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Incomplete Neutralization in Bengali Geminates: An Articulatory Phonology Investigation

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Abstract: This study investigates the phonetic manifestation of three types of Bengali geminates—true underlying geminates: e.g. /pat*t*a/ 'whereabouts', assimilated geminates: e.g. /kɔɹt*a/--> [kɔt*t*a] 'master', argued to be derived through total assimilation of a rhotic and a voiceless dental stop [ɹ+ t*], and concatenated, formed by the concatenation of two identical stops across a morpheme boundary e.g. /pat* +t*e/--> [patte] 'to spread out', in order to test the competing predictions of Distinctive Feature Theory (DFT) and Articulatory Phonology (AP) using experimental techniques. DFT predicts complete phonetic neutralization across all three types, based on previous acoustic studies. AP, however, allows for incomplete neutralization in assimilated geminates and phonetic variability in concatenated geminates due to gestural overlap and morpheme boundaries, respectively. Using Electromagnetic Articulography (EMA) on native Bengali speakers, this research tested detailed articulatory parameters, including tongue displacement, peak velocity, and gesture activation duration. The findings revealed significant differences between true and assimilated geminates, indicating incomplete neutralization. Specifically, evidence for traces of rhotic articulation were observed in the assimilated geminates, with a notable pattern being the higher velocity of the tongue blade for assimilation compared to true geminates. Concatenated geminates showed variability in timing compared to true geminates which also support the predictions of articulatory phonology and that the pattern is not identical to true geminates. While perceptually both assimilated and concatenated geminates may sound similar to the true geminates, also supported by acoustic study findings, the current articulatory investigation showed different phonetic manifestations. Results support the AP framework and suggest that, despite overall similar acoustic and articulatory patterning, there are some key differences which distinguish assimilated and concatenated geminates from true geminates.

Keywords: Bengali geminates, Articulatory Phonology, Electromagnetic Articulographer, Incomplete Neutralization, Bengali Stops.

1. Introduction

Geminates are units of speech that have been described to be longer in duration than their singleton counterparts (Leben 1980). The words in (1) and (2) from Italian (Payne: 2006), illustrate this contrast, the intervocalic consonant in (1) is a singleton while the intervocalic consonant in (2) is a geminate.

(1) /fata/ - 'fairy' *(Italian)*

(2) /fat:a/- 'done (f.sg)'

In addition to phonemic geminates, some languages have geminates which are formed through phonological or morphological processes as well. Bengali is one of the languages that exhibit phonemic geminates, and two kinds of derived geminates. The underlying geminates will be referred to as 'true' geminates in this study. Lahiri and Hankamer (1988) illustrate the three types with the following examples shown in table 1:

In case of the Assimilated geminates, when the rhotic and the dental stop sequence are produced together, perceptually they sound identical to the true geminates. Lahiri and Hankamer (1988) analyze this process as a phonological rule where a rhotic assimilates totally with the following dental stop to form a geminate (the process is to be described later in greater depth). While in their illustration the assimilation process occurs across a morpheme boundary, this kind of assimilation is also seen word internally as in the following example (3).

(3) / ʃɔrt*o/→ [ʃɔt*t*o] 'condition'.

The third type of derived geminate are concatenated geminates. Lahiri and Hankamer (1988) analyze them as geminates formed by the concatenation of identical stops across a morpheme boundary shown in example (c) in table 1. Once again, these forms are perceptually similar to 'true' geminates.

Table 1. Types of Bengali geminates.

Geminate Type	Underlying	Surface	Gloss
a) True	/pat*:a/	[pat*:a]	'whereabouts'
b) Assimilated	/kor+t*e/	[kot*:e]	'Do' infinitive
c) Concatenated	/pat* + t*e/	[pat*:e]	'Spread out'

According to Lahiri and Hankamer's illustration, these three kinds of geminates are different in their underlying forms while their surface forms are the same. This representation is based on the predictions of Distinctive Feature Theory (DFT), which takes the basic phonological elements to be phonological features. An alternative view to the Distinctive Feature Theory is Articulatory Phonology (AP), which treats articulatory gestures, such as tongue raising, tongue backing, and lip protrusion as phonological primitives, rather than features (Browman and Goldstein 1986). These articulatory gestures form constellations which coordinate with each other in order to produce phonological contrast. Having articulatory gestures as primitives means that phonological contrasts are made based on the presence or absence of one or more gestures. AP treats assimilation as an overlap of gestures, i.e. some gestures can occur before the completion of the previous gesture due to co-articulatory effects, which causes hiding or 'masking' of one gesture by another. Due to the masking of one gesture, there are possibilities of perceptual similarities between the assimilated geminates and true geminates. However, the articulatory assimilation may not be total. The articulatory assimilation depends on how much or to what degree the overlap has taken place. Hence, the theory allows for the possibility of perceptual similarities in spite of phonetic differences. Hence, according to AP, for Bengali, even though articulatory assimilation of the rhotic and the dental stop takes place for the assimilated geminates, there is a possibility that the rhotic may not totally assimilate with the following dental stop and there may be incomplete neutralization. Additionally, recent experimental studies based on the articulatory phonology theory and the use of the Electromagnetic Articulographer have shown that this method can capture incomplete neutralization of underlying palatalization gestures in Russian (Oh 2022, Roon and Whalen 2019).

Articulatory Phonology also suggests that in case of concatenated geminates, variation in phonetic patterns is possible. The reason for such a prediction is that, according to AP, when morpheme boundaries are involved, the phonetic manifestation can be through a range of variable timings. Since concatenated geminates are heteromorphemic, their phonetic manifestation can have a different manifestation from true geminates that do not have a morpheme boundary. This variation may not be only through timings, but can be manifested through other phonetic parameters too such as how much the articulators were displaced for the gesture or for how long the gesture took place etc. (Browman and Goldstein 1986).

Lahiri and Hankamer (1988) tested certain acoustic measures with the Distinctive Feature theory as the theoretical background. The acoustic measures for their study included the duration of the closure of the stop geminates, the VOT of the stop geminates and the duration of the preceding vowel. Their acoustic data supported the idea of DFT that three types of geminates are phonetically identical. The current study tests a more detailed set of articulatory measures in order to verify whether assimilated and concatenated geminates are, indeed, phonetically identical to true geminates. In particular, this study tests firstly, whether there are traces of the rhotic in the articulation of the assimilated geminates. A rhotic articulation involves rounding of lips, narrow opening between tongue blade and the alveolar ridge and constriction at the back of the tongue. Hence the measurements of these articulators were taken in order to check for any traces of the rhotic articulation during the geminate articulation. It is hypothesized that if there is a rhotic remaining in the assimilated geminates, the tongue will be displaced less compared to the true geminates because the tongue will cause a narrowing at the alveolar ridge instead of a complete closure. Since articulatory data provides minute details about each movement for each of the geminate types, a clearer picture is available with articulatory data than with acoustic data.

The articulatory data collected for the current study revealed that there were differences between true geminates and assimilated geminates in certain crucial articulatory parameters. Evidence from the articulatory data is indicative of a rhotic articulation and differences are seen in the manifestation of the assimilated geminates indicating non-identical manifestation of the geminates. There were notable differences between the speakers, however, in how they manifested this distinction. For instance, measurements revealed that subjects produced traces of the rhotic in different ways, with some subjects manipulating the anterior portion of the tongue while some others manipulated the back of the tongue. In addition, a similar pattern was found for all speakers in which movement of the tongue blade showed higher velocity for assimilated geminates to distinguish them from the true geminates. Both the results were indicative of the fact that the true geminates and assimilated geminates were not identical in their phonetic manifestation.

The next section provides a description about the articulatory predictions from Distinctive feature theory and Articulatory phonology theory. The hypothesis for this study will be based on the predictions of the two theories.

1.2. Treatment of geminates by DFT and AP theories

1.2.1. Prediction for Assimilated Geminates by Distinctive Feature Theory

The DFT treats features as phonological primitives. In this theory, true geminates are represented as one unit in the segmental tier but are associated to two units on the time tier (Leben: 1973, Hayes: 1986). The two units on the time tier represent the longer duration of geminates. This representation is shown in Figure 1.

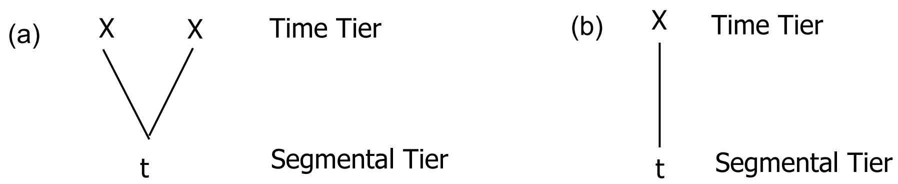

Figure 1. CV-phonology representations of (a) a geminate and (b) a singleton.

According to Distinctive Feature Theory (DFT), feature spreading takes place when features of one segment spread to another segment (Hall, 2011). Figure 2 shows an example from English where nasals assimilate by place of articulation to the next segment. In this case the nasal assimilated to the bilabial place of articulation because the following consonant is a bilabial stop. This kind of assimilation is seen in words like 'impossible' where the [n] in prefix 'in' assimilates by place of articulation to become 'im'.

