instrument (the Articulograph AG500) is commercially available from Carstens, Inc., Munich, Germany (Zierdt et al., 2000; Hoole et al., 2003). In this 3D system, a clear acrylic cube surrounds the speaker's head (see Figure 2.6).
- The cube consists of 6 transmitters, placed in a spherical arrangement, each of which produces a magnetic field of differing frequencies. Sensors are placed on oral structures of interest, each of which generates an alternating signal that varies with relative distance from the transmitters. Sensor location is described by 5 parameters: 3 axes-x, y and z and two angles- azimuth and elevation. The two angles characterise the tilt of a

- The 3D machine has a spatial resolution of 1 mm and an angular accuracy of one degree.
- Because of its rapid tracking rate, and the ability to track multiple articulators simultaneously, interaction among the articulators can be measured, and questions about inter-articulator timing and programming can be answered. These features make study of coarticulated speech a lot easier

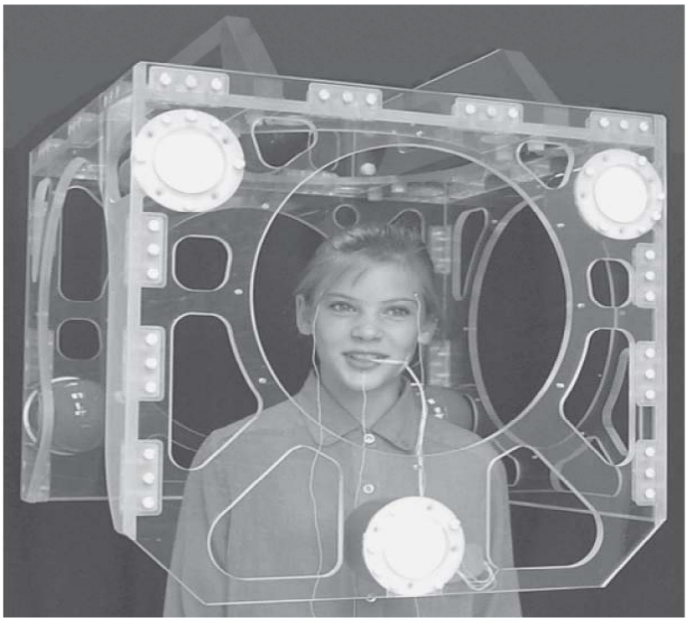


Figure 2. 6, 3D Electromagnetic Articulographic track markers in the mouth using a magnetic field

EMA studies on coarticulation

Considerable research on speech production and coarticulation using has been carried out using EMMA. Kochetov, Sreedevi, Kasim and Manjula (2014) investigated the production of geminate retroflex stops using ultrasound and AG500 electro-magnetic midsagittal articulograph. Data obtained form 10 native speakers of Kannada showed that retroflex gesture is dynamically complex and asymmetrical. Production of retroflex stops is marked by anticipatory retraction of the tongue tip, followed by the raising of this articulator towards the hard palate, and subsequent rapid flapping-out movement during the closure and the release. These movements were facilitated by the simultaneous fronting of the posterior tongue body, flattening of the anterior tongue body, and lowering of the jaw. Also, retroflex stops were shown to exhibit greater anticipatory and perseverative coarticulatory effects on adjacent vowels as compared to dental and velar stops. The results also confirmed the general predictions coarticulation directionality described by the Degree of Articulatory Constraint model (Recasens et al., 1997) described earlier. The greater involvement of the tongue dorsum in the retroflex production before achieving closure (both the tongue body stabilization and the considerable retraction of the tip to the palate) contributed to greater anticipatory coarticulation.

Fowler and Brancazio (2000) aimed to explore coarticulatory resistance offered by lingual and nonlingual consonants on the following vowels in the schwa + CV disyllables in two native speakers of English. In order to assess this, the authors looked for articulatory and acoustic evidence. Articulatory evidence for the effect of anticipatory coarticulation was obtained by comparing tongue body positions during schwa produced in disyllables ending in different vowels. This data were obtained by the use of EMMA. Systematic variations in vowel to vowel coarticulation were also observed by deriving locus equation. An attempt was also made to correlate findings of EMMA with locus equation slopes to provide an explanation on an articulatory basis for the magnitude of variation in locus equation slopes. Results showed that acoustic measures of F2 taken at consonant release and at two later points in the vowel showed parallel and consistent effects of consonantal coarticulation resistance to the articulatory measures.

Katz and Bharadwaj (2001) analysed coarticulation by measuring tongue positioning during fricative- vowel productions by children and adults. Eight adults (four men, four women), six 7-year old children, and three 5-year old children produced the syllables /si su ʃi ʃu/ presented in a carrier phrase. Tongue tip and tongue body measurements were obtained through EMMA, collected with a Carstens AG-100 EMA system. Kinematic data analysed through horizontal movement over time revealed that children exhibited a larger extent of anticipatory coarticulation than adults. Perceptual examination of target production of 3 speakers from each age group was also carried out. Listeners were 10 college aged students. The findings from perceptual examination also mirrored that of kinematic data. However, a strict developmental trend was not seen. Also, the perceptual data revealed some evidence of children showing earlier coarticulation than adults for /sV/, but not for /ʃV/. The authors contended that this disparity could be because of coarticulation resistant properties of the fricative /ʃ/.

Amelot and Rossatto (2007) attempted to compare velar movements for nasal vowels and consonants by investigating contextual nasalisation. Velar movements were measured for VCV sequences for all phonemes in French. Comparison was made between nasalised oral phonemes and nasal phonemes. The consonants in the stimuli were [p t k b d gf s ʃ v z ʒ ʁl m n]. In the vocalic context, oral vowels were [i e a o u] or nasal [ɛ̃ ã ɔ̃ œ̃]. The articulatory movements were recorded with an electromagnetic midsagittal articulograph (EMA Carstens AG100). Results of the study revealed that the velum height was lower for nasal vowels as compared to nasal consonants. Also, the contrast between nasal and oral vowels is maintained in nasal context. Velum height targets for nasal and oral segments showed some overlap, especially sequences of nasal consonant + oral vowels.

X-ray Microbeam

- The X-ray Microbeam tracks tissue-points on the surface of the articulators, resulting in data similar to 2D EMA. Here, x-ray beam is used to track the motion of small gold pellets which are fixed on the articulators by means of dental adhesives.
- Gold pellets are used as it is an inert metal and as the X-ray dosage used is on a very minute scale, only a very dense metal can be detected.
- The system is designed to reduce radiation dosage to as minimal extent as possible in order to avoid radiosensitive areas such as the eyes and to also reduce the possibility of secondary photon scatter.
- The X-ray beam is focussed only on the pellets so as to avoid the rays from entering adjoining tissues or structures.
- Rapid sampling rate and accuracy of tracking make it an excellent system for examining timing related coarticulatory effects, kinematic parameters such as velocity and acceleration, and the inter-coordination of the articulators.
- In addition, the technique is unobtrusive and the low radiation dosage allows for reasonably large data sets to be collected on each subject.

2.6 Acoustic analysis to study coarticulation

Despite the many uses of aforementioned instruments in measuring articulation, they do have their own practical limitations. Most of these instruments are not widely available in speech laboratories or clinics because they are expensive and have high maintenance and operation costs. Thus these instruments are restricted by their use only in specialised laboratories or medical set-ups. Some techniques are invasive and hence uncomfortable for the subject thus impeding collection of naturalistic speech samples and large sets of data. The procedural techniques associated with the use of these sophisticated instruments make them unsuitable for use in clinical population. Finally, analysis of instrumental data can be technically complex and time-consuming which often involves processing of large amounts of data. All these demerits can be significantly reduced by the use of acoustic analysis. The softwares employed for acoustic analysis are often less expensive and easily available. They are non-invasive for the subject and non intrusive for the clinician. Also, it provides a greater insight into the non linear nature of speech which is not apparent in instrumental analysis.

In the arena of acoustics for the coarticulation, locus equations and formant transition rates (FTRs) have been used extensively. FTRs (Hz/ms) are obtained by dividing the difference between F2 onset and F2 onset by transition duration. This measure is said to reflect the speed with which the articulators move from one position to another (Yaruss & Conture, 1993). The concept of locus equations has been described in great detail in the forthcoming sections.

2.7. Locus equation metrics as a measure of coarticulation

The idea that formant transitions could provide cues to the place of articulation dated back to the 1940s by the work of Potter, Kopp, and Green (1947) and by the work of perception experiments in 1950s carried out at the Haskins Labaratories (Liberman et al., 1954; Delattre et al., 1955). These perception experiments revealed that place of articulation could be distinguished by making F2 point to a 'locus' on the frequency axis close to the time of the stop release. Lindblom (1963) was the first person to put forth the concept of locus equations. They were defined as "linear regressions of the onset of F2 transition on the F2 target, measured at the vowel nucleus." This can be mathematically represented by the equation F2 onset=kxF2 vowel +c where 'k' and 'c' are the slope and intercept respectively. Lindblom showed that data points occurred around the regression line and that the slope and intercept varied according to the place of articulation of the consonant.

Nearey and Shamass (1987) derived locus equations by plotting F2 onset at the first glottal pulse on the y-axis and a vowel steady state measured at a fixed 60ms post-release. Ten speakers producing [CVd] syllables were C=[bdg] preceding 11 medials were acoustically analysed. The authors concluded that “the slopes and intercepts for the three consonants are distinct and thus represent partly distinctive invariant properties (p.17).’’

Various acoustic studies (Lehiste & Peterson, 1961; Ohman, 1966; Fant, 1973; Kewlet-Port, 1982) attempted to find F2 locus in natural speech. However, these studies did not find an invariant locus but showed the greatest convergence towards a locus frequency for /d/.

2.8 Theoretical basis of locus equations

Of late, a number of studies in particular by Sussman et al. (e.g., Sussman, 1994; Sussman et al., 1993, 1995; Modaressi et al; 2004) have used locus equations as a metric to decipher the relationship between formant transitions and place of articulation.

According to Sussman (1991), “locus equations are linear regressions of the frequency of the second formant transition sampled at its onset (F2 onset) on the frequency of the second formant sampled in the middle of the following vowel (F2 midpoint) for a single consonant co articulated with a range of vowels.” The F2 onset is plotted on the y axis and the F2 vowel on the x axis. In short, locus equations representing a particular consonant can be represent by the equation $F2_{onset} = k \text{ X } F2_{vowel} + c$ where k and c are the constants, slope and y-intercept respectively. The slope indicates the amount of change of F2 at the beginning of the vowel transition for a unit change in F2 at the vowel midpoint, and the intercept indicates F2 at the beginning of the vowel transition for a zero F2 at vowel midpoint. That is, the intercept is at the intersection of the regression line with the dependent variable axis.

Locus equations represent the F2 onset of a given vowel as a function of the F2 for the midpoint of a given vowel. That is, the F2 onset value corresponding to the release of a particular stop consonant is observed to co vary with the target F2 of the following vowel. For this reason, locus equations are found to be useful in studying the extent to which place of articulation of particular stops can be influenced by the positioning of the tongue during the production of following vowels.

Considerable research has proved the fact that F2 onset values are accurate predictors of place of articulation of consonants appearing before the sampled vowel (Liberman et al. 1954). Krull (1987) proposed that the locus equation slope quantified the extent to which the imminent vowel affected the frequency onset of the F2 transition. The locus equation slopes were shown to range from 0 to 1. Flatter slopes characterise those stops that are relatively resistant to co-articulatory effects regardless of the following vowel. Flatter slopes (closer to 0.0) occur when F2 onsets following a particular consonant are relatively fixed and are not greatly influenced by the F2 of the following vowel’s (Fig. 2.7 upper panel). Conversely, more positive locus equation slopes (closer to 1.0) are indicative of greater degrees of coarticulation between a stop and the vowels that follow the stop. (Fig 2.7 lower panel).

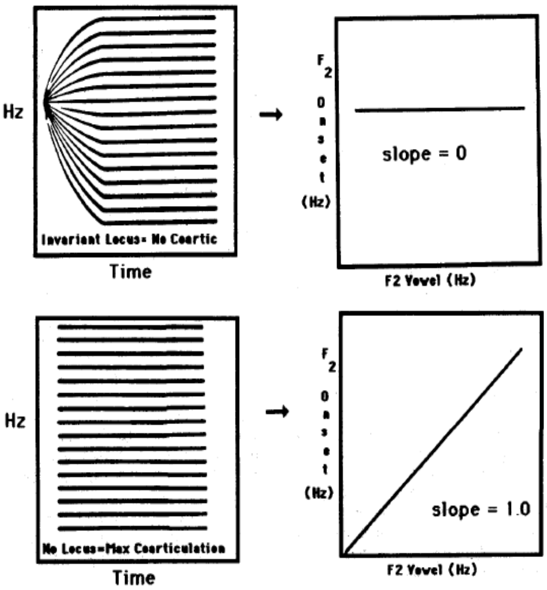


Figure 2.7, Hypothetical extremes of locus equation slopes. The upper panel illustrates a situation that would occur with an invariant consonantal locus when no coarticulation is present between consonant and vowel. The lower panel reflects a condition of no consonantal locus and maximum coarticulation between consonant and vowel (*Source: Sussman et. al., 1996).*

For a lucid attempt at understanding the concept of locus equations, let us review the findings of Sussman, Mc Caffrey and Mathews (1991). They found that, the locus equation for the voiced bilabial /b/ could be represented by the equation y=0.813x+231. This means, F2 onset value for /b/ is supposed to be 0.813 times the value of the F2 vowel midpoint value, plus 231 Hz. (R^2=0.959) . Likewise, locus equation for alveolar /d/ for the same speaker was represented by y=0.394x+1217 (R^2=0.831) and the same for /g/ was described using two contexts-one with respect to front velars ,y=0.261x+1614 (R^2=0.831) and another with respect to back velars , y=1.223x+169 (R^2=0.749).

2.9 Locus equations: invariant cue to place of articulation

Sussman et al (1991) investigated F2 transitions as potential invariant acoustic cues for stop consonant identification across varying vowel contexts using locus equations. 60 locus equations were derived from multiple repetitions of consonant. CVC syllables beginning with the initial consonants /b/, /d/, or /g/ were produced by 10 male and 10 female speakers and locus equations were plotted for the target stop consonants. Statistical analysis of these locus equations revealed a remarkable linearity (the mean r^2 value across all regression functions was 0.89) and distinct slope and *y* intercept terms for each stop consonant place of articulation. Thus, locus equation slopes and *y* intercepts were found to effectively serve as descriptors for place of articulation.

McLeod, Baillargereon, Metz, Schiavetti and Whitehead L R (2001) attempted to replicate a study by Sussman, McCaffrey &Matthews (1991) to confirm if locus equation slope and *y* intercepts varied systematically as a function of place of articulation. Six male and six female English speakers with no history of speech, hearing and language deficits participated in the study. Each utterance consisted of a CVC target word embedded in the carrier phrase “Say ______ again.” The CVC target words began with the voiced stop consonants /b/, /d/, and /g/ and ended with the stop consonant /t/. Ten different vowels (/i/, /I/, /e/, /Ï/, /a/, /o/, /¿/, /O/, /u/, and /e/) were used with each of the three initial stop consonants, which yielded a total of 30 test words per subject. Results showed a significant difference between the male group and the female group in regard to slope (*F* = 9.977; *df* = 1, 10; *p* = .0102). Females in the present study exhibited lower slope values than males across all three stop consonant categories. Variability in participant samples was said to have contributed to these differences. Also, a significant effect of place of articulation (/b/ vs. /d/ vs. /g/) on slope (*F* = 9.98; *df* = 1, 10; *p* = .0102) is consistent with the findings of Sussman et al. (1991).

In the replicated study, unique slope values were associated with different places of stop consonant articulation; words beginning with /b/ showed the steepest slopes, words beginning with /d/ showed the flattest slopes, and words beginning with /g/ had slope values in between /b/ and /d/. The gender-by-place of articulation interaction was not significant.

Analysis of y-intercept values between the male and female groups also showed significant difference (*F* = 19.421; *df* = 1, 10; *p* = .0013). The replicated study found a significant effect of place of articulation (/b/ vs. /d/ vs. /g/) regarding *y* intercept (*F* = 116.82; *df* = 2, 20; *p* = .0001) that is consistent with the findings of Sussman et al. (1991). In both studies, unique *y* intercept values were associated with different places of stop consonant articulation; words beginning with /d/ had the highest intercept values, words beginning with /b/ had the lowest intercept values, and words beginning with /g/ had intercept values in between /d/ and /b/.

As is evident from the studies described above, slopes descend in the series labial>velar>alveolar, and the magnitudes of the intercepts increase in the reverse fashion. Later, Chennoukh et al. (2007) put forth the concept of second order locus equations that describes a linear relation between the slope and intercept. Here, intercepts were taken as dependent variable and the slopes as independent variable.

2.10. Can locus equations serve as effective predictor of manner of articulation?

Sussman (1994) attempted to explore if locus equations could serve as a cue to identify various manners of articulation, namely-nasals, fricatives and approximants, as well as voiceless unaspirated stops /p,t,k/. The main aim of the study was to find out if locus equation slopes could uniformly capture feature based attributes of CVs, i.e., place of articulation across varied manner classes- stops, fricatives and approximants. i.e., will alveolars /d/, /t/, /n/, /s/, /z/, /l/, /r/, be similarly characterised by locus equation functions as they all share a similar place of articulation. For this, ten speakers of American English, 5 male and 5 female, produced monosyllabic words beginning with /sC/ clusters (C= p, t, k). Ten medial vowels were used (/i,I,ɛ,e,æ,a,o, ʌ, ɔ, u/). In order to analyse nasals, fricatives and approximants, four speakers of American English, 2 male and 2 female, produced monosyllabic CVC words beginning with /m, n, v, ð, z, ʒ, w, j, r, l/. Results showed that, among the nasal stops, labial /m/ had a mean slope of 0.86 compared to alveolar /n/ with a slope of 0.32. These results are entirely consistent with expectations as /m/ V gestures exhibit maximum co articulation as compared to the lingually involved n/v/ gestures. Among the 4 fricatives, the labiodental /v/ had the most distinguished locus equation slope (slope=0.74). other fricatives had relatively flatter slopes dental ð=0.34, alveolar /z/=0.28 and post alveolar/ ʒ/= 0.37. Approximants /w, j, r, l/ revealed zero coarticulation. Among the voiceless unaspirated stops, mean slope values showed /k/>/p/>/t/. An attempt was made to cluster various manners of articulation on the basis of locus equations. It was revealed that the approximants /w, j, r, l/ occupied a non overlapping area of locus equation space to the far left corresponding to zero slope. While the labial and velar clusters ‘shared’ the lower right quadrant of space, no overlap is seen as /b/, /p/, /m/ and /v/all have lower y-intercepts than /g/ and /k/.

2.11. Development of coarticulation: A locus equation perspective

Locus equations were used as a phonetic index in a number of studies to understand development of coarticulation in children. Sussman, Hoemeke and Mc Caffrey (1992) studied sixteen children, aged 3-5 years. They produced /bVt, /dVt/, and /gVt/ tokens embedded in a carrier phrase and repeated in randomized order a minimum of three times. Six medial vowel contexts were used [i, I, ae, ʌ, a, u]. Results revealed extremely linear individual and group mean scatterplots and were reminiscent of were of adult prototypes. Though, labial and velar slopes were seen to overlap, labial versus alveolar and alveolar versus velar slopes were significantly different. All y-intercepts as a function of place of articulation were significantly different. Compared to adult norms, intersubject variability of slope and y-intercept ranges were greater for children. Thus, the authors concluded that locus equations can reliably serve as a phonetic descriptor for a child's attainment of stop place categories in an attempt to achieve the adult pattern of balance between coarticulatory adjustments and contrastive distinctiveness.

Sussman, Minfie, Buder, Stoel-Gammon and Smith (1996) studied CV productions at two different linguistic stages of development in a single female child. At 12 months, canonical babbling syllables (144 tokens) were acoustically analysed to derive locus equation slope and intercept for the tokens [bV], [dV] and [gV]. A regression analysis performed on F2 onset and F2 vowel midpoint scatterplot indicated differential slope and y-intercept values for the three tokens. The same analysis was repeated 9 months later when the child was able to produce real words. 243 CV utterances were taken into consideration. Slope values for CV utterances produced at both 9 and 21 months of age was of the order: velar [g]>bilabial [b]> and alveolar [d], though there were changes within each stop distribution. This data was compared with those of adult American English speakers where locus equation slopes were of the order /b/>/g/>/d/. Thus, it can be observed that in both age groups the alveolar /d/ exhibited the shallowest slope. While labial and velar slopes and intercept values at 21 months of age approached adult values, alveolar slope and y-intercept moved away from adult patterns in the direction of decreased coarticulation. Greater scatter of data points was observed during this stage than during babbling stage.

In yet another study to track development of coarticulation using locus equation was conducted by Sussman, Duder, Dalston and Cacciatore (1999). A 7 month old Caucasian female child participated in the study. Recording began when she was reliably producing canonical syllables at around 7 months of age. The child was initially recorded during 1-hour weekly sessions in the child's home. From 16th month of age to 40th month, monthly recording sessions were made. A total of 7,888 tokens were acoustically analyzed; tokens consisted of 3,103 [bV], 3,236 [dV], and 1,549 [gV] syllables. Kay Elemetrics Computerized

Speech Lab (CSL) was used. During the initial months of babbling, labial+vowel productions had very low slopes, but across months 10–13 they sharply increased, moving in the direction of adult target values. Alveolar+vowel productions initially revealed high slopes that rapidly decreased from 7 to 12 months, also moving toward the adult target. Labials permit maximal coarticulation because the tongue has very limited role in its production. In a true co-production sense (Fowler & Saltzman, 1993), labials permit "anatomical independence" and hence maximal temporal overlap. In the present study, the steady slope elevation after month 10 strongly suggests that the child began to produce independent tongue placements for the vowel portion of the CV. These independently controlled tongue positions most likely originated from random tongue placements during lip closure, but they yielded a greater diversity of vocalic-like sounds and, hence, steeper locus equations slopes. Once the motoric independence between lip closure and tongue positioning was achieved it was maintained by the child as [bV] slopes remained relatively high throughout the analysis period.

In order to produce alveolar+vowel syllables, the child must learn to coordinate between two parts of the same articulator. The two active articulators, tongue tip and tongue body become capable of separate adjustments during CV productions. Universally, locus equation slopes for alveolars are relatively flat (modal range = .35–.50), as F2 onsets are minimally influenced by upcoming vocalic contexts. As the tongue tip makes contact with the alveolar ridge thereby attaining a fixed locus, the tongue body must simultaneously adopt a requisite shape to produce the subsequent vowel. At 7 months the locus equation slope was a very steep .86, indicative of extensive CV "coarticulation." In the next few months, slope values steadily declined, and by first words at 12 months, locus equation slopes for [dV] syllables were already close to the normal adult range of CV coarticulation. By this stage of development, the child has gained the ability to exercise independent motor control over the tongue body and tongue tip/blade during [dV] productions.

In order to produce velars, during the production of /gV/ utterances, there is complete anatomical overlap in the motor control of the two segments of the syllable. Because both C and V are produced by the same articulator, the tongue body, velar productions can be characterized as having the vowel “dragging” the C around.

Gibson and Ohde (2007) attempted to delineate coarticulatory trends in 10 children younger than 2 years of age. 1,182 voiced stop CV productions was analyzed using the locus equation metric which yielded 3 regression lines that described the relation of F2 onset and F2 vowel for /bV/, /dV/, and /gV/ productions. The results revealed significant differential effects for slope and y-intercept as a function of stop consonant place of articulation. The ordering of the mean slope values for stop consonant place of articulation was /g/>/b/ and /d/, indicating that /g/ was produced with significantly greater coarticulation than /b/ or /d/. However, the unique vowel allophonic pattern of [g] coarticulation reported in the literature for English-speaking adults was generally not learned by these young children.

2.12 Articulatory Basis of Locus Equation

Several studies have attempted to provide explanations on the basis of articulatory origins of locus equations. One school of thought proves locus equations as a degree of coarticulation between a consonant and a following vowel (Krull, 1987; Fowler, 1994). Studies have shown that increased manipulation of production parameters that increase degree of coarticulation increased slope values (Chennoukh et al, 1997; Lindblom and Sussman, 2004). Another hypothesis is that consonant coarticulation resistance, the degree to which different consonants resist influence of the adjoining vowels is the source of locus equations (Fowler & Braccanzio, 2000; Tabain, 2000). However the link between coarticulatory resistance and locus equations remained unclear. Another hypothesis to explain articulatory basis of locus equations was explained by Sussman et al’s (1998) Orderly Output

Hypothesis. According to this hypothesis, there is a constraint on the speech production mechanism that results in different amounts of coarticulation for different vowels and consonants.

Iskarous, Fowler and Whalen (2010) attempted to explore the articulatory basis of locus equations. They correlated data obtained from Electromagnetic Midsagittal Articulography (EMMA) and X-Ray microbeam with locus equations. They explained that locus equations to measure tongue body synergy could be used by to comparing the patterns of slopes and intercepts for speakers of different languages or for a typical or disordered population. If the locus equation slope is low for a consonant, it implies that the tongue back plays an important role in the consonant production. This explains why the slope values are high in hypoarticulated speech. Though this study recommends the use of locus equation parameters in explaining articulatory basis, the results did not garner enough evidence to show that locus equations could be used as invariant cues for stop location. This is because the slopes could not distinguish between labial from velar place of articulation.

2.13 Variables affecting locus equation

Lindblom et al. (2007) explored if **stress** had an effect on CV coarticulation apart from the stress-induced shifts in relative vowel positions in F1/F2 space. Using a modified locus equation (LE) regression metric, lower locus equation slopes were observed during emphatically produced CV sequences relative to non-stressed CV productions. They reasoned that in emphatically stressed CVs there is an expansion of F1/F2 vowel space, as increased vowel durations allow for F2 vowel nuclei to more closely approach their idealized target positions.

Aguwele, Sussman and Lindblom (2008) attempted to replicate this study to confirm if these findings can be applicable but in the opposite direction, for CVs produced at **fast**

speaking rates. 6 native speakers of American English, 2 female and 4 male, were acoustically recorded. They were not aware of the aim of the study. speech stimuli consisted of VCV sequences embedded in a carrier phrase. They were instructed to read the sentences aloud, beginning with a habitual rate/ tempo, labelled normal (N), and then increase their speaking rate, labelled fast (F), ending with a third rate condition labelled the "fastest" (Fst) such that they were 'as fast as possible without sacrificing intelligibility or clarity'. Analysis of the samples showed a marked decrease in the duration of the samples as a function of rate. Results showed that, for labial productions the mean LE slope increased from normal to fast rate (0.77 to 0.81), and from fast to fastest rate (0.81 to 84); alveolar productions showed the same pattern (0.58 to 0.70 and 0.70 to 0.78) as did velar stops (0.85 to 0.96, 0.96 to 0.99).

Comparison between front and back vowels did not show any consistent pattern for back vowels, as some speakers showed increased, and others, decreased slopes as rate increased. Front vowels showed a completely different pattern as 5/6 speakers showed higher slopes as speech rate systematically increased. For all three stops, the observed LE plot had a higher slope than the predicted function. This was most noticeable in alveolar stops. This difference was attributed to articulatory adjustments affecting F2 onsets during increased speaking rates, but unrelated to vowel reduction influences.

Cole, Choi and Kim (2003) attempted to investigate how **phrasal accent** conditions induced acoustic variation in the radio news speech. They attempted to gather evidence for CV coarticulation in the pattern of second formant transitions in stop-vowel sequences, by comparing accented and unaccented CVX syllables. Speech sample was obtained from one professional radio news announcer from the Boston University Radio News. The data consisted of word-initial stop-vowel sequences. The CV tokens obtained from the speech sample were labelled as accented or unaccented. It was observed that accent had a considerable effect on locus equation slope and y-intercept. Steeper slopes and lower y-intercepts were observed in accented tokens. This was because the F2 onset was strongly influenced by the ensuing vowel in an accented token.

Sussman, Dalston and Gumbert (1998) studied the effect of **speaking style** on locus equation patterns. They attempted to investigate if locus equations maintained stability for stop consonants when derived from reduced or hypoarticulated speech forms. Twenty-two American English speakers, 11 male and 11 female in the age range 21 to 55 were recruited for the study. Citation style samples were obtained by asking the participants to hyper articulate. Also, spontaneous speech samples were obtained from the participants. The results clearly indicated that locus equations showed sensitivity to style differences, but still managed to maintain acoustic distinctions across stop place categories. Locus equation slopes increased during spontaneous speech due to greater coarticulatory influences of the vowel on the prevocalic stop. The labial slopes for citation speech were considerably greater, ranging from a low of 0.71 to a high of 0.97, with a mean of 0.85. Both labial and [g] velar productions exhibited maximally steep slopes in citation forms. Significant slope increases were found only for stops that are inherently more resistant to coarticulation under ideal speaking conditions – alveolar /d/ and [g] palatal.

2.14 Efficacy of Locus Equations

Despite the copious literature advocating the use of locus equations as an invariant cue to identify place of articulation of stop consonants, (Sussman et al, 1991; 1992; 1993; 1995) there have been studies that questioned their efficacy. Locus equations were said to indicate the degree of coarticulation with slope of 1 indicating maximum coarticulation between the consonant and vowel and 0 indicating minimum coarticulation. (Krull, 1987).

Lofquist (1999) and Tabain (2000) set out to test this hypothesis with apparent contrasting results. Lofquist (1999) conducted an articulographic study of stop consonants /b, d, g/ and found that there was no correlation between slope values and articulatory gestures where greater overlap of gestures and/or reduced amplitude of gestures were indicative of greater coarticulation. The three measures used were (1) the temporal phasing of onset of lip movement for the production of bilabial /b/ and the onset of tongue movement from the first vowel to the second in a VCV sequence, (2) magnitude of tongue movement during oral stop closure, averaged across four receivers on the tongue (3) amount of tongue movement from the onset of the second vowel to the tongue position for that vowel. None of these measures matched with the slope value generated by the locus equation.

By contrast, in an electropalatographic (EPG) study, Tabain [2000] found a good fit for velar and alveolar stop and nasal consonant data /d, g, n, ɳ/, but not for fricative data /ð, z, ʒ/ (labial consonants were not tested as EPG does not provide information on lip movement). Tabain [2000] used a regression analysis of the EPG data – where total electrodes contacted in the consonant was the dependent variable and total electrodes contacted in the vowel was the independent variable – thereby making the EPG and locus equation data more comparable. It is not clear why results are so different for these two (i.e. articulograph and EPG) studies.

In Tabain's study (2000), results revealed poorer correlation between EPG and locus equation slopes for fricatives as compared to stops and nasals. Two possible reasons given were- (1) locus equations can capture only gross differences in coarticulation that involves different active articulator (for e.g., tongue body and tongue tip for English stop consonants) rather than subtle differences caused by the same active articulator (for e.g., tongue tip/ tongue blade for English fricatives, where some articulatory changes affect F3 and F4 rather than F2). (2) the frication noise of the fricative got transferred to the following vowel thereby obscuring the visibility of the second formant which in turn reduced the accuracy of locus equation. Also, correspondence between locus equation and EPG data for voiceless stops was less because of greater VOT for voiceless stops. To add on, Tabain and Butcher (1999) showed that locus equations could not separate coronal places of articulation in Yanyuwa and Yindjibarndi, wherein stops and nasal series have four coronal places of articulation.

Tabain (2002) assessed the suitability of locus equations by correlating its data with that of EPG for voiceless stops and fricatives in Australian English. It was hypothesised that slope values would be greater for voiceless stops than for voiced stops owing to delayed VOT in the former. It was also hypothesised that there would be no difference in EPG data for voiced and voiceless consonants in terms of lingual coarticulation. Four female speakers of Australian English were considered for the study. CV syllables embedded in the carrier phrase 'Doctor _ba' served as stimuli for the study. The 12 monophthong vowels were /I, e, æ, ɒ, ɔ, ʊ, i:, e:, ɒ:, o:, ʉ, ɜ:/ and the consonants were /t, k, ɵ, s, ʃ/. Thus, there were a total of 60 CV combinations. Statistical comparison between voiced-voiceless fricative and stops pairs showed no difference between voiced-voiceless consonants in EPG data. However, comparison of locus equations slopes for voiced and voiceless pairs showed significant difference. To add on, overall correlation of slopes generated from locus equation and EPG regression analysis was lower for voiceless consonants than for voiced. This showed that locus equation was not a reliable measure of coarticulatory differences when voiceless and voiced consonant pairs are compared.

2.15 Studies in non English Languages on locus equations

Studies on locus equations for investigating locus equations have been carried out in different languages such as Thai, Cairene Arabic, Urdu (Sussman, Hoemeke, and Ahmed

1993). In each case, the locus equations proved to be a reliable cue to place of articulation. Despite their limitations as mentioned in the above studies, locus equations are still helpful in revealing certain articulatory and perceptual correlates characterizing particular consonants. On a similar note, Idsardi (1998) notes that while locus equations cannot "characterize final consonants or their relation to pre-vocalic consonants," they "are approximately abstract enough to define the upper limit on phonological distinctions for places of articulation."

Mounir et al. (2012) investigated coarticulation in CV and VCV syllables produced by Arabic native speakers. The study was regarding coarticulation between C-to-V, V-to-CV and V-to-V. Ten male native Moroccan Arabic speakers participated in this study. They were asked to perform nine utterances for each series of —CV and —VCV. The syllables consisted of one initial voiced stop consonant /b d k/, one of three vowels /a/, /i/ and /u/. Thus, there were a total of 108 utterances per subject. Results revealed that, in the CV context, the slopes varied according to the place of articulation for each consonant category. The value of the slopes was stronger for velar consonant and low for alveolar consonant. In the VCV context, the locus equation was performed for the final vowel. The slopes obtained respectively for /b/, /d/ and /k/ were 0.814, 0.632 and 0.945 which were higher than that calculated in CV context. This could be due to influence of the initial vowel introduction. Otherwise, by performing locus equation for CV (F2 onset-consonant vs F2 midvowel), the slopes obtained respectively for /b/, /d/ and /k/ were 0.798, 0.766 and 1.011. This result denotes strong coarticulation between the initial vowel V and CV (V1 onto C) and then confirms the carry-over (left-to-right) effect reported in earlier studies. The slopes performed from locus equation for VC (F2vowel offset vs. F2 midvowel) respectively for /b/, /d/ and /k/ were 0.895, 0.704 and 1.126. The values obtained show strong coarticulation between the consonant and the initial vowel (C onto V1) and then imply the anticipatory effect (right-to-left). A careful observation of slope values reveals that anticipatory effect exceeds carry-over with velars (1.126 vs 1.1011) and bilabials (0.895 vs 0.798) except for alveolars (0.704 vs 0.766).