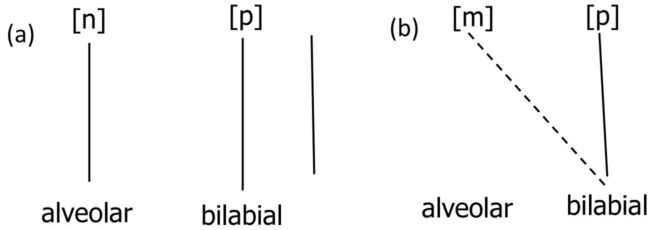

Figure 2. Feature spreading by place of articulation.

In Figure 2, first the places of articulation are alveolar and bilabial when the prefix 'in' gets added to 'possible' shown in (a). However, the nasal loses its association to the alveolar place, shown by a delinking in (b) and then an association line spreading from the bilabial place of articulation shows that the bilabial feature spreads to the nasal. Hence while all else remains the same, the place feature changes for the nasal.

According to this proposal of DFT where features spread from one segment to another, for Bengali this would mean that when a rhotic and a dental stop sequence are produced, the rhotic gets completely assimilated with the dental stop. When this happens, all of the features such as [-sonorant, -continuant, +coronal] of the dental stop, spread to the rhotic, wherein, the rhotic loses its properties and assimilates with the dental stop. Then the resulting unit is a longer dental stop because the dental stop occupies two units in the time tier as shown in figure 3.

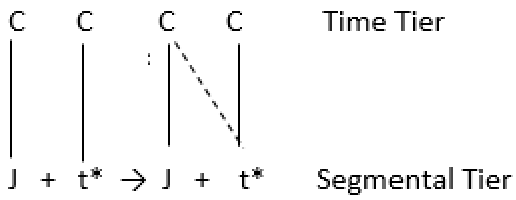

Figure 3. Autosegmental representation of assimilated geminates.

Figure 3 shows the delinking of the rhotic with its time unit and the feature spreading from the dental stop. The resulting phonological representation of the assimilated geminate becomes identical to the representation of true geminates, i.e., one unit in the segmental tier is associated with two units in the time tier. Due to this phonological neutralization, Distinctive Feature Theory suggests that the final phonetic manifestation of the assimilated geminate will be identical to true geminates, i.e. the phonological neutralization will lead to phonetic neutralization. From an articulatory standpoint, Distinctive Feature Theory predicts the rhotic will assimilate with the following dental stop similar to what is observed perceptually, and articulatory data will show that assimilated geminates are identical to true geminates. So, if the predictions of the Distinctive Feature Theory are true then articulatorily it is expected that the assimilated geminates will not show any trace of the rhotic in any of the articulatory parameters.

1.2.2. Predictions for Concatenated Geminates by Distinctive Feature theory

Bengali concatenated geminates are described as bisegmental (McCarthy, 1986) because the identical stops that concatenate together are separate individual segments across the morpheme boundary (Figure 4). True geminates are described as consisting of a single segment:

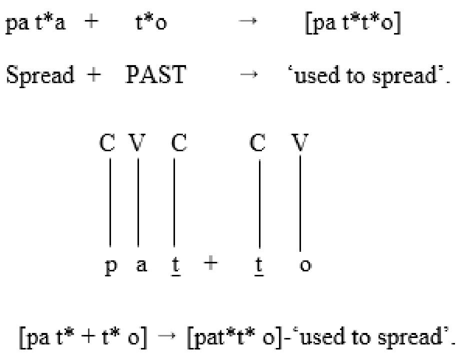

Figure 4. Autosegmental representation of concatenated geminates.

Concatenated geminates are hypothesized to become monosegmental like the true geminates (McCarthy, 1986) after undergoing a process called Tier Conflation (Younes, 1983). This process ensures that Obligatory Contour Principle (OCP) requirements are not violated. OCP requires that two identical segments cannot be adjacent to each other and through the process of Tier Conflation, two identical segments are folded into one, which can then be represented as one segment, spanning across two time units.

McCarthy (1986) proposes that, in cases such as the one illustrated in Figure 5, identical adjacent segments may undergo Tier Conflation (Younes, 1983).

According to this account, information about morpheme junctures is erased at the phonetic level, and the resulting form does not reflect the morphological origin of the sequence. Hence, tier conflation reduces a morphologically derived form to the same phonetic form as a non-derived form.

This process has also been used to explain Bengali concatenated geminates (Lahiri and Hankamer, 1988). As shown in example (4a), the two segments are initially separated by a morpheme boundary, but after gemination the boundary is lost because the two tiers are folded into one. After this fusion process, the resulting segment is represented as a single segment occupying two units on the time tier.

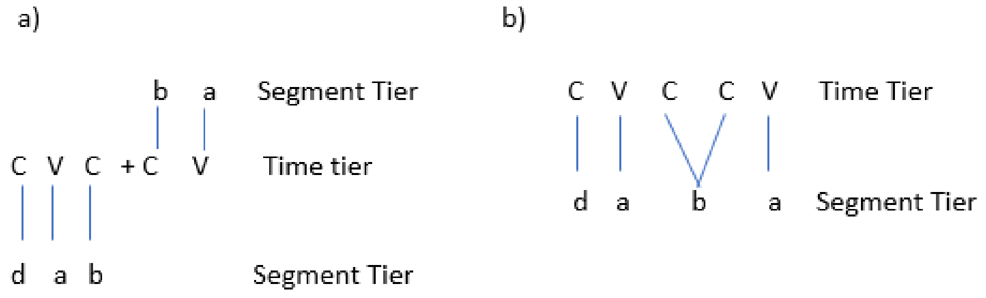

Figure 5. Tier conflation in concatenated geminates: (a) before conflation, two identical consonants are represented separately across a morpheme boundary; (b) after conflation, they are represented as a single geminate linked to two timing units.

After this process takes place, the geminate cannot be broken up by vowel epenthesis and therefore appears structurally identical to a true geminate. McCarthy (1979) suggests that this loss of morphological boundary information is similar to Bracket Erasure (Pesetsky, 1979; Kiparsky, 1982; Mohanan, 1982; Halle and Mohanan, 1985), a modification that removes morphological boundaries once they become inaccessible to phonological rules. This process thoroughly erases the distinction between heteromorphemic and tautomorphemic geminates.

DFT proposes that phonetically the concatenated geminates will be identical to the true geminates even in articulatory data because the process of removal of morphological information will still take place at the articulatory level. This means that DFT predicts that there will not be any variation in the phonetic patterns between the true geminates and concatenated geminates.

1.2.3. Predictions for Assimilated geminates by Articulatory Phonology Theory

The AP theory proposes an alternative approach for predicting the phonetic manifestation for both assimilated geminates and concatenated geminates. Vocal tract articulators (e.g. tongue tip, tongue blade, lower lip, upper lip) contribute to formation of articulatory *gestures*. In AP, lexical items are said to contrast with each other based on the presence or absence of crucial gestures, and utterances are modelled as organized patterns or constellations of gestures. Each sound that we hear, e.g. vowel or consonant sound, in AP theory they are made up of one or more gestures which work together to form a specific sound. For example, in order to produce a bilabial nasal in English /m/, both the lips have to come together and create a closure. This closure of the lips is the crucial gesture for /m/, compared to for example the crucial gesture for /n/ which would be a constriction at the alveolar ridge by the tongue blade. In the absence of the bilabial closure gesture, /m/ will not be produced. However, there are also other gestures that contribute towards the formation of /m/, such as opening of the velum to let the air pass through the nose, which coordinate with the bilabial closure to successfully form the consonant /m/.

Figure 6 shows what the coordinating gestures look like during the production of the name "Sam" (Browman and Goldstein, 1989). This representation is called a gestural score (Browman and Goldstein, 1989).

In this gestural score, the velic closing and the alveolar fricative gestures indicate that /s/ is being articulated in the initial position. This means that the velum is closed to let air pass through the oral cavity instead of the nasal cavity, and the tongue tip forms a narrow constriction at the alveolar ridge to facilitate an alveolar fricative. Second, the pharyngeal wide indicates the wide opening of the pharynx as the tongue is moved forward for the front vowel /æ/. Initially, there is velic opening for the nasal /m/ when air passes through the nasal passage, accompanied by bilabial closure for /m/.

When gestures are produced as a part of a natural, casual utterance, they overlap with each other in time. This overlap causes coarticulation of certain gestures which leads to gestural reduction (Browman and Goldstein 1989).

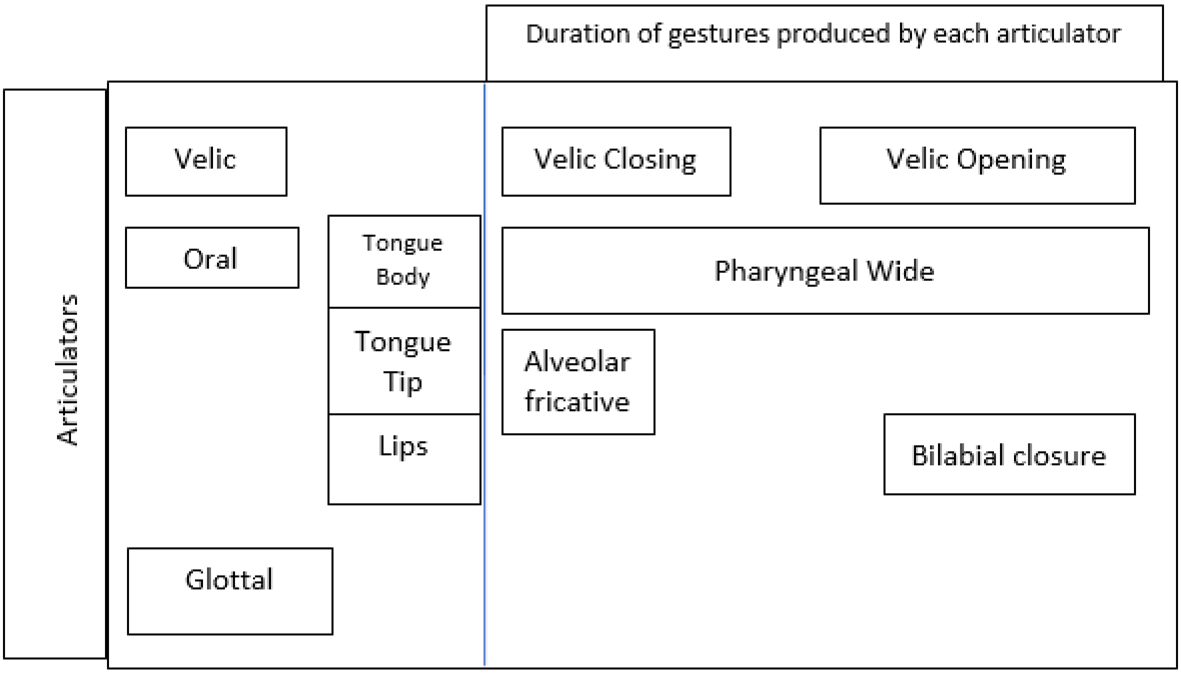

Figure 6. Gestural score for the English word "Sam."

Reduction has been found to cause weakening of certain gestures, to the extent that constriction degrees for the weakened gesture is reduced or changed. Browman and Goldstein also suggest that when two gestures involve the same constriction location and the same articulators, co-articulation in these cases lead to blending of the movement of the two separate gestures. This kind of blending is also referred to as 'assimilation' (Catford, 1977) where two separate gestures get blended together.

The degree of overlap may vary. If the degree of overlap is greater, one gesture can be completely overlapped by the other in time (Figure 7a), which Browman and Goldstein (1989) call complete synchrony. If the degree of overlap is lower, there can be partial overlap or minimal overlap in time (Figure 7b-c) (Browman and Goldstein, 1987). Overlap can also occur between identical gestures, for example when a sequence of two identical gestures occurs across a morpheme boundary. Browman and Goldstein (1989) illustrate these different degrees of overlap and represent them as gestural scores (Figure 7a to 7c). In these representations, there are three kinds of overlap: velic-oral, oral-glottal, and oral-oral. In some cases, such as Figure 7a where a nasal is produced [n], a complete overlap takes place between velic-oral gestures. An oral-glottal overlap is shown in the case of the voiceless unaspirated [t], and oral-oral overlap occurs when double articulation takes place for [gb]. In this case, listeners hear the overlapping gesture rather than the overlapped gesture.

However, in 7b, a partial sliding of gestures take place which results in partial overlap for three articulatory level, velic oral for pre-nazalised stop [nd], oral-glottal for voiceless aspirated stop [t^h] and oral-oral for secondary articulation of [g^w]. In this case both the gestures are audible to the listeners to a certain extent. In 7c, a minimal overlap takes place because of very little sliding of gestures into one another. This can be seen in cases where nasalized- oral sounds are produced with velic and oral overlap, oral-glottal minimal overlap is seen in oral+h sounds such as [dh]. Oral-oral minimal overlap is seen in consonant clusters such as [gb]. In the case of minimal overlap, both the gestures are audible to the listener and to a larger extent than the partial overlap case.

A gestural score for double articulation (6a) and consonant cluster (6c) specifically, will show how the oral gestures overlap in languages, especially when a word boundary, morpheme boundary or a syllable boundary are involved. Onset clusters have also been shown to differ in the level of their overlap when compared with heteromorphemic cluster sequences. The English example of 'tight rate' and 'titrate' can be used to illustrate this phenomenon for the medial [tr] sequence. 'Tight rate' has a word boundary while 'titrate' does not. Utterances that involve a word boundary, morphological boundary or a syllable boundary, have been found to have lesser overlap than in word internal conditions (Keating, 1990), indicated by timing relations. Word boundaries are expected to have least overlap, syllable and morpheme boundaries have more overlaps and word internal sequences are expected to have most overlaps. Hence more overlap is expected in 'titrate' and lesser overlap is expected in 'tight rate'.

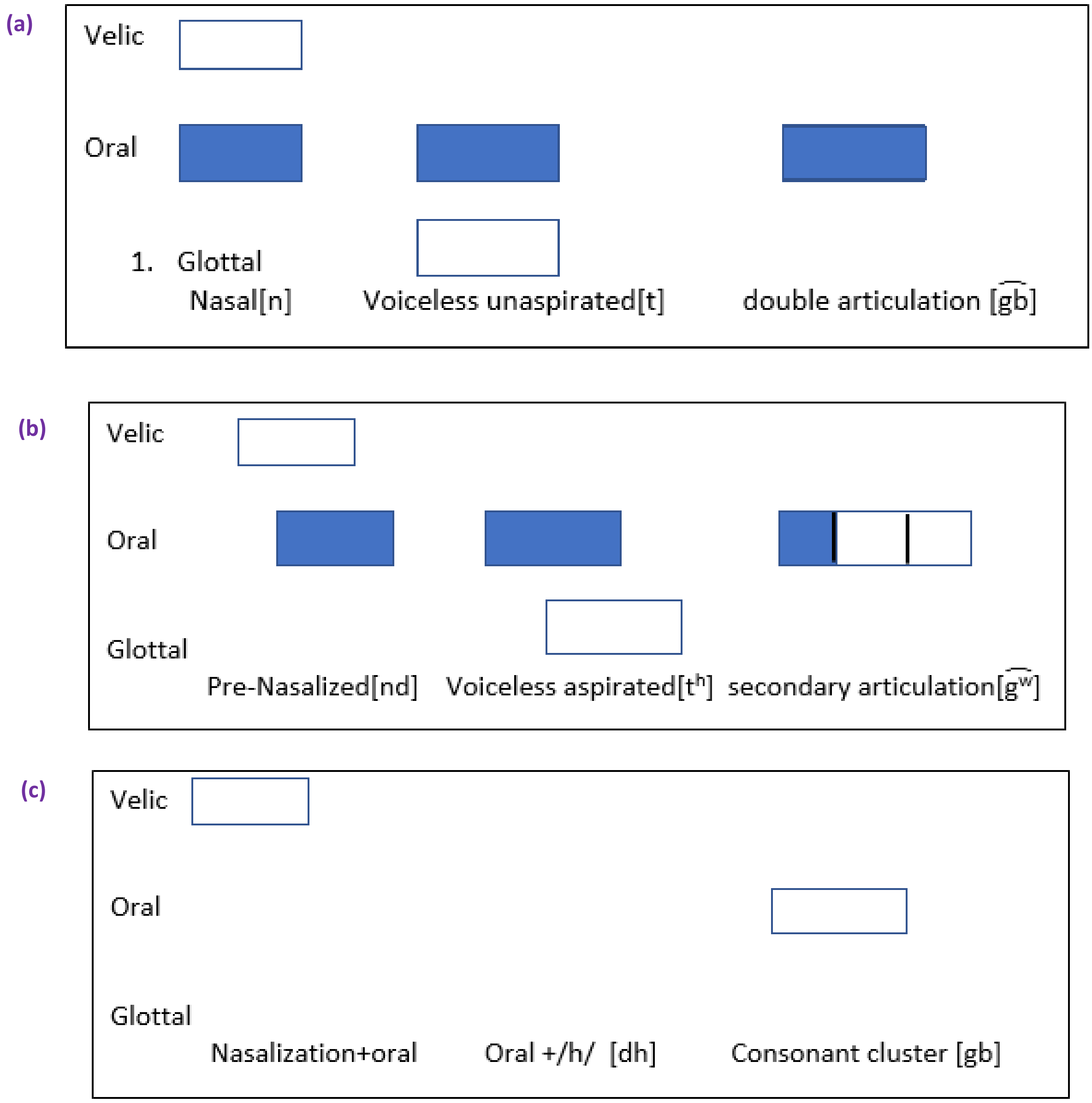

Figure 7. Gestural scores illustrating complete, partial, and minimal overlap of gestures.

In Figure 8(a) and 8(b), complete synchrony and minimal overlap are shown for the stop [t] and approximant [r] in the words 'titrate' and 'tight rate', respectively.