Noiray, Menard and Iskarous (2012) focussed on differences in lingual coarticulation between French children aged 4-5 years and adults. Adults have consistently been observed to use their tongue back to assist the tongue tip in achieving alveolar closure in CV syllables (Iskarous et al, 2010, Sussman et al., 1999). But it was not clear whether children aged 4-5 years used this articulatory strategy. Hence, the authors transposed measures of locus equation to the articulatory domain to observe if the children produced larger extent of coarticulation in labial and velar contexts but lesser coarticulation in alveolar context. Kinematic data were obtained through ultrasound imaging. Results of the study showed that the children have developed d a pattern of coarticulatory resistance depending on consonant place of articulation, also, they were able to achieve a control of the different functional subparts of the tongue to achieve a proper /t/. Moreover, the lower correlation coefficients (obtained by deriving locus equations) associated with children's regressions compared to adults' were attributed to more variability in coarticulatory patterns (e.g., for alveolar) that can be due to the immaturity of the speech motor system and organization of the articulatory gestures to produce distinct goals (e.g., an oral closure in the alveolar region for the alveolar stops).

2.16. Acoustic analysis based studies on coarticulation in Indian context

There are only a few studies in the area of coarticulation in the Indian context. Perumal (1993) attempted to track development of coarticulation in six children aged from 4-7 years by analysing their productions of CVCV utterances. Measures such as transition duration of F2, terminal frequency of F2, extent of transition, speed of transition were computed. Results revealed no specific developmental patterns for any of the parameters and the measures were found to be highly variable. However, when the measurements obtained in children aged 7 years were compared with those aged 4.6 years, it was noticed that the transition duration, speed of transition and extent of transition were longer and the terminal frequency of F2 was reduced in the older age group.

Jayaradha (2001) investigated co articulation in hearing impaired population for their CV utterances and results revealed longer and more restricted coarticulation in hearing impaired when compared to the normal. Suchitra (1985) studied coarticulation in persons with stuttering by analysing the extent of first and second formant transitions in their fluent and disfluent speech and by comparing this with the fluent utterances of normal speakers. A list of 54 VCV nonsense disyllables consisting of short vowels /a,i,u/ and stop consonants /p, t, k, b, d, g/ served as stimuli. Comparison between fluent and non-fluent utterances of stutterers and non-stutterers showed that though the rising and falling trend of the formant frequency transition was the same in fluent speech of stutterers and non stutterers, the extent of such transitions were different in the two groups. It was also observed that in certain occasions, the second formant was missing in a number of VCV utterances in the fluent speech of stutterers.

Mili (2003) studied the effect of labial coarticulation in fifteen native Malayalam speaking adults of age 18-39 years. Four bisyllabic (C_1aC_2a) words were used as control. Five (C_1uC_2a/ C_1oC_2a) words were used to study carry over effects and three (C_1aC_2u) words were used to study anticipatory effects. The consonants C_2 were /ʃ/, trill /r̝/, tap /r/, and the laterals /l/ and /l̝/. Sustained /a/, /u/, /o/, and consonants /ʃ/, /l/, /l̝/, /r/ and /r̝/ also formed the controls. Wideband spectrograms were used to measure transition duration of F2, F2 terminal frequency of the preceding/ following vowel and F2 at every 10ms of the consonant from the preceding/ following vowel were measured. The results showed a stronger anticipatory coarticulation effect as compared to the carry over effect. Anticipatory coarticulatory effects lasted for 10-60ms while carry over effects lasted for 0-30 ms.

Banumathy and Manjula (2005) studied coarticulatory effects in Kannada in which they investigated the variations of coarticulation in prepositional and non-prepositional speech. Preceding vowel duration, closure duration and preceding vowel transition duration were significantly different between tasks and the authors concluded the need of voluntary and conscious processing for prepositional speech compared to non prepositional task.

Sreedevi, Smitha, Irfana and Nimisha (2012) studied coarticulation in hearing impaired population. They used F2 locus equation as a metric and the slope of the regression lines provided a numerical index of coarticulation which showed variation across hearing aid users, cochlear implantees and normal controls among places of articulation. Velars showed higher degree of coarticulation and bilabials and dentals revealed weaker coarticulation effect. Among children with hearing impairment, the hearing aid users showed comparatively poorer performance than cochlear implantees particularly for velar coarticulation. Though studies have been attempted in the area of coarticulation, studies on developmental changes of coarticulation is lacking, especially in Indian languages. Hence the present study aims to compare the patterns of coarticulation across children and adults of native Kannada language using F2 locus equation.

CHAPTER 3

METHOD

3.1 Participants

The participants were native Kannada speakers, 30 children each in the age groups of 3-4, 4-5, 5-6, 6-7 years and adults of age 20-30 years. The children were recruited from schools in Mysore, Karnataka and were ensured that they did have any record of speech, hearing or cognitive impediments. Their speech samples were audio-recorded only after obtaining consent from Principals of the respective schools. Thus, a total of 150 subjects, 30 in each group, 15 males and 15 females participated in the study. In line with studies conducted on development of speech motor control that report decline in refinement of jaw displacement patterns by 7 years of age (Susan & Sharkey, 1987, Green et al., 2000), the age range of the current study has been restricted to 7 years.

3.2 Material

The test material consisted of non meaningful $C_1V_1C_2V_2$ sequences with both C_1 and C_2 being either the voiced bilabial stop /b/, dental /d̪ /, retroflex /d̟/ or velar /g/. The vowels V_1 and V_2 were high front vowel /i/ , low central vowel /a/ and high back vowel /u/. It should be noted that in $C_1V_1C_2V_2$ sequences, C_1-C_2 and V_1-V_2 were identical in order to maintain a uniform phonetic environment. Table 3.1 shows the test items.

Table 3.1

Test material for the study

Phonemes	**/b/**	**/d̪ /**	**/d̟ /**	**/g/**
/a/	/baba/	/d̪ad̪a/	/ɖaɖa/	/gaga/
/i/	/bibi/	/d̪id̪i/	/ɖiɖi/	/gigi/
/u/	/bubu/	/d̪ud̪u/	/ɖuɖu/	/gugu/

Non meaningful words were chosen, firstly, to maintain a constant vowel and consonant environment, and secondly, to induce a non-emotional neutral context. Moreover, it was not possible to decide upon meaningful words whilst maintaining a uniform consonant-vowel context. The material included only voiced stop consonants for the ease to mark the first glottal pulse during the F2 locus analysis as indicated by Krull (1989). The three vowels /a, i, u/ considered would allow for testing diverging tongue positions. Children were asked to imitate CVCV sequences embedded in short carrier phrase. For example, /na:nu i:ga */baba/* anta h:elthini/ ("Now I will say ***/baba/***").

3.3 Instrumentation and Procedure

A digital recorder (LS 100 Olympus Multi track linear PCM recorder) with sampling frequency of 44000 Hz was used for recording the utterances. All the participants were selected from native Kannada speaking background. They were made to sit comfortably and the recorder was kept at a distance of 10 cm from their mouth. Stimuli were elicited from each participant using "repeat after me" procedure. Three repetitions of each CVCV sequence were recorded from each participant with an inter stimulus interval of 30 seconds. Thus a total of 12 utterances were recorded from each participant. 1080 CVCV sequences were collected from each age group thus yielding a total of 5400 (1080*5) utterances.

3.4 Data Analysis

The recorded data from the digital recorder was transferred on to a computer and was analysed to extracting spectral features using PRAAT software (Version 5.1.14). Locus equation requires onset and midpoint of F2 vowel. F2 is considered to be a significant cue for place of articulation. F2 vowel onset and midpoint of V1 of each $C_1V_1C_2V_2$ utterance was measured. The first vowel V1 was considered for the analysis since it has the effect of both preceding and following consonants. Spectral measures were obtained from wide-band spectrographic displays as shown in Figure 3.1.

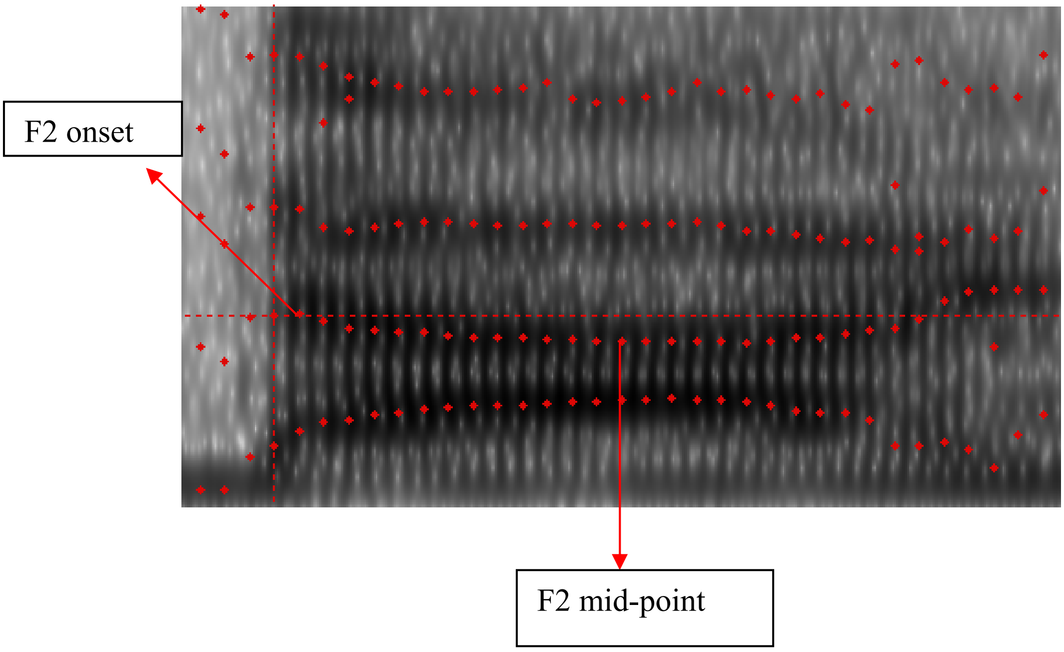


Figure 3.1, F2 onset and F2 mid-point as seen in a wideband spectrogram

As described by Sussman et al. (1991), F2 onset was measured at the first noticeable glottal pulse after the release burst, and the mid of F2 was located as per the following criteria:

(i) If the formant resonance has a steady state on visual inspection, a midpoint frequency of steady state portion was taken. (approximately 60-110 ms post transition onset depending on vowel duration)

(ii) If the F2 pattern was diagonally rising or falling, midpoint was once again chosen on visual inspection

(iii) If the F2 pattern was either “U-shaped” or the reverse, the “minimum” or maximum frequency was taken as F2 midpoint.

These measured F2 onset and F2 mid-point values were tabulated and statistically analyzed using regression analysis. Thus, locus equation for each consonantal place of articulation was derived statistically.

3.5. Inter and Intra judge reliability

To examine intra-judge and inter-judge measurement reliability on F2 transitional measures (F2 onset and F2 midpoint frequencies). Samples obtained from 10% of the total subjects, i.e. 15 subjects, were randomly chosen and re-analysed. Inter-judge measures were obtained following re-analysis by a speech pathologist trained in acoustic analysis. The values thus obtained were subjected to Cronbach's test of reliability which yielded fairly good interjudge (0.7-0.8) and intrajudge (0.8-0.9) reliability.

CHAPTER 4

RESULTS AND DISCUSSION

The study was conducted in order to address the following objectives:

- Can locus equations capture age-related developmental changes in CV coarticulation of place of articulation across different vowel contexts?
- Are locus equation parameters, in this study, namely the slope, sensitive enough to capture coarticulatory effects as a function of place category (/b, d̪, d̟, g/) and vowels /a, i, u/ in children and adults?

The results of the study will be discussed accordingly. As a prerequisite to obtain locus equations, mean F2 onset (F2o) and F2 midpoint frequencies (F2mp) of the participants in different age groups in each vowel context when preceded by stops (/b, d̪, d̟, g/) were computed, results of which are presented in Tables 4.1 (a) -4.1 (d).

Studies on development of formant frequencies usually consider frequency at mid-vowel region for analysis as formants are found to be stable and devoid of influence of the following and preceding consonant. It is of interest to understand change in F2 frequencies as a function of age and gender. Hence, as a prerequisite, Kolmogrov-Smirnov's test for normality was performed on F2 onset and F2 midpoint frequencies within each age group. Results of this test revealed that the values followed a normal distribution ($p>0.05$).

Table 4.1. (a)

Mean (standard deviation) of F2 onset ($F2_o$) and F2 midpoint frequencies (F2mp) in Hz for vowels /a/, /i/ and /u/ in Hz in 3-4 year old males

	3-4 years - Males					
	/a/		/i/		/u/	
Stop Categories	$F2_o$	$F2_{mp}$	$F2_o$	$F2_{mp}$	$F2_o$	$F2_{mp}$
/b/	1627	1752	2824	3113	1335	1281
	(134.1)	(133.2)	(226.5)	(150.3)	(259.3)	(268.1)
/d̪/	2147	1954	3074	3174	1880	1506
	(259.9)	(147.6)	(103.1)	(102.9)	(327.5)	(240.5)
/d̟/	2261	1987	2971	3102	1883	1522
	(127.6)	(144.5)	(144.1)	(148.5)	(164.05)	(216.9)
/g/	1870	1838	3038	3023	1525	1155
	(85.6)	(105.9)	(238.2)	(101.9)	(242.6)	(233.1)

Table 4.1. (b)

Mean (standard deviation) of F2 onset ($F2_o$) and F2 midpoint frequencies (F2mp) in Hz for vowels /a/, /i/ and /u/ in 3-4 year old females

	3-4 years-Females					
	/a/		/i/		/u/	
Stop Categories	$F2_o$	$F2_{mp}$	$F2_o$	$F2_{mp}$	$F2_o$	$F2_{mp}$
/b/	1728	1885	2969	3235	1314	1242
	(136.4)	(109.9)	(235.1)	(84.9)	(270.37)	(176.5)
/d̪/	2256	2041	3078	3233	1917	1442
	(270.7)	(121.2)	(147.3)	(102.3)	(264.4)	(192.6)
/d̟/	2359	2025	3054	3171	1865	1392
	(119.1)	(140.9)	(140.4)	(119.5)	(162.2)	(143.9)
/g/	1996	1877	3152	3149	1322	1237
	(149.8)	(137.1)	(146.2)	(119.7)	(198.4)	(177.9)

From Tables 4.1(a) and 4.1 (b), it is evident that vowel /a/ had the highest F2 mid-point when preceded by retroflex /ḍ/ and lowest F2 when preceded by bilabial /b/ in male children of 3-4 years. Similarly the female subjects of the same age group showed highest and lowest F2 for vowel /a/ when preceded by dental /d/ and velar /g/ respectively. Likewise, for the vowel /i/, while males showed highest and lowest F2 values when preceded by dental /d̪/and retroflex /ḍ/ respectively, females showed highest and lowest F2 values when preceded by bilabial /b/ and retroflex /ḍ/ respectively. Further, for the high back vowel /u/, males had the highest F2 midpoint values when preceded by retroflex /ḍ/ and lowest F2 when preceded by velar /g/. Females showed the highest and lowest F2 values in contexts of dental /d̪/ and velar /g/ respectively. Overall, the standard deviation was higher for the vowel /u/ in both male and female children.

Table 4.1 (c)

Mean (standard deviation) of F2 onset (F2o) and F2 midpoint frequencies (F2mp) in Hz for vowels /a/, /i/ and /u/ in 4-5 year old males

	4-5 years- Males					
	/a/		/i/		/u/	
Stop Categories	$F2_o$	$F2_{mp}$	$F2_o$	$F2_{mp}$	$F2_o$	$F2_{mp}$
/b/	1639 (210.5)	1788 (138.9)	2899 (359.5)	3192 (145.1)	1496 (264.7)	1399 (224.1)
/d̪/	2132 (264.7)	1949 (160.7)	3073 (123.1)	3259 (120.2)	2013 (223.3)	1547 (220.5)
/ḍ/	2249 (154.5)	1908 (136.6)	3048 (120.8)	3160 (120.1)	1943 (200.2)	1495 (280.1)
/g/	1861 (159.7)	1799 (141.4)	3276 (62.7)	3242 (131.6)	1570 (310.2)	1451 (362.6)

Table 4.1 (d)

Mean (standard deviation) of F2 onset (F2o) and F2 midpoint frequencies (F2mp) in Hz for vowels /a/, /i/ and /u/ in 4-5 year old females

	4-5 years- Females					
	/a/		/i/		/u/	
Stop Categories	F2$_o$	F2$_{mp}$	F2$_o$	F2$_{mp}$	F2$_o$	F2$_{mp}$
/b/	1737	1870	2933	3148	1481	1242
	(112.5)	(112.2)	(233.4)	(137.5)	(218.6)	(218.3)
/d̪/	2260	2042	3045	3226	2140	1614
	(229.9)	(129.5)	(118.9)	(101.2)	(136.9)	(168.5)
/ḍ/	2373	2053	3062	3170	2114	1611
	(151.6)	(164.1)	(158.2)	(118.7)	(195.0)	(205.9)
/g/	1963	1928	3080	3020	1563	1391
	(151.9)	(152.9)	(203.5)	(187.6)	(155.4)	(139.9)

From Tables 4.1 (c) and 4.1 (d), we can note that, in male subjects of age 4-5 years, vowel /a/ evidenced a high F2 midpoint value in the context of dental /d̪/ and low F2 value in the context of bilabial /b/, but in females, highest and lowest F2 values where noted in the contexts of velar /g/ and bilabial /b/ respectively. Further, for the high-front vowel /i/ and high-back vowel /u/, while male subjects showed the highest F2 midpoint when preceded by /d̪/ but lowest values in the presence of /ḍ/ and /b/ respectively, female participants showed the highest F2 values in contexts of /g/ and /d̪/ but the least in the context of bilabial /b/. From the data presented, it can be surmised that, 4-5 year olds also showed a relatively high standard deviation in the context of vowel /u/.