Both of these consonants are produced at the same place of articulation, i.e. alveolar, but 'titrate' is like the case of double articulation because the sequence is word internal and has more overlap, and 'tight rate' is like the case of consonant cluster and lesser overlap. Interestingly, the overlap can occur between the /t/ gesture and the /r/ gesture for any of the articulators, which means that the lip rounding for the rhotic can remain for the whole <tr> sequence, or the tongue blade gesture for /r/ can begin before the end of the tongue blade gesture for the stop /t/ and the tongue dorsum constriction can also start occurring before the tongue blade gesture for /r/ ends.

In this gestural score a major overlap is seen for the oral gestures during the production of the [t] and [r] sequence. [t] involves an oral gesture made by the tongue blade and no pharyngeal gesture. For rhotics, a narrow constriction formed by the upper lip and lower lip, tongue blade and the alveolar ridge and a constriction is also formed at the tongue back gesture. The tongue blade narrowing gesture however is expected to be longer in duration than the corresponding tongue blade closure gesture for [t].

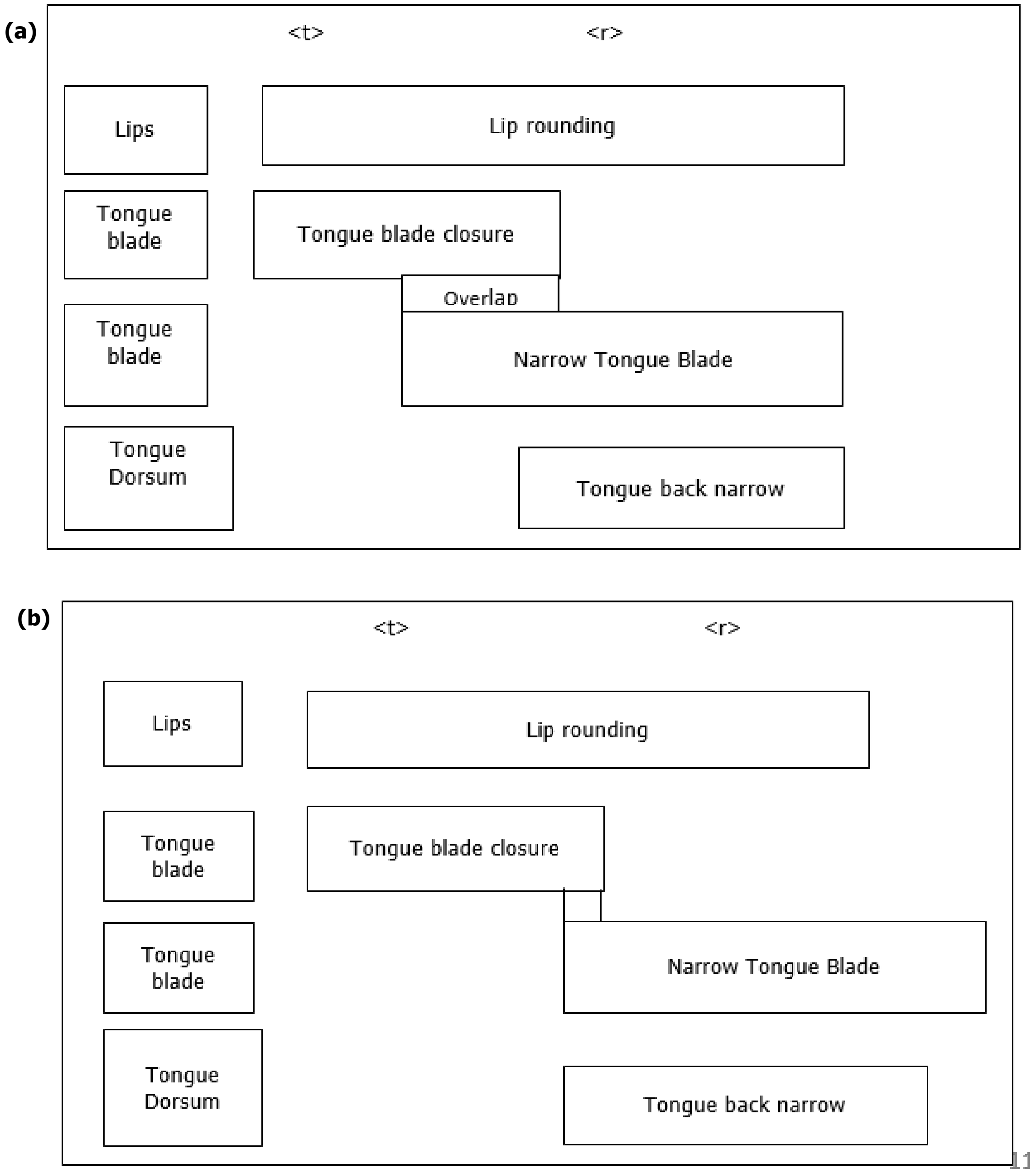

Figure 8. Gestural scores for the alveolar stop–rhotic sequence [tr]: (a) onset cluster in 'titrate', showing greater overlap; (b) heteromorphemic cluster in 'tight rate', showing minimal overlap.

In Figure 8(b), a minimal overlap is seen for the oral gestures during the production of the [t] and [r] sequence. [t] involves an oral gesture made by the tongue blade and no pharyngeal gesture. For the rhotic, there is a narrow constriction formed by the tongue blade and a narrow constriction at the tongue dorsum.

Assimilated geminates in Bengali are predicted to be a result of an overlap between a rhotics and a dental stop. This assimilation is dependent on the articulatory nature of the rhotic as well as the dental stop. Bengali rhotic involves constrictions at the pharyngeal level and coronal level (Mizan, 2014). The place of articulation of the Bengali rhotics is in the alveolar ridge area and the constriction is made by the tongue blade. Hence, it can be speculated that when the rhotic and the dental stop are produced, the oral-oral constriction for the rhotic at the alveolar ridge and the back of the teeth for the dental stop, causes the oral gesture at the alveolar ridge to get overlapped by the oral gesture of the dental stop.

The gestural organization of assimilated geminates can be understood better by comparing the timing relationship of the gestures involved in their articulation with the help of gestural scores for Bengali (Figure 9). Gestural scores indicate the temporal organization of the presence or absence of a gesture. The horizontal dimension shows time while each row represents gestures of oral constrictions. Labels in the boxes indicate constriction degree and location of the gesture. The gestural score of an assimilated geminate (9b) is projected by comparing it with a rhotic-dental stop sequence without overlap (9a), a true geminate (9c), and a concatenated geminate (9d).

A non-assimilated [r] [t] sequence is expected to be longer than an overlapped [rt], i.e. in assimilated geminates. This is because when two gestures overlap, it is expected that the total sequence will reduce in duration as one gesture spans over another. However, that is not the case with the assimilated geminates. The timing of the assimilated geminates are found to be the same as true geminates and concatenated geminates. Normally we would expect that when an overlap occurs, the combined duration of the sequence should reduce, however, since rhotics have longer duration for the tongue blade gesture, the overall assimilated geminates are the same duration as the true and concatenated geminates. This is also captured through the gestural scores in Figure 9a-9d.

The timing relationship between each of the sequences is shown in Figure 9(a) to Figure 9(d). Figure 9(a) shows the timing of [r] and [t] as a sequence of consonants with no overlap or assimilation. The gestural score of concatenated geminate's shows the organization of gestures when two identical gestures are in a sequence, i.e. in case of Bengali, it is two dental stops, [t*t*]. This is predicted to be the same as that of the true geminates.

Hence, the gestural score of assimilated geminates shown in Figure 9(b) shows that there is overlap of all three components of the rhotic with the dental stop. The lip gesture starts early and ends after the dental stop gesture has already begun. The tongue dorsum starts sequentially after the lip and tongue-blade gestures (Campbell et al., 2010); however, the timing of the tongue dorsum is also overlapped by the tongue-blade gesture. It is not overlapped by any pharyngeal gesture because there is no active pharyngeal gesture during the articulation of the following dental stop. Hence, while there is an overlap of the oral gesture by the oral gesture of the dental stop, there is no additional overlap of the tongue-dorsum gesture. This is because a dental stop does not have a tongue-dorsum gesture to overlap the tongue-dorsum gesture of the rhotic. This is why, when the overlap takes place, the timing of the whole sequence is not changed even though there are overlaps. The two tongue-blade gestures in the assimilated geminates are equal in duration to the tongue-blade gestures of the true and concatenated geminates. This is due to the fact that the tongue-narrowing gesture of the rhotic is longer in duration.

Additionally, the position of the tongue blade differs for the rhotic as it is normally produced and the stop as it is normally produced. For the rhotic, there is a narrow opening but for the dental stop there is a complete closure. Therefore, if there is substantial overlap between the rhotic and the stop, that can influence the rhotic to become more like a stop. The reason for this is that the tongue narrowing gesture of the rhotic is going to get truncated due to overlap with the tongue closure gesture of the stop. Hence, the full tongue narrowing gesture that is expected for the rhotic is shortened. This then gives the perceptual illusion that the rhotic is absent.

Due to this complexity in timing and spatial coordination of the rhotic and the dental stop, AP theory allows more phonetic variability and a possibility for the assimilated geminates to be dissimilar from true geminates in certain phonetic aspects.

Figure 9(b) shows that the gesture for the dental stop overlaps with the gesture for the tongue blade narrowing of the rhotic. The degree of overlap can cause a complete overlap or a partial overlap, or a minimal overlap of the gestures (Browman and Goldstein 1989). An incomplete overlap, whether minimal or partial, will indicate an incomplete neutralization of the assimilated geminates. Incomplete neutralization means there will be difference between the true and assimilated geminates in terms of phonetic patterns and they may not be completely identical to each other. The part that is not overlapped will show certain traces of a rhotic, for example lesser displacement of the tongue blade because the part for rhotic involves narrow opening rather than a complete closure that usually happens for stops. Hence a lesser displacement of the tongue blade is expected for the rhotic because the tongue blade will not go all the way to the alveolar ridge and create a closure. However, this possibility of an incomplete neutralization is not allowed by the DFT theory.

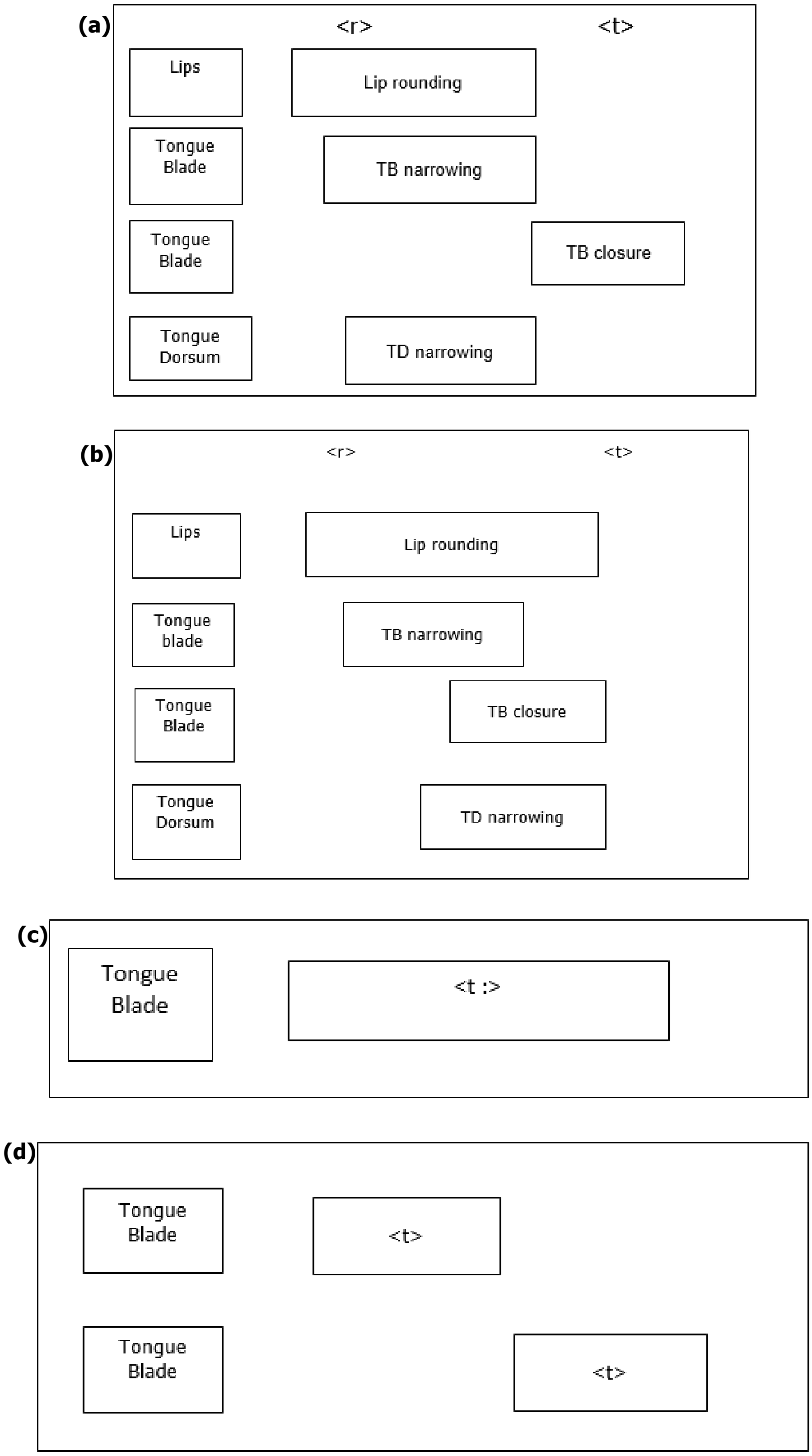

Figure 9. Gestural scores for Bengali geminates: (a) timing of the [r][t] sequence; (b) assimilated geminate; (c) true geminate; (d) concatenated geminate.

1.2.4. Predictions for Concatenated geminates by Articulatory Phonology Theory

AP theory also proposes alternative predictions from DFT for concatenated geminates. It leaves open the possibility of more variability and does not necessarily require the concatenated geminates to be identical to the true geminates due to the fact that concatenated geminates involve a morpheme boundary. The morpheme boundary plays an important role in this prediction. This is because the morpheme boundary is said to have an effect on the temporal and spatial relationship of gestures that are across a morpheme boundary. These timing and spatial relations are called 'phases' in AP terms. (Keating, 1990). There are mechanisms of coordinating gestures called phasing rules which state that a phase in one gesture is synchronized with a phase in another gesture (Keating, 1990). However, when these gestures overlap factors such as phrase boundary, morpheme structure, stress etc., affect their degrees of overlap.

The main effect of these factors is thought to be on the weight of the phase window. Weight of a phase window determines where in the range of possible values the actual intergestural overlap will be implemented and how narrow the range will be Zsiga & Byrd, (1990) proposes that the morpheme boundary acts as a weighting factor, which is manifested as a narrower window for gestures within a morpheme and wider for gestures across a morpheme boundary. The effect of morpheme boundary on gestures were tested in Cho, (2001) with regards to intergestural timing patterns. The study collected Korean data using the EMA and Electropalatography system and tested the intergestural variability of adjacent gestures across word boundaries. The comparison was between lexicalized items vs non-lexicalized items where each morpheme that produces lexical entries after affixation constitutes a separate lexicalized item, for example, in Korean, /hak-pi/ means 'tuition' which is a lexicalized item, but each morpheme means /hak/ -'study' and /pi/- 'expense' respectively, when they get affixed, they form a new lexicalized item /hak-pi/. In contrast a non-lexicalized compound is /hak-pi/ which means "school corruption" where each morpheme of the word means 'school' and 'corruption' which does not form a new lexicalized item. Hence the lexicalized and non-lexicalized compounds were compared. Additionally the effect of a morpheme boundary was also tested by comparing a monomorphemic word to a heteromorphemic word. Comparisons were made using articulatory parameters such as peak velocity of closures and releases of the stops and the maximum displacement in the vertical dimension for each consonant in the cluster.

The results from the EMA study showed that any gestural sequence within a single gestural entry, i.e. lexicalized compounds and monomorphemic words, had a more stable intergestural timing pattern compared to non-lexicalized entries and heteromorphemic compounds. Intergestural timing was measured by the C-Center analysis. C-Center analysis is the measure of time from the articulatory mid-point of a consonant until the end of the next vowel. This measure tells us about the extent of coarticulation between consonants and consonants and consonants and vowels. This was found to be more stable if the morpheme boundary was inside a lexicalized compound compared to a non-lexicalized compound and consonant vowel timing was more stable when the sequences were in tautomorphemic conditions as opposed to heteromorphemic conditions. This study showed the variability in intergestural coordination is induced by a morpheme boundary.

Given the Keating model, greater variability of articulatory patterns is expected in some cases at morpheme boundaries. The current study however, examines identical gestures across the boundary, i.e. dental stop at the end of the root and dental stop at the initial position of the suffix, so unlike Korean (Cho, 2005) which tested different consonants. Hence, there may be less potential for variation than if it were two different segments which could potentially show different coarticulation patterns. Nonetheless, greater variability in articulatory patterning is still a possibility in this case, and this is allowed by AP, but not by DFT.

Since a concatenated geminate involves a factor which a true geminate does not, going by the AP model, there is a possibility that concatenated geminates will not be identical to true geminates. The current study tests whether concatenated geminates show variations in articulatory patterns when compared to true geminates. It is hypothesized that the concatenated geminates will vary from true geminates in duration of the geminate gesture. This is because morphological boundaries seem to affect the timing of the gestures, hence it is speculated that the duration of the concatenated geminates would be different from the true geminates.

A complete study to test the predictions of both the theories has not been done in the past. Although the claims from DFT were tested acoustically, a complete test using articulatory data to also test the claims of AP, is not currently available.

The current study tests the claims of DFT and AP with acoustic and articulatory data from Bengali geminates. Bengali articulatory data collected with the Electromagnetic Articulographer (EMA) shows the movement of the articulators in the form of trajectories. These movements provide us with information about the physical characteristics of the gestures.