Table 4.1 (e)

Mean and standard deviation of F2 onset (F2o) and F2 midpoint frequencies (F2mp) in Hz for vowels /a/, /i/ and /u/ in 5-6 year old males

	5-6 years- Males					
	/a/		/i/		/u/	
Stop Categories	$F2_o$	$F2_{mp}$	$F2_o$	$F2_{mp}$	$F2_o$	$F2_{mp}$
/b/	1546 (113.5)	1677 (69.9)	2672 (261.3)	3136 (163.5)	1718 (274.7)	1368 (225.1)
/d̪/	2136 (274.7)	1861 (125.1)	2907 (251.8)	3220 (216.9)	2064 (144.7)	1527 (163.2)
/ḍ/	2147 (114.5)	1858 (83.2)	2877 (214.4)	3061 (220.0)	1982 (153.3)	1471 (195.5)
/g/	1756 (97.4)	1695 (92.34)	3184 (126.9)	3125 (143.8)	1604 (241.4)	1421 (290.5)

Table 4.1 (f)

Mean and standard deviation of F2 onset (F2o) and F2 midpoint frequencies (F2mp)in Hz for vowels /a/, /i/ and /u/ in 5-6 year old females

	5-6 years- Females					
	/a/		/i/		/u/	
Stop Categories	$F2_o$	$F2_{mp}$	$F2_o$	$F2_{mp}$	$F2_o$	$F2_{mp}$
/b/	1627 (74.6)	1769 (108.4)	2974 (199.6)	3265 (131.6)	1528 (229.9)	1390 (201.2)
/d̪/	2139 (229.9)	1953 135.9)	3042 (103.4)	3204 (117.4)	2113 (95.5)	1650 (94.1)
/ḍ/	2239 (99.8)	1916 (100.4)	3117 (187.5)	3205 (119.5)	1895 (184.2)	1472 (179.7)
/g/	1866 (110.9)	1832 (110.6)	3225 (139.8)	3161 (142.1)	1470 (207.3)	1458 (225.1)

From Table 4.1. (e) and 4.1. (f), it can be inferred that male subjects aged 5-6 years, showed the highest F2 midpoint values for vowels /a/ and /u/ when preceded by retroflex /ḍ/ and dental /d̪/ respectively but lowest values in the context of /b/. However in the case of high front vowel /i/, highest and lowest F2 were evidenced when preceded by /d̪/ and /b/ respectively. Similarly, for vowels /a/ and /u/, the female participants of the same group showed the highest values when preceded by /d̪/ but the lowest when preceded by /b/. However, in case of /i/, highest F2 was seen in the presence of /b/ and the lowest in the presence of /d̪/. As in the case of 3-4 and 4-5 year olds, the standard deviation continued to be high in case of vowel /u/.

Table 4.1 (g)

Mean (standard deviation) of F2 onset (F2o) and F2 midpoint frequencies (F2mp) for vowels /a/, /i/ and /u/in Hz in 6-7 year old males.

	6-7 year Males					
	/a/		/i/		/u/	
Stop Categories	$F2_o$	$F2_{mp}$	$F2_o$	$F2_{mp}$	$F2_o$	$F2_{mp}$
/b/	1560	1651	2933	3195	1217	1260
	(127.4)	(128.6)	(152.5)	(109.8)	(225.5)	(231.3)
/d̪/	2166	1885	2957	3220	1976	1466
	(102.1)	(94.5)	(91.7)	(75.2)	(243.8)	(143.3)
/d̟/	2247	1894	2955	3134	1874	1425
	(157.8)	(120.3)	(146.4)	(164.1)	(177.5)	(134.8)
/g/	1829	1733	3274	3248	1421	1261
	(137.9)	(125.2)	(144.8)	(107.8)	(163.5)	(121.4)

Table 4.1 (h)

Mean (standard deviation) of F2 onset (F2o) and F2 midpoint frequencies (F2mp) for vowels /a/, /i/ and /u/ in Hz in 6-7 year old females.

	6-7 year Females					
	/a/		/i/		/u/	
Stop Categories	$F2_o$	$F2_{mp}$	$F2_o$	$F2_{mp}$	$F2_o$	$F2_{mp}$
/b/	1668	1785	2914	3187	1433	1204
	(142.9)	(120.6)	(209.5)	87.8)	(271.7)	(171.4)
/d̪/	2201	1894	2989	3204	1893	1449
	(79.9)	(131.9)	(147.9)	(161.4)	(200.1)	(183.4)
/d̟/	2306	1937	2951	3222	1927	1432
	(128.1)	(134.7)	(163.1)	(128.8)	(158.8)	(157.2)
/g/	1917	1820	3239	3231	1410	1220
	(124.1)	(98.2)	(89.2)	(108.5)	(200.5)	(131.0)

From the data presented in Table 4.1 (g) and 4.1 (h), it can be surmised that male participants of age 6-7 years, vowels /a/ and /i/ evidenced the highest F2 when in the presence of dental /d̪/ and lowest F2 in the presence of bilabial /b/. However for the vowel /i/, highest and lowest F2 were seen when preceded by /g/ and /ḍ/ respectively. Likewise, for vowels /a/, /i/ and /u/, female subjects of the same groups showed the highest F2 mid-vowel frequencies when preceded by stops /ḍ/, /g/ and /d̪/ respectively whereas the lowest values were observed for /d̪/ and /b/ respectively. Vowel /u/ continued to exhibit a high standard deviation in this group as well.

Table 4.1 (i)

Mean (standard deviation) of F2 onset (F2o) and F2 midpoint frequencies (F2mp) for vowels /a/, /i/ and /u/ in Hz in adult males

	Adult-Males					
	/a/		/i/		/u/	
Stop Categories	$F2_o$	$F2_{mp}$	$F2_o$	$F2_{mp}$	$F2_o$	$F2_{mp}$
/b/	1163 (136.6)	1223 (109.7)	2091 (302.2)	2301 (109.8)	992 (119.3)	918 (179.3)
/d̪/	1584 (68.8)	1382 (137.7)	2065 (68.8)	2273 (278.8)	1518 (188.8)	1061 (135.4)
/ḍ/	1689 (87.7)	1425 (128.8)	2203 (206.9)	2327 (207.5)	1404 (120.2)	1032 (134.8)
/g/	1575 (110.1)	1407 (141.5)	2394 (273.0)	2343 (236.4)	971 (167.9)	903 (124.1)

Table 4.1 (j)

Mean (standard deviation) of F2 onset (F2o) and F2 midpoint frequencies (F2mp) for vowels /a/, /i/ and /u/ in Hz in adult females

	Adult- Females					
	/a/		/i/		/u/	
Stop Categories	F2$_o$	F2$_{mp}$	F2$_o$	F2$_{mp}$	F2$_o$	F2$_{mp}$
/b/	1371 (87.8)	1458 (120.6)	2467 (261.2)	2837 (148.2)	1403 (135.2)	928 (112.6)
/d̪/	1891 (76.5)	1612 (150.9)	2541 (76.5)	2847 153.5)	1679 (85.4)	1180 (130.3)
/d̟/	1988 (104.8)	1673 (103.5)	2576 (220.9)	2782 (230.1)	1425 (169.2)	1118 (173.8)
/g/	1773 (102.1)	1617 (112.9)	2899 (242.3)	2848 (261.4)	1125 (156.3)	974 (115.1)

From Table 4.1 (i) and 4.1 (j), it can be deduced that, for vowels /a/, /i/ and /u/, adult males showed highest F2 mid-vowel frequencies in the presence of /d̟/, /g/ and /d̪/ respectively whereas lowest values were seen in the presence of /b/, /d̪/ and /g/ respectively. Similarly, in females, highest F2 frequencies in /a/ and /u/ were noted when preceded by /d̟/ and /d̪/ respectively and lowest values were seen when preceded by the stop /b/. However for vowel /u/, highest F2 midpoint corresponded to /g/ while the lowest F2 value was associated with /d̟/. In both males and females, the standard deviation was relatively high in vowel /i/ which was contrasting with the observation seen in other age groups.

As depicted in the Tables 4.1 (a)-4.1 (j), it is also implied that the formant frequencies decreased in older participants because of progressive lengthening of the vocal tract. This is in consonance with findings of Sreedevi (2000) who also observed a considerable decrease in F2 from childhood to adulthood in native Kannada speakers. Age-related differences in formant frequencies were also noted in findings of Eguchi and Hirsh, (1969) who reportedly observed reduced variability in children aged 11-12 years as opposed to younger children. In order to examine the effect of age on F2 frequencies, MANOVA was performed, the results of which revealed significant main effect of age (p<0.05).

MANOVA results also demonstrated significantly higher F2 values in female participants aged 5-6 years, 6-7 years and adults (p<0.05). These findings show significant parallels with findings of Sreedevi (2000), Eguchi and Hirsh (1969), Venkatesh (1995) and White (2000) who reported significantly higher F2 values in females as compared to males owing to their shorter vocal tract lengths. However, participants aged 3-4 years did not show any significant gender differences (p > 0.05).

A thorough perusal of the data presented in the Tables 4.1 (a) - 4.1 (j) reveal the differences in F2 transition pattern across the 4 places of articulation. From these tables, it is apparent that the bilabial /b/ exhibits a transition of rising pattern in the context of low central vowel /a/ and high front vowel /i/ but a falling pattern in /u/ in children of all age groups considered and adults. Considerable research has proven that the origin of F2 for the bilabial /b/ is very low and hence during the production of the subsequent vowel, F2 rises (Baken & Orlikoff, 2010). However in the context of the back vowel /u/, F2 exhibits a falling pattern. This is because of the apparent lengthening of the vocal tract during the production of /u/ which lowers all the formants.

Furthermore, it is implicit that the values of F2 onset for dental /d̪/ and the retroflex /d̟/ are in the mid frequency region. Hence, dental /d̪/ and retroflex /d̟/ exhibited falling patterns in the context of vowels /a/ and /u/ but a rising pattern in the context of /i/ because of the high F2 of vowel /i/. However, the fact that the velar /g/ showed falling F2 transition pattern in all three vowel contexts could be explained by its high F2 origin (Baken & Orlikoff, 2007).

Subsequently, the anticipatory coarticulatory effect of vowels on the preceding stop consonants was obtained using locus equation as a metric. The usefulness of locus equations in this regard has been widely documented in literature concerning acoustic phonetics (Sussman et al., 1991, 1992, Kuhl, 1991). The regression lines thus obtained serve as a phonetic index to measure coarticulatory effects over a varied vowel space. Moreover, locus equations are based on a “relationally derived” algorithm and thus incorporate a degree of “spectral normalization” (Sussman et al, 1992). In the present study, locus equations were obtained by sampling F2 midpoint at the following vowel nuclei at the X-axis (independent variable) against F2 onset on the y-axis (dependent variable) for the four places of articulation (/b, d̪, d̟, g). By-products of this regression analysis are slope, y-intercept (SE), R^2 and standard error of estimate (SE). The slope describes the degree of coarticulation in each CV context. The y-intercept, together with the slope, gives an accurate representation of coarticulatory extent. The standard error describes the extent of variability and R^2 value describes the goodness of fit. In the current study, anticipatory coarticulatory effects on the target stop consonants are described using slope as an index.

Slopes, calculated trial wise using regression analyses, for the five age groups were statistically compared. As MANOVA results showed significant effect of age and gender on F2 frequencies, statistical comparisons were carried out for each age group and gender separately. The slope values were calculated by drawing regression analysis on entire age groups and not for individual subjects. Thus, for a given age group, three slope values were obtained for three trials respectively. As the slope values varied greatly amongst each other, non parametric tests were administered to compare the slopes. Comparison of slopes across gender was obtained through Mann-Whitney test, results of which revealed no significant differences in slope values between males and females ($p > 0.05$). Thus for further statistical analyses, males and females were combined. The fact that slope values of males and females were not significantly different is in consonance with a study by Sussman et al. (1992) who studied coarticulation in 3-5 year olds from a locus equation perspective.

The results of the study will be presented under the following headings

I. Coarticulation across age groups

II. Coarticulation across children (as a single group) and adults

III. Coarticulation across places of articulation in different vowel contexts in each age group

The first two sections relate to the first objective of the study, that is, to capture age-related developmental changes in CV coarticulation, while, the last section seeks to address the other objective, that is, to document changes in anticipatory coarticulation as a function of place of articulation and vowel context in children and adults. Tables 4.2-4.5 represent slopes, y-intercept (int.), R^2 and standard error (SE) values in the five age groups. The y-intercept and standard error values have been rounded to the nearest Hz.

As observed in Tables 4.2 and 4.5, slopes measuring above the value of one have been observed in four instances in children (slope of 1.14 and 1.08 for /ba/ and /bi/ respectively in children aged 4-5 years, slope of 1.05 for /gi/ in children aged 3-4 years, and a slope of 1.07 for /gu/ in children aged 6-7 years). These high slopes in children resulted in relatively low y-intercept values, some of them being negative. This may reflect the young childrens' greater attempt in articulatory manipulation and therefore greater extent of anticipatory coarticulation during the production of the target stimuli. In cases where the slope value exceeds a value of 1, onset of F2 transition and their corresponding mid-vowel nuclei are fairly similar. Thus, it is implicit that the magnitude of variation of tongue position during the onset of production of the stop from the production of the subsequent vowel is very less. Greater differences between F2 onset and F2 vowel midpoint values entail lower slope values, which means, lesser extent of coarticulation (Everett, 2008). Incidences of slope values measuring above the value of 1 have been reported by Gibson and Ohde (2007) and Sussman et al. (1992, 1997) in young children.

4.1. Study of coarticulatory effects across age groups

From Table 4.2, it can be noted that the slope values for /b/ in the context of /a/ and /i/ were relatively shallow in 3-4 year olds, but a sudden spurt in slope value was observed in participants aged 4-5 years. Following this, the slope value reduced in participants aged 5-6 years after which a steady rise was observed in 6-7 years and adults. This gradual increase in bilabial slope value has also been documented in a study on 3-5 year olds by Chang, Ohde and Conture (2002) who observed a rising tendency in slope values of bilabials as a function of age. It is also obvious from Table 4.2 that slope values for bilabial /b/ in the context of /a/ and /i/ in participants aged six years began to approximate adults slope values.

Table 4.2

Locus equation data in voiced stop /b/ across vowel contexts /a, i, u/ as a function of age

	/ba/				**/bi/**				**/bu/**			
Age groups	**Slope**	**Int.**	**R^2**	**SE**	**Slope**	**Int.**	**R^2**	**SE**	**Slope**	**Int.**	**R^2**	**SE**
3-4 years	0.51	610	0.32	119	0.57	1089	0.117	216	0.75	326	0.53	136
4-5 years	1.14	-398	0.74	90	1.08	-530	0.263	260	0.65	583	0.40	140
5-6 years	0.69	394	0.47	76	0.92	-112	0.395	186	0.63	616	0.38	208
6-7 years	0.82	191	0.69	78	0.61	963	0.262	158	0.60	487	0.39	150
ADULTS	0.88	64	0.80	74	0.72	417	0.590	204	0.83	342	0.20	245

Ample of striking observations can be made from examination of data presented in Tables 4.2-4.5. For instance, as seen in Table 4.2, slope values showed a declining trend as a function of age for the stop + vowel stimulus /bu/ whereas in Tables 4.2 and 4.4, slope values for /ba/ and /ḍi/ were prominent for participants aged 4-5 years.

Tables 4.3-4.5 showed distinctly reduced slope values for /d̪u/ and /ga/ and pronounced slope for /d̝i / in 5-6 year olds as compared to other groups of children. The fact that the children aged 4-5 years and 5-6 years exhibited values that were discernible from the other groups could be the consequence of their underlying anatomical and psychological changes. In this age, children see themselves as incompetent in comparison with adults, and they are realistically so. But their inability to always cope with the demands of adults reinforces their feelings of incompetence. In fear of progressing into the increasingly demanding adult world, children may behave in a way that might seem less mature than before (Joseph & Braga, 1974). Literature elsewhere has also documented striking observations in age group of 5-6 years as compared to other ages. Savithri (1992) reported interestingly longer VOT duration in 5-6 year old participants. Physiologically, the change in pitch has been reported by Negus, (1962) that is the voice of the child of 5 years loses the piping pitch of the first years and the child’s speaking voice settles under the influence of the environment at a median pitch in the range of middle C, or may be 2 or 2.5 semitones higher.