A thorough investigation of the geminates will also reveal whether the abstract featural representation of the geminates is adequate to account for the phenomenon or not. Since AP treats gestures as phonological primitives which are based on physical movement of articulators, the articulatory investigation can improve our understanding of the nature of the geminates.

Data from the current study showed evidence of incomplete neutralization in case of assimilated geminates suggesting that the featural representation does not entirely capture the phonetic manifestation of the geminates and the DFT analysis may not be able to capture what actually happens at the gestural level.

2. Methodology

Geminates have been studied from an articulatory standpoint in several languages. Articulatory correlates of geminates were found by comparing geminates with singletons. One of the primary hypotheses of geminate-singleton distinction was the fact that geminates have longer closure durations than singletons (Beckman, 1982, Han, 1994, Hirata and Whiton, 2005). Löfqvist (2007) suggests that the longer duration can be maintained in two ways, first, the speaker has to stop moving the tongue momentarily and second the speaker has to slow down the tongue movement for geminates (Löfqvist, 2007). The second possibility has been considered to be more probable, because previous studies report that the tongue does not stop moving even during stop closure productions (Mooshammer *et.al.,* 1995, Kent and Moll, 1972). Löfqvist and Gracco (2002) have also shown that during the production of alveolar stops, both the tongue tip and the tongue body move forward and upward, hence confirming the fact that the tongue does not stop moving during stop production.

Löfqvist (2007) hypothesized that the speed of the tongue movement would be slower for a geminate compared to a singleton. Second, the magnitude of the tongue movement will be larger during a geminate compared to a singleton, i.e. tongue displacement during geminate production will be higher compared to the tongue movement during singletons. The results of this study showed that the speakers decreased the speed of the tongue during geminate production while the overall displacement was the same. This has been considered as an additional evidence for active, task-dependent control of tongue-movement speech in speech production (Löfqvist, 2007), i.e. if the goal is to produce a geminate, the articulators will be controlled in such a way that the speed is controlled even if the target is same. This finding supported an earlier study of Japanese and Italian bilabial geminates (Smith, 1995) where the closing movements of lips were slower for geminates compared to singletons.

Previous studies also report the possibility of 'virtual targets' of articulators (Löfqvist and Gracco, 1997). Virtual targets have been described (Löfqvist and Gracco, 1997) as the target that the articulators aim to reach during the closure or constriction formation of the consonants. This target can go beyond what the articulators can physically reach (Gili-Fivela *et. al.,* 2007), i.e. the target may indicate that the lips are aiming to move past one another. It was proposed while studying bilabial stops through tissue compression of the lower lip pushing up against the upper lip (Löfqvist and Gracco, 1997). The study (Löfqvist and Gracco, 1997) showed that by shifting the position of a 'virtual target', speakers could vary the duration of oral closure for geminates. Although the findings of this study was based on bilabial closure, Löfqvist and Gracco (1997) proposed the same possibility for other articulators as well. Other studies (Fuchs *et. al.,* 2001, Löfqvist and Gracco, 2002, Perrier *et.al.,* 2003) have also shown that the tongue can move at high velocity even during the oral closure phase, indicating the possibility of a virtual target that the articulators can move beyond each other.

These results motivated the investigations of Peak Velocity in order to distinguish between geminates and singletons. Peak velocity is the highest velocity reached by an articulator during an active gesture at a certain point in time. Vowels and sonorants are associated with lower peak velocity than stops and other obstruent. Peak velocity of the lips during and before contact were measured in a study of bilabial stops in Japanese and Swedish (Löfqvist, 2005). These studies measured the peak velocity of the lower lip primarily because the lower lip is the articulator that moves more than the upper lip. Results showed that the Swedish geminates had shorter closure duration and had some overlaps with singletons in terms of duration while Japanese did not. Japanese closure duration constrictions were longer for geminates than singletons. The Japanese results also confirmed the predictions (Löfqvist, 2005) that lower lip reached a higher vertical position during geminate closure constriction compared to singletons indicating more displacement for geminates. Interestingly, for the Japanese geminates, the closing peak velocity was not higher than the closing peak velocity for the singletons as was predicted initially in this study. It was concluded that speakers of Japanese not only control the position of the virtual target, but also control the timing of when the target is reached. It was also concluded that variations in lip displacement can also be used to make changes in closure duration for labial consonants.

It has been observed that different languages have different strategies to manifest a geminate. While some languages such as Tarifit Berber (Bouarourou *et. al.,* 2008) have reported to have higher peak velocity during closure of the stop for geminates as compared to singletons, some languages have been reported to have lesser peak velocity in geminates compared to singletons, e.g. Estonian (Türk *et. al.,* 2017).

While the previous studies compared the articulatory differences only between singletons with geminates, the same parameters were tested in order to compare the different types of geminates seen in Bengali. Based on the previous studies, peak velocity, displacement and the duration for which a gesture was active, i.e. activation duration of a gesture will be measured for three types of Bengali geminate. Predictions for each type of geminate depends upon the composition of the geminates and how they compare with the true geminates. True geminates are expected to have lower peak velocity than singletons. For assimilated geminates, the prediction is that when they are compared to the true geminates, they will probably have lesser displacement of the tongue due to the narrow constriction of the approximant nature of the rhotic. This aspect of the rhotic should affect the overall displacement of the assimilated geminates. For concatenated geminates, it is predicted that since they are two singleton stops concatenating with each other, they should retain the articulatory characteristics of each singleton stop. Hence the concatenated geminates are expected to have higher peak velocity than true geminates. For coronal geminates the active articulators are tongue tip and tongue blade. Additionally, measurements were taken for tongue dorsum in order to account for tongue back constriction of the rhotic and also upper lip and lower lips, in order to account for the labial constriction for the lip rounding involved in rhotics. The rhotic manifestation could be reflected through any of the constriction locations, hence all three constriction locations are tested for the assimilated geminates.

2.1. Participants

Four native speakers of Bengali (2 male, 2 female) participated in the study. All four subjects were graduate students at the University of Delaware but have lived the majority of their lives in India. They were trilingual in Hindi and English. The speakers were from four different dialectal areas, Murshidabad, Midnapur, Durgapur and Kolkata.

2.2. Stimuli

Although most Bengali consonants can form geminates, the current investigation focuses on voiceless dental stop geminates /t*/. This consonant is available in an optimum environment in Bengali words for comparing singletons and underlying geminates. They also occur after rhotics as clusters in word medial positions resulting in assimilated geminates. Additionally, several suffixes of Bengali begin with the voiceless dental stop such as /t*o/- 'used to' which is also ideal for formation of concatenated geminates (Table 2). The stimuli consist of a set of five real words containing word medial geminates of the three types.

Table 2. Stimuli words with singletons and three kinds of Bengali geminates, lexical, assimilated and concatenated

Singletons.	Lexical geminates	Derived geminates	
		Assimilated	Concatenated
pat*a-leaf	pat*t*a- whereabouts	gɔrt*o >gɔt*t*o- hole	pat*a+ t*o=patto- used to spread.
tʃʰat*a- umbrella	d*ɔt*t*o- bestowed	kɔrt*a> kɔt*t*a- master	pot*a+ t*o=put*t*o- used to bury.
pot*a- buried	t*ɔt*t*o- tray containing presents	ʃɔrt*o> ʃɔt*t*o- condition	t*ãt*a+to= t*ãt*t*o- used to heat.

b^{h}ot*a-blunt	mɔt*t*o- engrossed	mɔrt*o> mɔt*t*o- earth	kat*t*o- nonce
mɔt*o- similar	ʃɔt*t*o- juice/ extract	d*^{h}orto>d*^{h}ot*t*o- used to hold.	bat*t*o- nonce

2.3. Equipment

Electromagnetic Articulography (EMA) data was collected from four native speakers of Bengali (2 male) using the NDI Wave Speech production system. Sensors were attached to Tongue Tip, Tongue Blade, and Lower Incisor, reference sensors Nasion and Mastoids. Acoustic data was collected using an external microphone in PRAAT.

2.4. Data collection Procedure

Stimuli were presented using the OpenSesame program through a computer screen. The subjects faced the computer screen while the sensors were attached to their crucial articulators for this study. Three subjects' (s02,s03 and s06) Tongue Blade, Tongue Tip, Tongue Dorsum and Lower Incisor data was collected and for one subject (S2007)the Tongue Dorsum and Tongue Tip data were not collected, instead sensors were attached to her upper lips and lower lips. The upper lip and lower lip data were collected in order to check whether the assimilated geminate shows instances of lip rounding due to the presence of the rhotic in the sequence. Articulatory data was collected using the EMA and Acoustic data was collected using PRAAT.

Stimuli were presented as blocks. There were a total of 10 blocks with two repetition of each word in the same block. This yielded 50 targets in each block. With 10 blocks in total there were 500 sentences produced by each of the speakers.

2.5. Data Analysis

Data was analyzed using MVIEW. Gestural onset of the consonant was determined using a 20% threshold of peak velocity (cm/s). DISPLACEMENT (DISP; in mm) of the tongue blade at the trajectories of vertical and horizontal movement were measured, as was PEAK VELOCITY (PVEL; in cm/s) toward the target. Articulatory duration was measured as the time between the gestural onset and offset in milliseconds (GOFFS-GONS). Acoustic duration of geminates was measured from amplitude drop at start of the closure to the beginning of the following vowel using PRAAT.