Table 4.3

Locus equation data in voiced stop /d̪/ across vowel contexts / a, i, u/ as a function of age

	/d̪a/				**/d̪i/**				**/d̪u/**			
Age groups	**Slope**	**Int.**	**R^2**	**SE**	**Slope**	**Int.**	**R^2**	**SE**	**Slope**	**Int.**	**R^2**	**SE**
3-4 years	0.71	790	0.56	90	0.68	885	0.33	103	0.71	853	0.29	180
4-5 years	0.86	476	0.54	122	0.76	566	0.50	86	0.64	1060	0.43	149
5-6 years	0.46	1243	0.28	106	0.85	252	0.61	127	0.22	1739	0.07	121
6-7 years	0.55	1133	0.45	68	0.76	513	0.60	78	0.81	744	0.36	183
ADULTS	0.66	748	0.50	124	0.84	111	0.78	163	0.28	1276	0.06	163

Table 4.4

Locus equation data in voiced stop /d̟/ across vowel contexts /a, i, u/ as a function of age

	/d̟a/				/d̟i/				/d̟u/			
Age groups	Slope	Int.	R^2	SE	Slope	Int.	R^2	SE	Slope	Int.	R^2	SE
3-4 years	0.56	1176	0.37	106	0.77	587	0.573	97	0.31	1419	0.14	152
4-5 years	0.56	1187	0.33	136	0.50	1459	0.183	127	0.51	1227	0.36	173
5-6 years	0.50	1235	0.18	106	0.93	76	0.572	155	0.42	1316	0.20	157
6-7 years	0.53	1254	0.22	130	0.72	656	0.518	108	0.60	1028	0.3	135
ADULTS	0.75	663	0.52	126	0.77	405	0.753	143	0.42	1025	0.23	127

A detailed analysis of the locus equation data in Tables 4.2 -4.5 reveals further trends which are as follows:

- From Table 4.3, slope values for /d̪a/ began to approximate adult values from the age of 5-6 years.

- Slope values consistently lingered around 0.50 to 0.56 for the stop + vowel stimulus /d̝a/ among the four groups of children and then increased to 0.75 in adults. The reason for lower slope value of retroflex /d̟/ in children could be attributed to its frequency of occurrence to be as low as 2.24 % in Kannada language (Sreedevi & Vikas, 2013). As a result, the children in the present study, could have exercised greater articulatory effort in the production of /d̟/ and hence relatively lesser coarticulation.

- From Table 4.5, a descending trend is evident in slope values for /gi/ across the four groups of children.

Table 4.5

Locus equation data in voiced stop /g/ across vowel contexts /a, i, u/ as a function of age

	/ga/				/gi/				/gu/			
Age groups	**Slope**	**Int.**	**R^2**	**SE**	**Slope**	**Int.**	**R^2**	**SE**	**Slope**	**Int.**	**R^2**	**SE**
3-4 years	0.80	444	0.52	96	1.05	-209	0.375	164	0.96	109	0.69	118
4-5 years	0.87	281	0.74	84	0.73	842	0.50	129	0.76	474	0.70	134
5-6 years	0.57	800	0.36	95	0.63	1156	0.46	100	0.64	615	0.50	166
6-7 years	0.92	224	0.66	81	0.58	1361	0.27	104	1.07	80	0.57	120
ADULTS	0.59	768	0.47	108	0.90	310	0.86	126	0.93	171	0.42	138

One of the primary objectives of the present study was to capture age related developmental changes in CV coarticulation of the four places of consonants across the three vowel contexts. Accordingly, Kruskal-Wallis test was performed to investigate significant differences in coarticulation of the target stimuli as a function of age. From Table 4.6., it can be observed that the CV utterances /d̪a/, /d̪u/ and /ga/ exhibited significant variation in coarticulatory effects across age.

Table 4.6

Chi-Square values and p values for the four places of articulation across three vowel contexts

Tokens	χ^2 *(4)* *value*	*p*
/ba/	8.46	0.07
/bi/	6.18	0.18
/bu/	6.52	0.16
/d̪a/	15.49	0.004*
/d̪i/	5.04	0.28
/d̪u/	14.84	0.01*
/d̟a/	3.80	0.43
/d̟i/	0.29	0.99
/d̟u/	5.34	0.25
/ga/	13.48	0.01*
/gi/	6.40	0.17
/gu/	6.61	0.15

Comparison across individual groups of children and adults: As Kruskal-Wallis results revealed significant differences in coarticulation across age for utterances /d̪a/, /d̪i/ and /gu/, Mann-Whitney test was performed for pair-wise comparison of age groups. When the slope values of each of the four groups were compared with that of the adults, a significant difference was found. Subjects aged 3-4 years and 4-5 years exhibited significantly higher slope value than adults for all the three utterances (/d̪a/- $|Z|=2.882$, $p<0.05$; /d̪u/- $|Z|= 2.486$, $p<0.05$; /ga/- $|Z|=2.882$, $p<0.05$). However, the 5-6 year olds, showed significantly lower slope values than adults for the utterances /d̪a/ and /ga/ (/d̪a/- $|Z|=2.882$, $p<0.05$; /ga/- $|Z|=2.882$, $p<0.05$). The two groups did not reveal significant extent of coarticulation for the utterance /d̪u/. Thus, it is implicit that the younger group of children, that is, 3-5 year olds, exhibited greater extent of coarticulation than adults for /d̪a/, /d̪u/ and /ga/.

However, statistical comparisons drawn between 6-7 year olds and adults did not yield any definite pattern. While the participants aged 6-7 years showed significantly higher slope value than adults for /d̪a/, ($|Z| = 2.402$, $p<0.05$), their slope values were significantly lower than adults for /d̪u and /ga/ (/d̪u̪/- $|Z| = 2.722$, $p<0.05$; /ga/- $|Z| =2.822$, $p<0.05$).

Comparison across age groups in children: Significant differences in co articulation of the utterance /d̪u/ was also seen when Mann-Whitney test was performed for pair-wise comparison of age groups. The results revealed that children of 3-4 years , 4-5 years and 6-7 years showed significantly higher slope value for /d̪u/ as compared to the 5-6 year olds (3-4 years vs. 5-6 years- $|Z| = 2.242$, $p<0.05$; 4-5 years vs. 5-6 years- $|Z| = 2.486$, $p<0.05$, 5-6 years vs. 6-7 years- $|Z| =2.486$, $p<0.05$). However, no significant between-age group differences in slope values were noted for utterances /d̪a/ and /ga/.

Thus, it can be inferred that, in children, except for the utterance /d̪u/, no significant between age group differences in slope values were observed. The present observation is in par with findings of Turnbaugh et al. (1985), Chang et al (2002), Sussman et al (1992), Geitz (1998) and Perumal (1993), who reported similar extent of coarticulation in children aged 3-5 years as compared to adults. Thus, as per the findings of the present study, it would be logical to suggest that the slope, as an index of coarticulation, does not significantly differ as a function of age in children.

4.2 Coarticulation across children (as a single group) and adults

In order to obtain adequate reflection of the degree of coarticulation in children as a whole, grand regression analysis was performed trial wise for each stop consonant in each vowel context with F2 onset as the dependent variable and F2 midpoint as the independent variable. Visual perusal of slope values illustrated in Table 4.2-4.5, shows that extent of coarticulation for /b/ in children was of the order /ba/> /bi/> /bu. However, adults revealed a coarticulatory pattern of the order /ba/> /bu/> /bi/. Extent of coarticulation in children, for the stop /d̪/ was of the order /d̪i/> / d̪u/>/d̪a/ which was slightly unlike the adult pattern of /d̪i/>/d̪a/>/d̪u/. Coarticulatory pattern for retroflex /ḍ/ in both children and adults was of the order /ḍi/> /ḍa/> /ḍu/. It can be noted that in adults, slope values for /d̪/ and /ḍ/ were the maximum in the context of /i/ followed by /a/ and /u/ respectively. Comparison of slope values for /g / in children revealed coarticulatory pattern of the order /ga/>/gi/>/gu/ which was opposite to the adult coarticulatory pattern (/gu/>/gi/>/ga/).

Table 4.7 presents locus equation data from productions by children and adults. Visual examination of the data presented shows that in children, although velar contexts exhibited the highest slope values, closely followed by bilabials. The same result was observed in adults as well. In both groups, the stop class of retroflex exhibited the shallowest slope.

Table 4.7

Locus equation data for children and adults across the four stop consonants

	/ba/				**/bi/**				**/bu/**			
	Slope	***Int.***	***R^2***	***SE***	***Slope***	***Int.***	***R^2***	***SE***	***Slope***	***Int.***	***R^2***	***SE***
Children	0.81	192	0.58	94	0.78	386	0.23	208	0.66	516	0.36	184
Adults	0.88	64	0.80	74	0.72	417	0.59	204	0.83	342	0.20	245
	/d̪a/				**/d̪i/**				**/d̪u/**			
Children	0.63	950	0.44	101	0.80	444	0.50	107	0.68	954	0.34	165
Adults	0.66	748	0.50	124	0.84	111	0.78	163	0.28	1276	0.06	163
	/ḍa/				**/ḍi/**				**/ḍu/**			
Children	0.59	1123	0.32	120	0.76	600	0.44	130	0.49	1194	0.28	157
Adults	0.75	663	0.52	126	0.77	405	0.75	143	0.42	1025	0.23	127
	/ga/				**/gi/**				**/gu/**			
Children	0.81	398	0.60	91	0.78	658	0.43	129	0.78	410	0.61	142
Adults	0.59	768	0.47	108	0.90	310	0.86	126	0.93	171	0.42	138

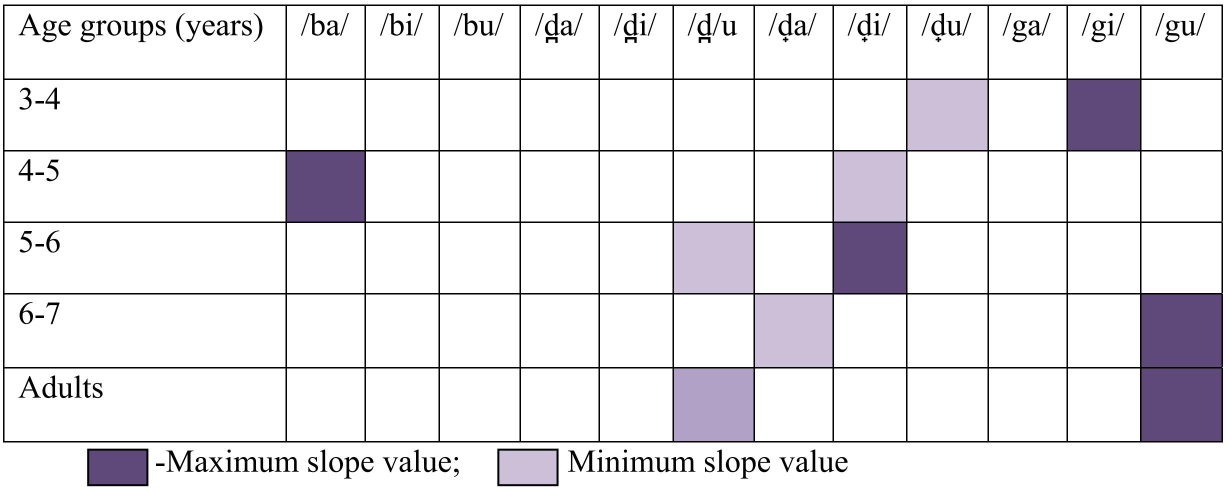
The fact that bilabials and velars showed high slope values in the present study implies that these stops are easily influenced by the following vowel albeit for different reasons. During the production of bilabial utterances, the tongue need not have to move to a different position as in the case of velar or alveolar utterances. Therefore, the tongue hardly plays any role in the production of the target bilabial utterance. This perspective is also consistent with the notion of DAC model of coarticulation (Recasens, 1987) which attributed the least DAC value to labials. However, during the production of a velar utterance, the tongue anticipates the production of the following vowel during the onset of the velar stop.

In order to examine significant differences in coarticulation between children and adults, Mann-Whitney test was performed. Results revealed similar coarticulatory extent in children and adults for all places of articulation in all vowel contexts ($p > 0.05$) except for the utterance /gi/ which showed significantly higher slope value for adults than for children ($|Z| = 2.486$, $p<0.05$).

The finding that children in the present study showed almost similar extent of coarticulation as in adults draws many parallels with findings of Repp, (1986), Sereno, Baum, Marean and Liberman (1987), Turnbaugh, Hoffman, Daniloff and Absher (1985) and Sussman, Hoemeke and Mc Caffrey (1992).

4.3 Coarticulation across places of articulation in different vowel contexts in each age group

The current section now seeks to address the final objective of the present study- is locus equation parameters, namely the slope sensitive enough to capture the coarticulatory effects as a function of place category (/b, d̪, d̟, g/) and vowels /a, i, u/. Figure 4.1 is a pictorial representation of maximum and minimum slope values on comparison of coarticulatory effects across places of articulation in five age groups.



Age groups (years)	/ba/	/bi/	/bu/	/d̪a/	/d̪i/	/d̪/u	/ḍa/	/ḍi/	/ḍu/	/ga/	/gi/	/gu/
3-4									░		▓	
4-5	▓							░				
5-6						░		▓				
6-7							░					▓
Adults						░						▓

▓ -Maximum slope value; ░ Minimum slope value

Figure 4.1, *Maximum and Minimum Slope values in children and adults.*

From Figure 4.1, it can be observed that, incidences of maximum slope values centered predominantly around the velar place of articulation (in children aged 3-4 years, 6-7 years and adults) and minimum slope values corresponded to retroflex /ḍ/ (in ages 3-4 years, 4-5 years and 6-7 years) and dental /d̪/ (in age 5-6 years and adults).

However, consistency of maximum and minimum slope values was marred by occurrence of a high slope of 1.14 for /ba/ in age 4-5 years and 0.93 for /ḍi/ in age 5-6 years. A comparative analysis of slope values in Tables 4.2 and 4.5 reveal that in participants aged 4-5 years, the second highest slope value was observed in /ga/ which closely followed the highest slope value seen in /ba/. Thus, in this age group, it can be inferred that extent of anticipatory coarticulatory effect for velar and bilabial places were overlapping. However, occurrence of a rather high slope value for /ḍi/ in participants of 5-6 years seems to be rather conspicuous. Literature elsewhere has also documented unusual observations in age group of 5-6 years as compared to other age groups (Savithri, 1992; Negus, 1962).

Coarticulatory influence on stop place of articulation as a function of vowel context

Coarticulatory effect on bilabial /b/

Table 4.8

Coarticulatory patterns in descending order in bilabial place of articulation

Age groups (years)	Anticipatory coarticulatory pattern in the context of /b/
3-4	/bu/>/ba/>/bi/
4-5	/ba/>/bi/>/bu/
5-6	/bi/>/ba/>/bu/
6-7	/ba/>bu/>/bi/
Adults	/ba/>/bu/>/bi/

On the basis of slope values presented in Table 4.2, anticipatory coarticulatory patterns as a function of vowel context on the bilabial stop /b/ has been decoded in Table 4.8 which reveals coarticulatory patterns in 6-7 year olds to resemble that of adults.

Statistical significance of slope values across vowel categories within each consonantal category for each age group was obtained separately with Friedman Test and Wilcoxon Signed Ranks Test, results of which have been discussed in relevant sections.

On performing Friedman test on bilabial productions of the five groups, it was found that the utterances were not significantly different ($p>0.05$), which implies, production of the bilabial remained essentially undifferentiated across vowel contexts. This could be because the tongue scarcely plays a role in the production of /b/. The tongue already takes its position for the production of the target vowel much prior to the lip closure, a prerequisite for the production of the bilabial /b/. Thus, the tongue position for target vowel production and the lip occlusion for /b/ are independent of each other and hence the vowels do not influence the bilabial production (Imbrie, 2005). The present finding draws significant support from a study by Sussman et al (1997) who reported limited variation in locus equation slopes for bilabials in varied vowel contexts.

Scatter-plots were constructed from F2 onset and F2 mid-vowels obtained in the target utterances produced by the five groups. These target utterances were representative of the four places of articulation /b, d̪, d̟, g/ embedded in three vowel contexts /a, i, u/. To bring uniformity in all the scatter-plots, scale was fixed from 500-4KHz along both x and y axes.

Figures 4.2-4.4 depict the scatter-plot obtained for /ba/, /bi/ and /bu/ for all the five age groups. All three figures show a tight clustering of data points around their respective slopes except for 4-5 year olds production of /bi/ which is indicative of a relatively high standard error. The R^2 values in the three vowel contexts /a, i, u/ ranged from 0.3-0.8, 0.1-0.6 and 0.1-0.5 which indicate moderate to strong goodness of fit in the context of /a/ and relatively weak to moderate goodness of fit for vowels /i/ and /u/. From Figures 4.2-4.4, we can see that the CV sequences /ba/ and /bi/ had the flattest and steepest slopes for 4-5 year olds and 3-4 year olds respectively. However, adults exhibited maximum extent of coarticulation for the utterance /bu/ while 6-7 years showed the least. The close clustering of slope lines in the five age groups across all three vowel contexts indicates that vowels contribute very little to the production of the bilabial /b/.

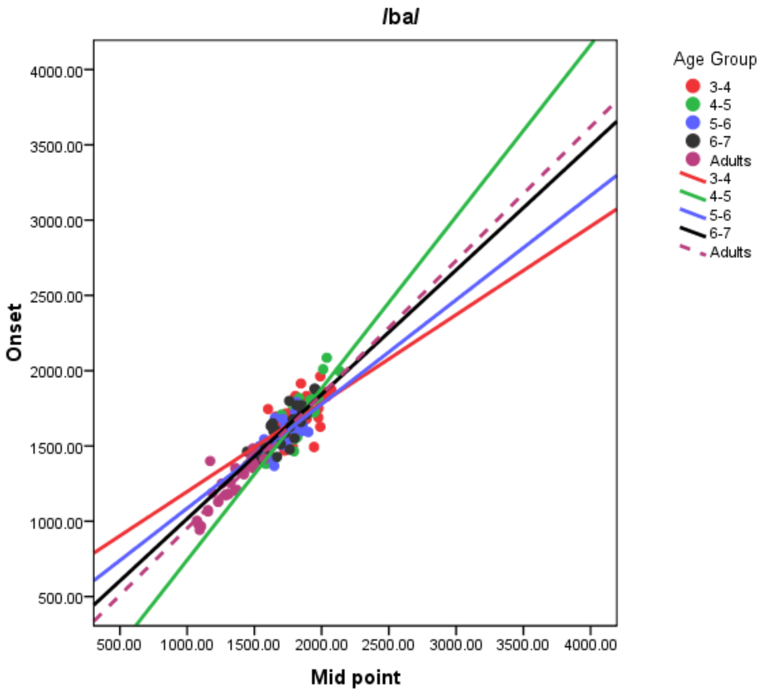


Figure 4.2, *Locus equation scatter-plot for /ba/*

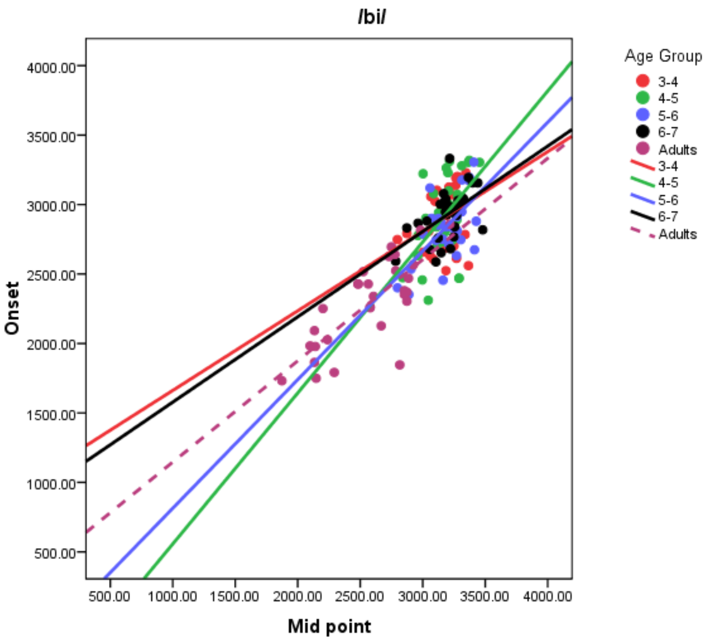


Figure 4.3, Locus equation scatter plot for /bi/

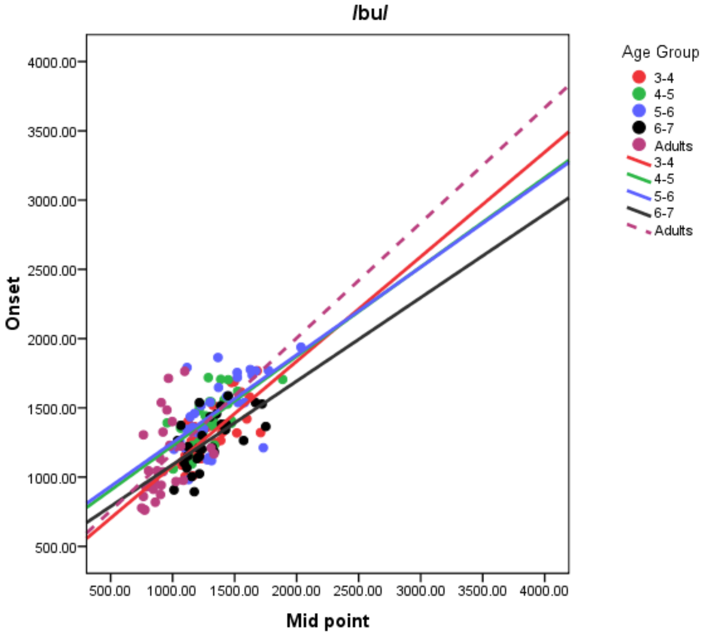


Figure 4.4, *Locus Equation scatter plot for /bu/.*

Coarticulatory effect on dental /d̪/

Table 4.9, based on slope values presented in Table 4.3, reflects anticipatory coarticulation of dental /d̪/ in the context of three vowels /a, i, u/. From Table 4.9, it can be inferred that participants aged 5-6 years displayed a coarticulatory trend that was similar to that of adults but there was a slight variation seen in subjects aged 6-7 year olds.

Table 4.9

Coarticulatory patterns in descending order for dental place of articulation

Age groups (years)	**Anticipatory coarticulatory pattern in the context of /d̪/**
3-4	/d̪u/>/d̪a/>/d̪i>
4-5	/d̪a/>/d̪i/>/d̪u/
5-6	/d̪i/>/d̪a/>/d̪u/
6-7	/d̪u/>/d̪i/>/d̪a/
Adults	/d̪i/>/d̪a/>/d̪u/

Statistical comparisons between slope values were drawn across vowel contexts in each age group. Data presenting the results of Friedman test in Table 4.10 showed the significant effect of vowels on dental /d̪/ in 5-6 year olds and adults ($p<0.05$).

Table 4.10

Chi-square (χ^2) and p-values for comparison of dental /d̪/ across vowel contexts

Age groups	**Consonant**	χ^2 *(2)*	*p*
3-4 years	/d̪/	3.38	0.15
4-5 years		2.33	0.31
5-6 years		8.33	0.02^*
6-7 years		2.33	0.31
Adults		10.33	0.01^*

Subsequent Wilcoxson's Signed Ranks test prove that slope values of dental /d̪/ evidenced significant difference across all the three vowel contexts ($p<0.05$) in both 5-6 year olds and adults. Both groups significantly coarticulated the dental /d̪/ to the highest extent in the context of high front vowel /i/, followed by low central vowel /a/ and low back vowel /u/. Thus, both the age groups showed a similar coarticulation pattern of the order /d̪i/>/d̪a/>/d̪u/.

Significant differences in the adult production of /d̪/ across vowel contexts can be demonstrated by their use of fronted tongue body gesture. Their use of excessive fronted tongue body gesture during the production of /d̪/ brings the tongue much further away from the vowel nucleus especially when the target vowel is a back vowel. Because of the maximal tongue body involvement in the production of /d̪u/, coarticulation is least for /d̪u/and marginally high in /d̪/. However, the production of /i/ requires a fronted tongue body position which is already achieved during the beginning of /d̪/ production and hence maximum coarticulation is seen in /d̪/. The absence of significant difference in the production of /d̪/ in the three vowel contexts in 3-4 and 4-5 year olds imply that these children have not yet acquired the fronted tongue body gesture. Interestingly, the occurrence of significant differences in /d̪/ production for 5-6 year olds and their subsequent absence in 6 year olds might imply that the use of fronted tongue body gesture has been achieved but not yet consistent (Imbrie, 2005).

Figures 4.5-4.7, are representational scatter-plots for the dental /d̪/ in three vowel contexts /a, i, u/. R^2 values centered around 0.28 to 0.56 in the context of low central /a/ indicating weak to moderate goodness of fit and 0.33-0.78 indicating weak to strong goodness of fit in the context of high front /i/. However, R^2 values in the context of /u/ were comparatively low which indicates poor co-variation between F2 onset and F2 vowel midpoint. We can also note that, despite their high slope value, data points were scattered for 6-7 year olds in the context of /u/ which is indicative of high standard error (Figure 4.7). From Figures 4.5-4.7, we can observe that, vowel contexts /a/ and /u/ influenced the dental stop to the highest extent in children aged 4-5 and 6-7 years. Least extent of coarticulation was seen in 5-6 year olds. However, in the context of /i/, 5-6 year olds and adults showed relatively steeper slopes as compared to 3-4 year olds who showed the flattest.

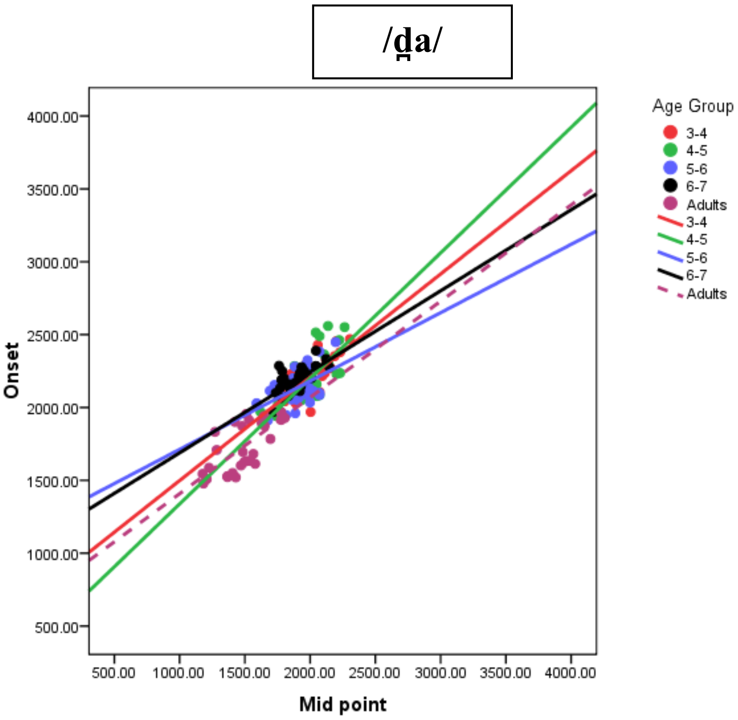


Figure 4.5, *Locus equation scatter-plot for /d̪a/*

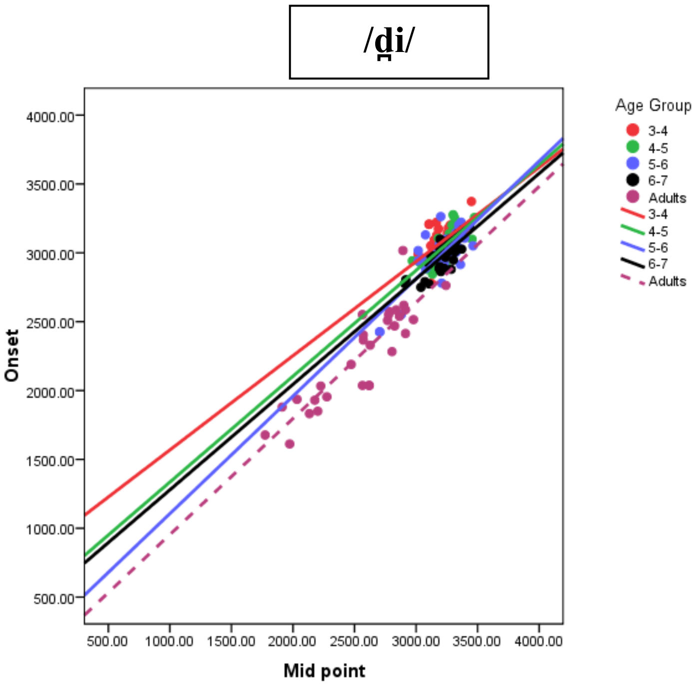


Figure 4.6, *Locus equation scatter-plot for /d̪i/*

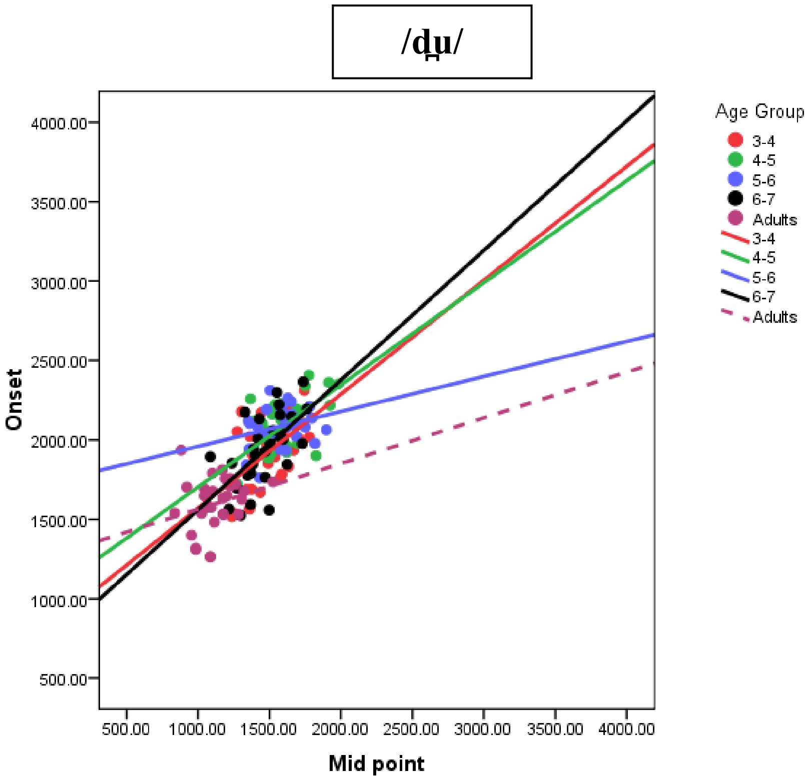


Figure 4.7, *Locus equation scatter-plot for /ḍu/*

Coarticulatory effect on retroflex /ḍ/

Table 4.11 presents anticipatory coarticulatory pattern for retroflex /ḍ/ in varied vowel contexts of /a, i, u/, on the basis of their respective slope values, in the five age groups. From Table 4.11, it is apparent that the retroflex /ḍ/ was coarticulated the most in the context of high-front vowel /i/ in all the age groups except in 4-5 year olds. Also, the coarticulatory pattern of /ḍi>/ḍa/>/ḍu/ existed in 3-4 year olds, but changed in 4-5 year olds. The trend again reoccurred in 5-6 year olds and the pattern persisted in 6-7 year olds and adults. Based on this finding, it is rational to suggest that the pattern might by achieved early in children but is not consistent.

Table 4.11

Coarticulatory patterns in descending order for retroflex place of articulation

Age groups (years)	**Anticipatory coarticulatory pattern in the context of /ḍ̟/**
3-4	/ḍ̟i>/ḍ̟a/>/ḍ̟u/
4-5	/ḍ̟a/>/ḍ̟u/>/ḍ̟i/
5-6	/ḍ̟i/> /ḍ̟a/ > /ḍ̟u/
6-7	/ḍ̟i/>/ḍ̟u/>/ḍ̟a/
Adults	/ḍ̟i>/ḍ̟a/>/ḍ̟u/

From Table 4.11, we can observe frequent occurrences of minimal extent of coarticulation of /ḍ̟/ when followed by a back vowel /u/ and maximum extent when followed by the front vowel /i/ (in ages 3-4 and 5-6 years and adults). This variation in extent of anticipatory coarticulation could be the consequence of modified realization of retroflex production under the influence of some specific vowels. Literature governing retroflex production has consistently confirmed that they are “strongly context dependent” and show large variability due to vowel coarticulation (Hamann & Fuchs, 2008, Dixit ,1990). It has been shown that retroflexes are articulated further back in the context of /u/ thereby appearing more retroflex like. This increased retroflexion of /ḍ̟/ when followed by /u/ could have attributed to greater tongue involvement, thereby resulting in lesser degree of coarticulation. However, when followed by a front vowel such as /i/, the retroflex stop /ḍ̟/ tends to be uttered more like a coronal, or, in other words, it is produced further front. This disparity in the stop realization attributes to lower degree of tongue body involvement and hence greater coarticulatory effect of vowel /i/.

Table 4.12, presents the results of Friedman test in each age group. It is evident that the target retroflex showed anticipatory coarticulatory influences only in 5-6 year old participants and adults ($p<0.05$), results of which are similar to that of dental /d̪/.