3. Hypothesis

The hypotheses tested based on the composition of the Bengali geminates and the previous reports:

1. Assimilated geminates may show differences in articulatory manifestation from true geminates due to the presence of rhotics. Since the rhotic and dental stop assimilation depends on the extent of overlap, there can be incomplete assimilation which will manifest through one of the articulatory parameters. It is expected that they will differ in terms of displacement due to lesser displacement of the tongue blade due to a narrow constriction formed at the alveolar ridge instead of a complete closure at the beginning unlike true geminates.
2. It is expected that the concatenated geminates will be the concatenation of two singleton stops, manifesting with similar peak velocity profiles as the singleton stops. Since singleton stops have higher peak velocity than true geminates, it is expected that when combined, the peak velocity of the concatenated geminates will be higher than the true geminates.

Variabilities are also expected in this result because a morpheme boundary is involved in concatenated geminates. Morpheme boundaries, according to the phase window model (Keating 1990) cause increased variabilities in the phonetic manifestation of the different phonetic parameters, hence it is possible that there will be increased variabilities in the concatenated geminates.

4. Results

A series of Linear Mixed effects models were run with different dependent variables including displacement, activation interval and peak velocity. One fixed effect was included that was a factor, Segment type. Segment Types had four factor levels-' singleton', 'true geminate', 'assimilated geminate' and 'concatenated geminates'. Simple coding was used in order to compare the different factor levels to the grand mean for one reference level each time. In the first model, the simple coding compared all the factor levels to singletons. In the second model, the simple coding compared the true geminates as to assimilated geminates and concatenated geminates. The Intercept was the grand mean of all the factor levels for both the models.

Peak velocity of Tongue Blade (TB) in the vertical dimension was compared first with singleton as the first factor level and compared with true, assimilated and concatenated geminates. No significant effect was found for Peak velocity of TB of singletons with true geminates (t value= -0.128, p value= 0.898). A significant effect was found for singletons and assimilated geminates (t value= 2.850, p value= 0.004) where assimilated geminates had higher peak velocity of TB. No significant effect was seen in the comparison of singleton with concatenated geminates (t value=-1.229 and p value= 0.219) (Figure 10).

No significant effect was found for Displacement of TB for singletons compared to true geminates (t value= -0.049, p value= 0.961) (Figure 11), no significant effect was found for displacement of TB for singletons compared to assimilated geminates (t value= 0.563, p value=0.574) and no significant effect was found for displacement of TB for singletons compared to concatenated geminates (t value= 0.026, p value= 0.979).

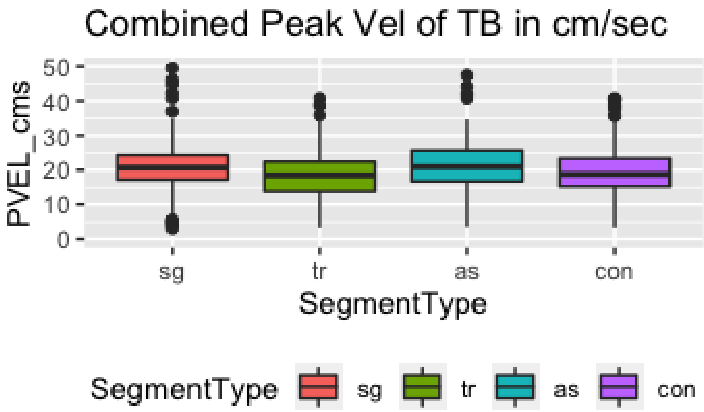

Figure 10. Combined tongue-blade peak velocity across segment conditions for all four subjects.

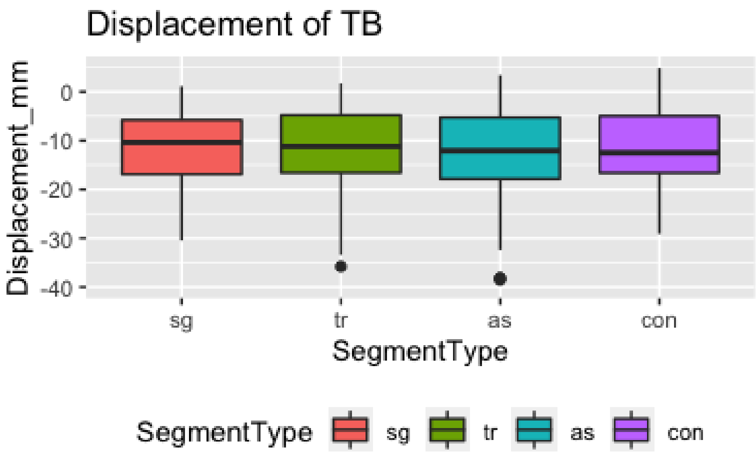

Figure 11. Combined tongue-blade displacement across segment conditions for all four subjects.

Significant effect was found for Activation Interval of TB for singletons compared to true geminates (t value = 2.212, p value= 0.027), with higher value of true geminates (Figure 12). Significant effect of activation interval of TB was found for singletons compared to assimilated geminates (t value= 3.528, p value= 0.0004) where assimilated geminates had higher activation interval. Significant effect was also found for singletons compared to concatenated geminates (t value= 2.339, p value= 0.019).

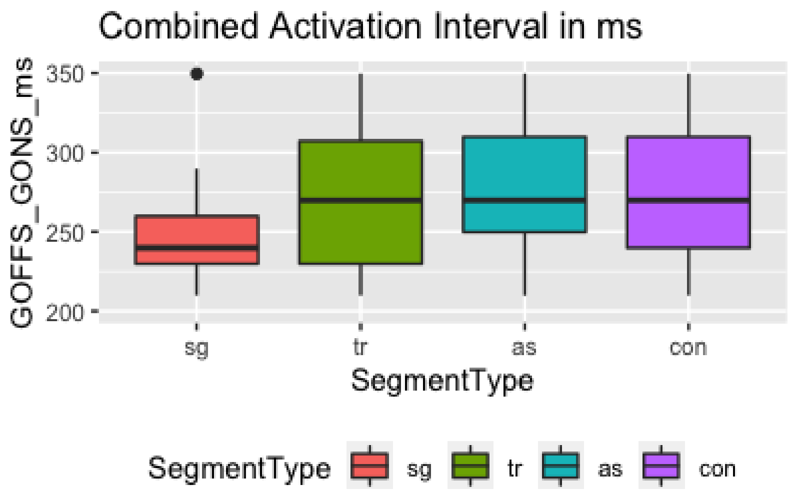

Figure 12. Combined tongue-blade activation interval across segment conditions for all four subjects.

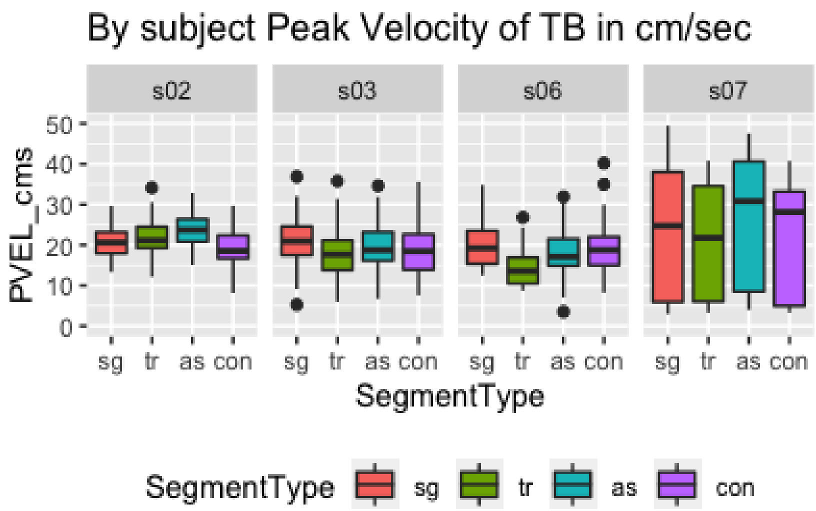

Figure 13. Individual tongue-body peak velocity across geminate conditions for all four subjects.

For the second comparison model the true geminates were compared with assimilated geminates and concatenated geminates. A significant result was seen in the comparison of peak velocity of TB between true geminates and the assimilated geminates (t value=2.850, p value= 0.004) (Figure 10), where assimilated geminates had higher peak velocity. No significant difference was found in the comparison between true geminates and the concatenated geminates (t value= -1.229, p value= 0.22) for peak velocity of TB.

When the true geminates were the first factor level, no significant effect was found in the comparison of displacement of TB between true geminates and the assimilated geminates (t value= 0.563, p value=0.574). No significant effect was also found between true geminates and concatenated geminates (t value= 0.026, p value= 0.979) for displacement of TB.

The same second linear mixed effects model was also run on the activation interval of TB, i.e. the time duration for which the geminate gesture of TB was active. When the true geminates were compared with assimilated geminates for activation interval, the results were significant (t value=3.528, p value= 0.0004), with higher values for assimilated geminates. The comparison of true geminates with concatenated geminates for activation interval was also significant (t value=2.339, p value= 0.019) with higher values of concatenated geminates.