Table 4.12

Chi-square (χ^2) and p-values for retroflex /d̟/ as a function of vowels

Age groups	**Consonant**	χ^2 *(2)*	***p***
3-4 years	/d̟/	4.33	0.12
4-5 years		3.00	0.22
5-6 years		6.33	0.04^*
6-7 years		3.00	0.22
Adults		6.33	0.04^*

On administering Wilcoxon signed ranks test, slope values of vowel combinations in /d̟/ showed a significant difference when vowel pairs /d̟a/-/d̟i/ ($|Z|$= 1.992, p<0.05) and /d̟u/-/d̟i/ ($|Z|$= 2.201, p<0.05) were compared in children aged 5-6 years. Highest coarticulation was seen for /d̟i/ which was eventually followed by /d̟a/ and /d̟u/. Adults showed significant difference only when consonantal pairs /d̝a/-d̝u/ and /d̟u/-/d̟i/ were compared ($|Z|$=2.201, p<0.05), with /d̟/ showing greatest coarticulation in the context of /i/, intermediate slope in the context of /a/ and the least slope value in/d̟u/. As described earlier in case of /d̪/, the enhanced fronted tongue body gesture perhaps played a significant role in high slope value of /d̟i/ as compared to that of /d̟a/ and d̟u/. The fact that the 5-6 year olds exhibited significant differences in production but not the 6-7 year olds perhaps indicates that the fronted body gesture has appeared but is not consistent.

Figures 4.8 -4.10 are locus equation scatter-plots for the retroflex stimuli /d̝a/, /d̝i/ and /d̝u/ in all the five age groups. The scatter-plot shows close clustering of data points for /d̝a/ and /d̝i/ but comparatively scattered data points are seen around the regression lines for /d̝u/ which is indicative of high standard error values. R^2 values ranged from 0.2 to 0.4 for the utterances /d̝a/ and /d̝u/which indicate somewhat weak co-variation between F2 onset and F2 midpoint. However, R^2 values were relatively higher for /d̝i/ which indicates moderately good predictability. As observed from Figures 4.8 -4.10 , adults showed the steepest slope for /ḍa/, while 5-6 years and 6-7 year old children showed steepest slopes for /ḍi/ and /ḍu respectively.

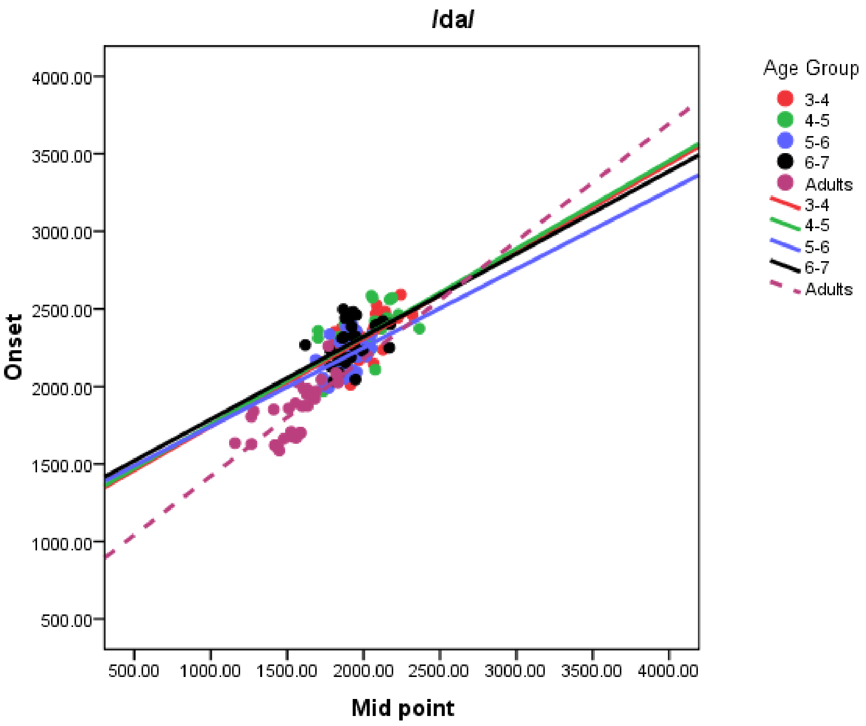


Figure 4.8, *Locus equation scatter-plot for /ḍa/*

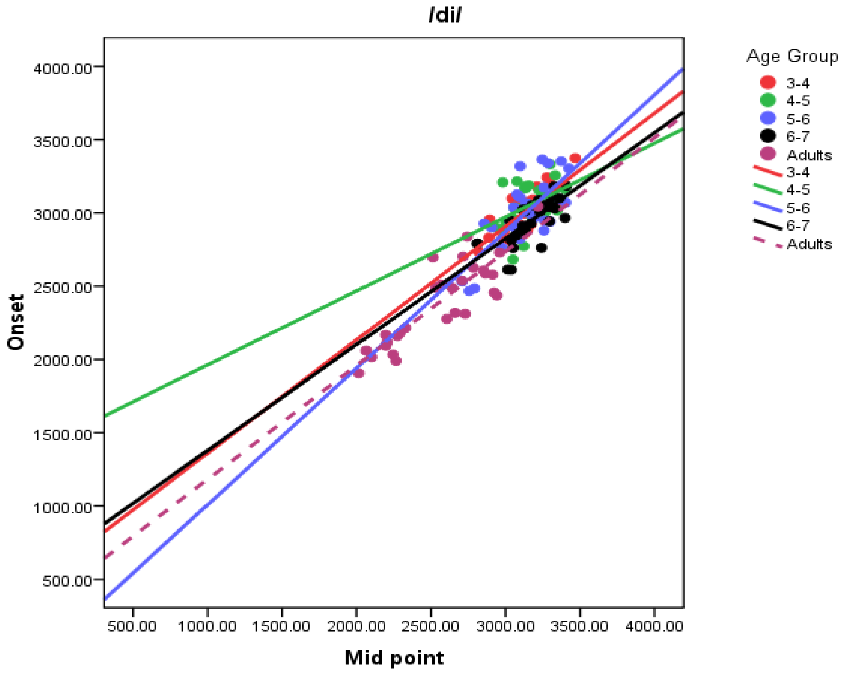


Figure 4.9, *Locus equation scatter-plot for /ḍi/*

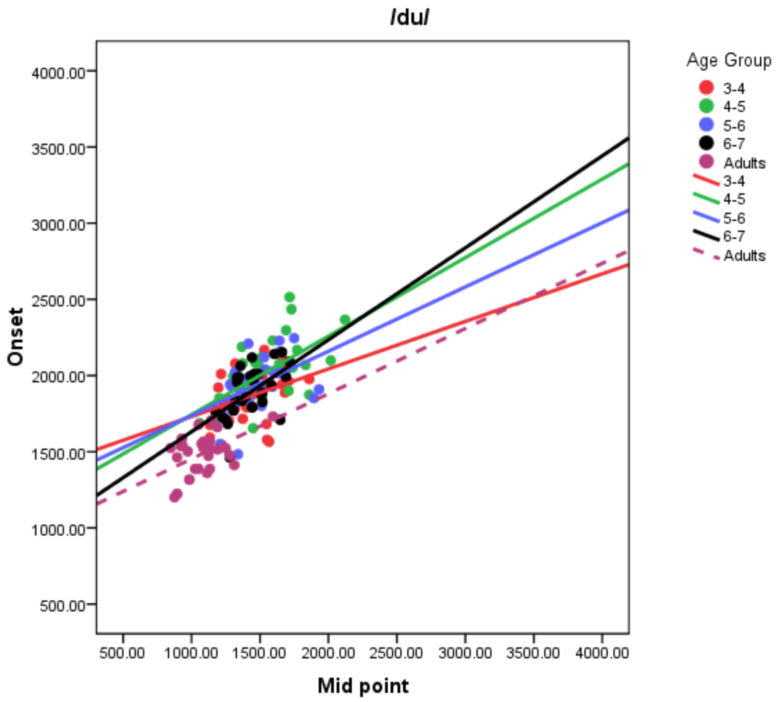


Figure 4.10, *Locus equation scatter-plot for /ḍu/*

Coarticulatory effect on velar /g/

Representation of slope values for the velar stop /g/, indicative of coarticulatory extent in varied vowel contexts /a, i, u/ for the five age groups is given in Table 4.13. It is obvious that anticipatory coarticulatory patterns are similar in 5-6 year olds and adults-a finding consistent with the other two stops, dental /d̪/ and retroflex /ḍ/. Furthermore, it can be observed that /g/ coarticulated to the maximum extent in the context of the high back vowel /u/ in 5-6 year olds and this finding continue to persist in 6-7 year olds and adults as well.

Table 4.13

Coarticulatory pattern in descending order in velar place of articulation

Age groups (years)	**Anticipatory coarticulatory pattern in the context of /g/**
3-4	/gi/>/gu/>/ga/
4-5	/ga/>/gu/>/gi/
5-6	/gu/>/gi/>/ga/
6-7	/gu/>/ga/>gi/
Adults	/gu/>/gi/>ga/

Table 4.14, presents results of Friedman test, used to determine right to left coarticulatory influence of the following target vowel to preceding velar /g/. It is evident that, velar /g/ was influenced by the following vowel only in adults ($p<0.05$) but not in children.

Table 4.14

Chi-square (χ^2) and p-values for velar/g/ as a function of vowel contexts

Age groups	**Consonant**	**χ^2 (2)**	**p value**
3-4 years	/g/	5.47	0.06
4-5 years		3.00	0.22
5-6 years		2.33	0.31
6-7 years		2.33	0.31
Adults		10.17	0.01*

Consequent Wilcoxon Signed Ranks Test in adults showed significant differences for velar /g/ when target pairs /gi/-/ga/ ($|Z| = 2.201$, $p<0.05$) and /gu/-/ga/ were compared ($|Z| = 2.201$, $p<0.05$). The CV combination /gu/ was seen to exhibit highest coarticulation with a slope value of 0.934, followed by /gi/ showing slightly smaller coarticulation in the context of /i/ (0.904) and /ga/ showing the least amount of coarticulation (0.599). As the vowels /u/ and /i/ require a higher tongue body configuration, combined with the fact that /g/ in itself requires the posterior tongue dorsum to contact high up the velum, coarticulatory extent for /gu/ and /gi/ were almost similar. Accordingly, there were no significant differences in slope values when velar pairs /gi/-/gu/ were compared. However, when the utterance /ga/ is produced, the tongue body is pushed from an originally elevated position to lower position, resulting in reduced coarticulation and hence lesser slope value.

Figure 4.11- 4.13 depicts locus equation scatter-plots for the velar utterances /ga/, /gi/ and /gu/ in all the five age groups. R^2 values centered around 0.3 to 0.7 which predicts moderately

good fit. As observed from the figures, it is evident that the 3-4 year olds showed the steepest slope for /gi/ while the 6-7 year olds showed the steepest slope for/ga/ and /gu/.

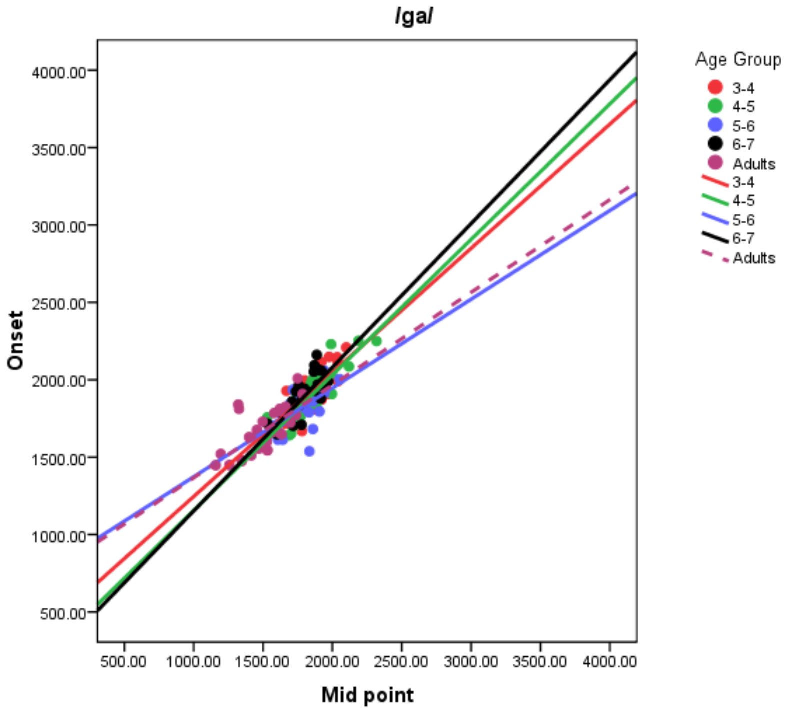


Figure 4.11, *Locus equation scatter-plot for /ga/*

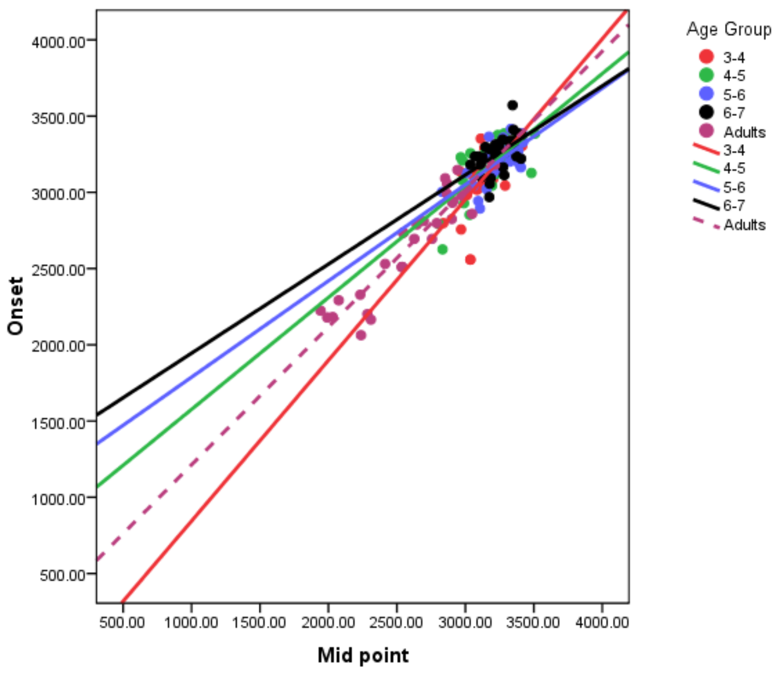


Figure 4.12, *Locus equation scatter-plot for /gi/*

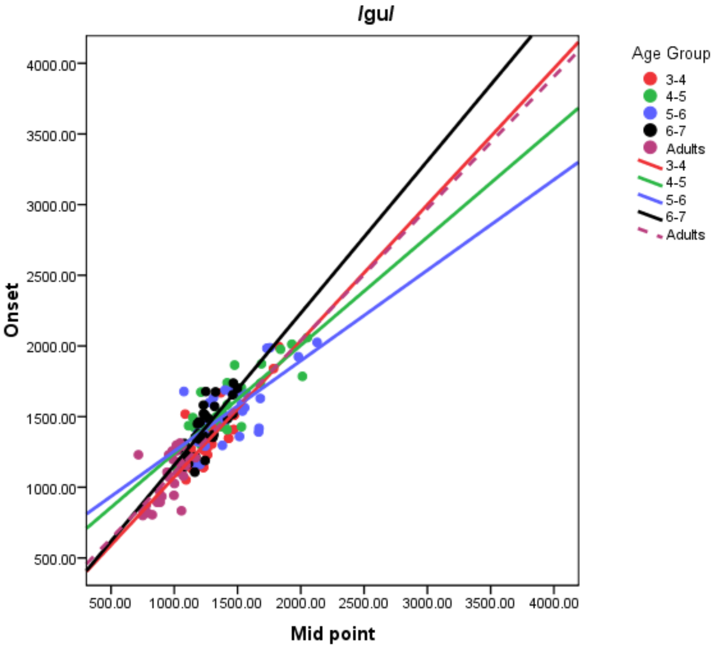


Figure 4.13, *Locus equation scatter-plot for /gu/*

Variation in slope metric, documenting allophonic variation of velar /g/-namely velar and palatal /g/, has been consistently noted in research pertaining to locus equations (Gibson & Ohde, 2007, Sussman et al., 1991, 1992, 1993, 1997, Lindblom & Sussman, 2012 etc). Velar and palatal /g/, in this context, primarily ascribe to presence of the stop in the context of back and front vowels. As per the above mentioned published reports, palatal /g/ was consistently found to have significantly lower slope values as compared to velar /g/. However, the present study did not observe such contrastive coarticulation for the target velar place of articulation. This difference could also be associated with the phonotactics of the languages studied, Kannada in the present investigation and English in the vastly reported literature on locus equation reflecting language specific nature of coarticulation.

From Tables 4.8, 4.9, 4.11 and 4.13, that depicted descending order of coarticulation in the five age groups, it could be observed that there was no linear trend in development of coarticulation pattern across the four groups of children. This finding draws significant support from Perumal (1993) who also observed the same in Kannada. This unpredictable rise and fall in slope values reflects change in physiological variation which in turn changes the acoustical properties of speech.

4.3.1 Coarticulation across stop places of articulation within each vowel category

In order to yield statistical significance across stop consonants in each vowel context, Friedman test and Wilcoxon signed rank tests were employed for all the age groups separately. Table 4.15 presents the chi-square and p-values for comparison across stop consonants within each vowel context for the five age groups. A brief perusal of the data presented in Table 4.15 shows that the low central vowel /a/ showed significant differences in all age groups except for the youngest group of 3-4 years. However, the vowel /i/ did not show any significant difference in any of the age groups. High-back vowel /u/ exhibited coarticulatory influence only in 3 -4 year olds and adults.

Table 4.15

Chi-square (χ^2) and p-values obtained by Friedman's test for comparison across stop consonants within each vowel context and age group

Age groups	Consonant	χ^2 (3)	p value
3-4 years	/a/	5.60	0.13
4-5 years		12.00	0.007*
5-6 years		8.20	0.04*
6-7 years		13.80	0.003*
Adults		11.00	0.01*
3-4 years	/i/	2.60	0.45
4-5 years		4.60	0.20
5-6 years		3.80	0.28
6-7 years		1.80	0.62
Adults		1.60	0.67
3-4 years	/u/	15.40	0.002*
4-5 years		3.60	0.30
5-6 years		6.60	0.08
6-7 years		4.40	0.22
Adults		11.00	0.01*

Comparison of stop places of articulation in the context of /a/

As Friedman Test revealed significant differences in coarticulation as a function of place of articulation in vowels /a/ and /u/ in certain age groups, Wilcoxon Signed Ranks Test was carried out to ascertain pair wise significance across the target stop places. Consequently, significant differences were obtained, in children aged 4-5 years, when retroflex–velar slopes ($|Z| = 2.201$; $p<0.05$) and retroflex- bilabial slopes ($|Z| = 2.201$; $p<0.05$). However, velar and bilabial slopes were not significantly different. In the present study, the retroflex /d̟a/ exhibited the least slope value, /g/ an intermediate slope value and /b/ the highest. In subjects of age 5-6 years, only stop values of stop pairs /b/ and /d̪/ were significantly difference ($|Z| = 2.201$; $p<0.05$) with /b/ exhibiting the highest coarticulation and /d̪/ exhibiting the least.

In 6-7 year olds, significant difference was observed when consonantal pairs /d̪a/-/ba/ ($|Z| =2.201$, $p<0.05$), /ga/-/d̪a/ ($|Z| = 2.201$; $p<0.05$) and /ga/-/d̟a/ ($|Z| = 2.201$, $p<0.05$) were compared. Maximum slope was observed for bilabial /b/ which was eventually followed by velar /g/, retroflex /d̟/ and dental /d̪/. In adults, significant differences were seen only when target pairs /d̪a/- /ba/ ($|Z| =2.201$; $p<0.05$) and /ga/-/d̪a/ ($|Z| = 2.201$; $p<0.05$) were compared. Thus, it is again interesting to note that velar and bilabial slopes were not significantly different. The present finding is in consonance with findings of Sussman et al (1992), Fowler (1994) who also reported of overlapping velar and labial slopes but significant demarcation between velar-alveolar and labial- alveolar slopes.

Comparison of stop places of articulation in the context of /i/

As is evident from Table 4.15, the high front vowel /i/ did not show any significant difference in any of the age groups. The present finding follows suit with a study by

Modaressi et al. (2004) in Persian, who also reported high front vowel regions to show greatest degree of overlap for /bV, dV, gV/ tokens.

Comparison of stop places of articulation in the context of /u/

Stop consonants were considerably influenced by the high-back vowel /u/ in the youngest (3-4 years) and the oldest group (adults). In both groups, Wilcoxon signed ranked test revealed significant difference when the target pairs /d̪u/-/bu/ ($|Z|=2.201$; $p<0.05$), /ḍu/-/bu ($|Z|=2.201$; $p<0.05$); /gu/-/d̪u/ ($|Z|=2.201$; $p<0.05$); and /gu/-/ḍu/ ($|Z|=2.201$; $p<0.05$); were compared. In 3-4 year olds, coarticulatory influence was of the order /gu/>/bu/>/d̪u/>/ḍu/ while adults revealed the following coarticulatory pattern- /gu>/bu/>/ḍu/>/d̪u/. The present finding is in par with Fowler (1994) who also reported velar /g/ to have the highest slope value as compared to /b/ and /ḍ/ in the context of back vowels. Further, slope of velar /g/ in the context of back vowels did not report of any significant difference from that of the bilabial /b/ in the same context- a finding, which is in conformity with the present study.

Based on the slope values presented in Tables 4.2-4.5, Table 4.16 summarizes the coarticulatory effects as a function of stop place of articulation in the three vowel contexts. From Table 4.16, it is evident that, in context of vowel /a/, the velar /g/ (3-4 and 6-7 years) and bilabial /b/ (4-5, 5-6 years and adults) were influenced to the maximum. It can also be deduced that, slope of /b/ and /g/ were often overlapping (in ages 4-5, 5-6 and 6-7 years) despite the higher slope value of the former. The retroflex /ḍ/ and dental /d̪/ offered maximum coarticulatory resistance in children except for adults. However the stop places did not reveal any definite trend when followed by vowel /i/. It was also discussed previously that the vowel /i/ did not bring about significant variation in coarticulation as a function of stop place of articulation. However, when followed by the vowel /u/, the velar /g/ consistently showed the greatest extent of coarticulation in all age groups. The slope of /b/ was closely followed by that of /b/ except in 6-7 year olds. Maximum coarticulatory resistance was associated with retroflex /ḍ/ in 3-4 and 4-5 year olds while dental /d̪/ offered the least in 5-6 year olds and adults.

Table 4.16

Coarticulation as a function of stop place of articulation

Age Groups (years)	**/a/**	**/i/**	**/u/**
3-4 years	/g/>/d̪/>/b/>/ḍ/	/g/>/ḍ/>/d̪/>/b/	/g/>/b/>/d̪/>/ḍ/
4-5 years	/b/>/g/>/d̪/>/ḍ/	/b/>/g/>/d̪/>/ḍ/	/g/>/b/>/d̪/>/ḍ/
5-6 years	/b/>/g/>/ḍ/>/d̪/	/ḍ/>/b/>/d̪/>/g/	g/>/b/>/ḍ/>/d̪/
6-7 years	/g/>/b/>/d̪/>/ḍ/	/d̪/>/ḍ/>/g/>/b/	/g/>/d̪/>/ḍ/=/b/
Adults	/b/>/ḍ/>/d̪/>/g/	/g/>/d̪/>/ḍ/>/b/	/g/>/b/>/ḍ/>/d̪/

On a general note, it has been observed that the velar /g/ showed maximum coarticulation as indicated by its high slope value and relatively high R^2 value. The present finding is in consonance with the findings of Sussman et al. (1993), who also revealed velars and labials to exhibit greater extent of coarticulation than the alveolars owing to the minimal involvement of the tongue as the primary articulator in the production of former consonantal categories. Studies from non-English languages such as Urdu, Cairene Arabic (Sussman et al, 1993), Modern Standard Arabic (Mounir et al., 2012) and Persian (Modaressi et al, 2004) have also shown velars to exhibit more coarticulation as compared to bilabials. Findings of Sreedevi et al (2012), higher slope values for velars in normal Malayalam speaking children, also lends support to the present finding. Thus, the fact that velars showed the most coarticulation as compared to any other class of stop consonants in the present study could indicate a characteristic feature of Asian languages.

In a nutshell, results of the present study show that slope values varied across place of articulation but not as a function of age. The low central vowel /a/ brought about anticipatory coarticulatory influence on target stops to the maximum extent while vowel /i/ contributed little to the coarticulation of the target stops. Among the stops, velar /g/ exhibited the least coarticulatory resistance while retroflex /ḍ/ offered the maximum, especially when followed by /u/. It was also observed that extent of coarticulation did not vary as a function of gender.

On the whole, the findings of the present study do not unanimously support either holistic or segmental theories of coarticulation because the magnitude of coarticulation varied as a function of place of articulation rather than age. Such idiosyncratic routes of development have been frequently reported in literature concerning coarticulation (Sussman et al, 1993, Gibson & Ohde, 2007, Katz et al., 1991, Sereno & Liberman, 1987, Goodell & Studdert-Kennedy, 1993 etc). Varied patterns of coarticulation seen in young children could be the result of the dynamic nature of articulatory subsystem in consideration (Sussman et al, 1993). Thus, it could be inferred that speakers are indeed free to employ any coarticulatory behaviour that is beyond the purview of their anatomical differences.

In order to clearly decipher the phase at which young children begin to adopt the degree and pattern of coarticulation as that in adults, it is imperative to study the same in a population much younger than 3 years. This will enable us truly understand gestural organization from childhood through adulthood.

Further, locus equations have consistently been deemed to serve as invariant cues to locate stop place of articulation (Sussman et al., 1991, 1992 etc). Ironically, in the current study, though we can observe that velars, followed by bilabials had steep slope values, overlapping slope values were also evident in different places of articulation as a function of vowel context. This observation weakens the contention that locus equations are invariant cues for stop place location and hence, one must exercise caution in interpreting slope values.

CHAPTER V

SUMMARY AND CONCLUSIONS

Coarticulation refers to overlapping of movements in the production of neighbouring / near neighbouring speech segments (Nittrouer & Studdert-Kennedy, 1987). Admittedly, the phenomenon of coarticulation is fundamental to ensure economy of speech. Plenty of studies have focused on studying development of coarticulation in children through adulthood and literature in this regard presents contrasting results. Nevertheless, developmental studies with regard to coarticulation have found to be wanting in the Indian context, and more so in Kannada language. This necessitates the need for the present study which seeks to focus on investigating degree and pattern of CV coarticulation in children and adults and to verify if locus equation metrics are sensitive to changes in CV production dynamics as a function of place of articulation in different vowel contexts in children and adults.

In the current study, locus equation metrics have been used as a tool to quantify degree and decode patterns of coarticulation in Kannada language. Locus equations are regression lines obtained by plotting F2 onset of a vowel following the target stop on Y-axis and F2 frequency at mid-vowel on the X-axis. When a target stop is articulated in the context of various vowels, the F2 onset was shown to vary as a function of F2 midpoint (Sussman et al., 1991). Thus, when a stop consonant is uttered in various vowel contexts, different data points are obtained which can be fit linearly though a regression line, namely the locus equation.

When a regression analysis is performed, slope, y-intercept, R^2 and standard error of estimate are obtained as by-products. In this regard, slopes are shown to range from 0 to 1, with 0 indicating a particular stop to have maximum coarticulatory resistance or as having a fixed locus and 1 indicating maximum coarticulation or an invariant locus (Krull, 1987). In the present study, slope was used as an index to measure coarticulation.

In the current study, five groups of thirty subjects each, 15 males and 15 females, belonging to ages 3-4, 4-5, 5-6, 6-7 and 20-30 years (adults) were recruited for the study. Thus, a total of 150 subjects participated in the study. It was ensured that they were bereft of speech, language and hearing impairments. The target stimuli were non-meaningful $C_1V_1C_2V_2$ sequences where C_1 and C_2 were voiced stops /b, d̪, ḍ, g/ characterizing bilabial, dental, retroflex and velar places of articulation and V_1 and V_2 were the vowels /a, i, u/ indicating diverging tongue positions. The target CVCV utterances were embedded in a carrier phrase and three repetitions were obtained from each participant, thus resulting in a total of 5,400 utterances. From the samples obtained, F2 onset and F2 midpoint at the corresponding vowel nucleus (V_1 of $C_1V_1C_2V_2$) was located and subsequently, regression analysis was performed trial-wise.

One of the primary objectives of the present study was to document degree and pattern of anticipatory coarticulation in children and adults. Preliminary analysis of slope values did not reveal any definite pattern. This could be attributed to observations predominantly in the ages of 4-6 years that did not align with the rest of the data. Occurrences of inconsistent observations in this age range have been frequently reported elsewhere in the area of normative research in children (Savithri, 1987, Joseph & Braga, 1974, Negus, 1967).

Slopes, calculated trial wise using regression analyses, for the five age groups and gender were statistically compared. Results revealed no significant differences in slope values between males and females. Statistical comparisons between each of the four groups with adults showed significant variation in anticipatory coarticulation only for the sequences /d̪a/, /d̪u/ and /ga/. The other target stimuli were coarticulated to a relatively similar extent amongst the five groups. Further, when between-age group comparisons were carried out amongst children, only the target stimulus /d̪u/ was coarticulated with a significant difference.

When locus equation data, in this context, the slope, was calculated for the four groups of children and then statistically compared with that of adults, it was observed that only the velar stimulus /gi/ exhibited significant differences. However, comparison of slopes for /b, d̪, ḍ, g/ in contexts of /a, i, u/ for children yielded a few results similar to that of adults-velars and bilabials had the steepest slopes or exhibited maximum coarticulation. The retroflex /ḍ/ was coarticulated to the least extent in the context of high back vowel /u/. These differences in coarticulatory patterns where attributed to variations in the tongue body involvement and the ensuing biomechanical constraints on the tongue tip-blade configuration involved in the production of the CV sequence in the target stop production (Recasens, 1997). However, the findings elaborated earlier reinforced the conclusion that the degree of coarticulation in children and adults are similar.

The study also sought to address right to left coarticulatory differences in children and adults in various places of articulation as a function of vowel context. An analysis of locus equation data revealed that occurrences of maximum slope values centered predominantly around the velar place of articulation (in children aged 3-4 years, 6-7 years and adults) and minimum slope values corresponded to retroflex /ḍ/ (in ages 3-4 years, 4-5 years and 6-7 years) and dental /d̪/ (in age 5-6 years and adults).

Investigation of V to C interaction in CV production dynamics of bilabial /b/ in children and adults indicated that the production of the voiced stop remained essentially undifferentiated in any vowel context. Nonetheless, coarticulatory pattern decoded on the basis of slope values revealed that children aged 6-7 years and adults possessed similar coarticulatory trend /ba/>/bu/>/bi/.

Likewise, it was observed that 5-6 year olds and adults exhibited a similar coarticulatory pattern of the order /d̪i/>/d̪a/>/d̪u/. Significantly, the two groups coarticulated the dental stop differently across vowel contexts which can be attributed to the use of fronted tongue body gesture.

The retroflex /ḍ/ also exhibited significant anticipatory effect as a function of vowel contexts in 5-6 year olds and adults. Both groups showed coarticulatory pattern of the order /d̪i/>/d̪a/>/d̪u/-a finding similar to that of stop consonant /d̪/. However, this variation in extent of anticipatory coarticulation was attributed to modified realization of the stop production under the influence of some specific vowels compounded with degree of tongue involvement. The occurrence of significant differences in production of /d̪/ and /ḍ/ production for 5-6 year olds and their subsequent absence in 6-7 year olds might imply that the use of fronted tongue body gesture and the modified realization of the stop /ḍ/ under different vowel contexts have been achieved but not yet consistent.

Interestingly, the velar /g/ exhibited distinct productions as function of vowel context only in adults but not in children. Further, 5-6 year olds and adults showed a similar coarticulatory trend of the order-/gu/>/gi/>/ga/. The velar /g/ exhibited maximum anticipatory influence in the context of /u/ but offered maximum coarticulatory resistance in the context of /a/, a finding which could be the consequence of differential involvement of posterior tongue dorsum.

With regard to place of articulation, it was evident that the velar /g/ (3-4 and 6-7 years) and bilabial /b/ (4-5, 5-6 years and adults) were influenced to the maximum when followed by vowel /a/. Slope of /b/ and /g/ were often overlapping (in ages 4-5, 5-6 and 6-7 years) despite higher slope value of the former. The retroflex /ḍ/ and dental /d̪/ offered maximum coarticulatory resistance in children except for adults. However the stop places did not reveal any definite trend when followed by vowel /i/. It was also discussed previously that the vowel /i/ did not bring about significant variation in coarticulation as a function of stop place of articulation. However, when followed by the vowel /u/, the velar /g/ consistently showed the greatest extent of coarticulation in all age groups. The slope of /b/ was closely followed by that of /b/ except in 6-7 year olds. Maximum coarticulatory resistance was associated with retroflex /ḍ/ in 3-4 and 4-5 year olds while dental /d̪/ offered the least in 5-6 year olds and adults.

In a nutshell, results of the present study show that slope values varied across place of articulation but not as a function of age. The low central vowel /a/ brought about anticipatory coarticulatory influence on target stops to the maximum extent while vowel /i/ contributed little to the coarticulation of the target stops. Among the stops, velar /g/ exhibited the least coarticulatory resistance while retroflex /ḍ/ offered the maximum, especially when followed by /u/. It was also observed that extent of coarticulation did not vary as a function of gender.

Thus, the findings of the present study do not unanimously support either holistic or segmental theories of coarticulation because the extent of coarticulation varied as a function of place of articulation. Varied patterns of coarticulation seen in young children could be the result of the dynamic nature of articulatory subsystem in consideration (Sussman et al, 1993). Thus, it could be inferred that speakers are indeed free to employ any coarticulatory behaviour that is beyond the purview of their anatomical differences. In order to clearly decipher the phase at which young children begin to adopt the degree and pattern of coarticulation as that in adults, it is imperative to study the same in a population much younger than 3 years. As a note of caution, the authors also wish to add that it is preferable to employ locus equations to study coarticulation in voiced stops.

FUTURE DIRECTIONS

- Formant estimating procedures could involve combination of procedures based on LPC (Linear Predictive Coding) and the customary wideband formant estimation for enhanced accuracy. This is because acoustic analysis using wideband spectrograms alone is often problematic in young children owing to their high fundamental frequency.
- Studying locus equation patterns in natural speech of children will provide a better perception about their coarticulatory dynamics.
- Studying locus equations in a population younger than 3 years will provide a better way to document developmental changes in anticipatory coarticulation.
- Locus equation patterns could be studied in 5 vowel contexts to understand coarticulation dynamics over a wide vowel space.

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