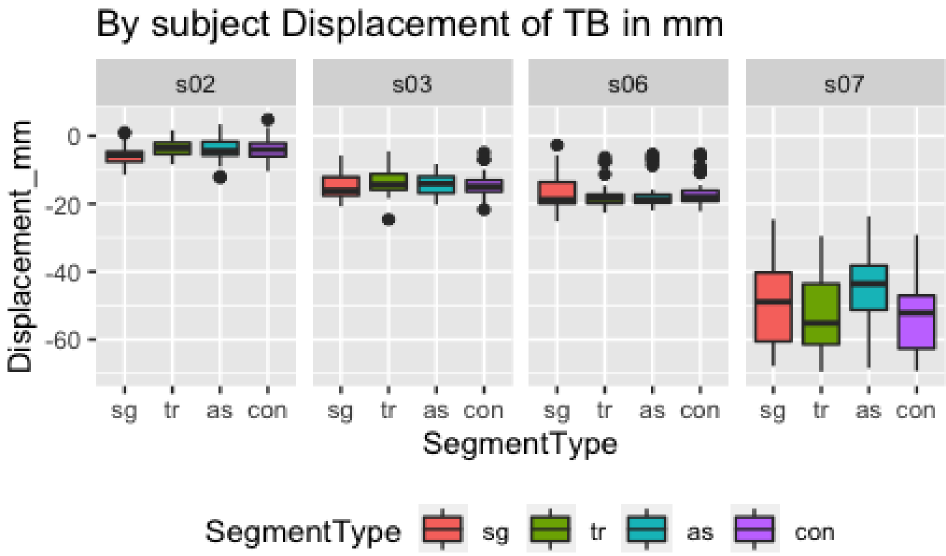

Figure 14. Individual tongue-body displacement across geminate conditions for all four subjects.

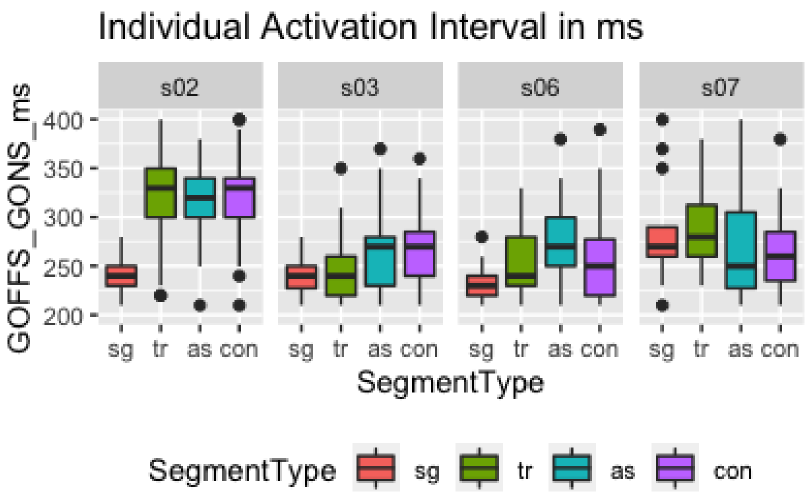

Figure 15. Individual tongue-blade activation interval across geminate conditions for all four subjects.

In order to check the individual patterns, individual results of four native speakers of Bengali were analyzed separately. Results show a higher peak velocity of Tongue Blade (TB) (Figure 13) in assimilated geminates than true geminates, even though their displacement profile (Figure 14) is the same as true geminates.

The interquartile range of the fourth subject (s07) in Figure. 13. and Figure. 14 indicates more variation in peak velocity and displacement values. The reason for the observed variation in the peak velocity and displacement for the fourth subject, which is also evidenced by their overall larger peak velocity values is that this subject had a faster speech than the others and his faster speech rate affected the articulatory parameters (Miller et. al.: 1984). However, the median indicates a similar pattern as the rest of the subjects, i.e. higher peak velocity of assimilated geminates compared to the true geminates. Results (Figure 13 and 14) from individual subjects show that there are some differences among the four subjects in peak velocity profiles. Three subjects (s02, s03 and s07) show lower peak velocity in concatenated geminates while one of the subjects (s06) show higher peak velocity for concatenated geminates than true geminates. The individual tongue-blade activation-interval patterns across the geminate conditions are shown in Figure 15.

Linear mixed effect model with simple coding was also tested in case of the Jaw movement measurements. For the peak velocity measurements analysis, no significant effect was found for comparison between singletons and true geminates (t value= -1.020, p value= 0.308), no significant result was also seen for the singleton and assimilated geminate comparison (t- value=1.099, p value= 0.2724) and no significant results were also seen between singletons and concatenated geminates (t value= -0.070, p value= 0.9442). The combined jaw peak-velocity results across segment conditions are shown in Figure 16.

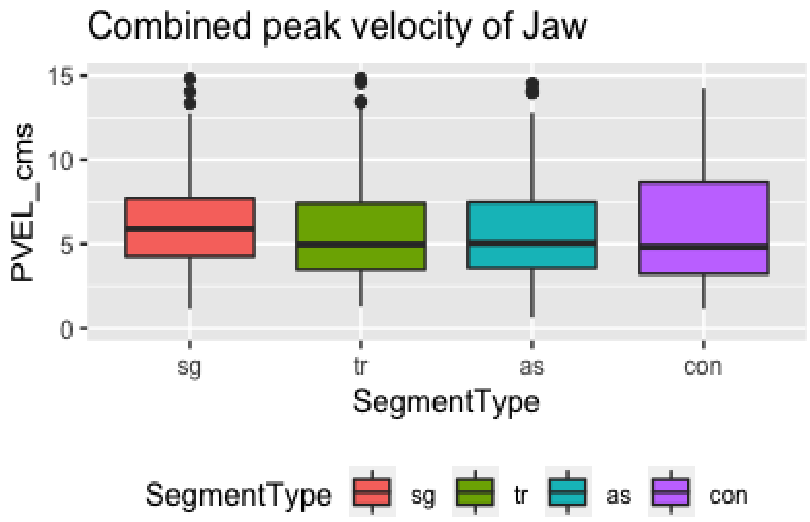

Figure 16. Combined jaw peak velocity across segment conditions for all four subjects.

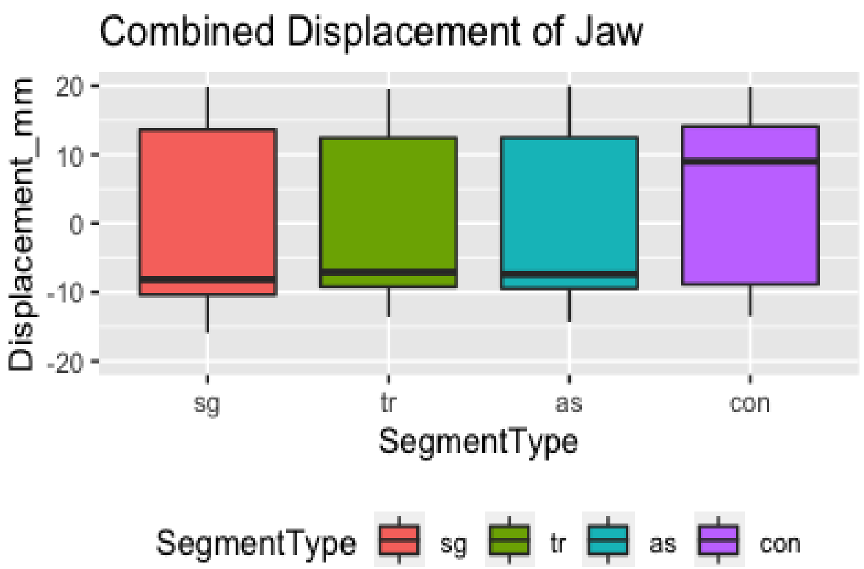

Figure 17. Combined jaw displacement across segment conditions for all four subjects.

Similarly displacement results were also not significant between singletons and true geminates (*t* value =-0.067, *p* value=0.946), singletons and assimilated geminates (*t* value =0.340, *p* value =0.734) and singletons and concatenated geminates (*t* value= 0.480 and *p* value=0.631). For the activation interval measure, the results were significant between singletons and true geminates (*t* value= 2.532, *p* value= 0.011) where true geminates were higher, no significant effect but a trending effect was seen in singletons and assimilated geminates (*t* value=1.492, *p* value= 0.136) where assimilated geminates were higher and no significant effect for singletons and concatenated geminates (*t* value= -0.484, *p* value= 0.628719). The combined jaw displacement results are shown in Figure 17, and the jaw activation-interval results are shown in Figure 18.

All three dependent variables for Jaw measurements were also compared using the second model, i.e. true geminates compared with assimilated geminates and concatenated geminates respectively. For peak velocity measures, no significant results were seen when the true geminates were compared to assimilated geminates (*t* value=-1.020, *p* value= 0.3083), no significant results were seen for true geminates and concatenated geminates comparison either (*t* value=1.099, *p* value= 0.2724).

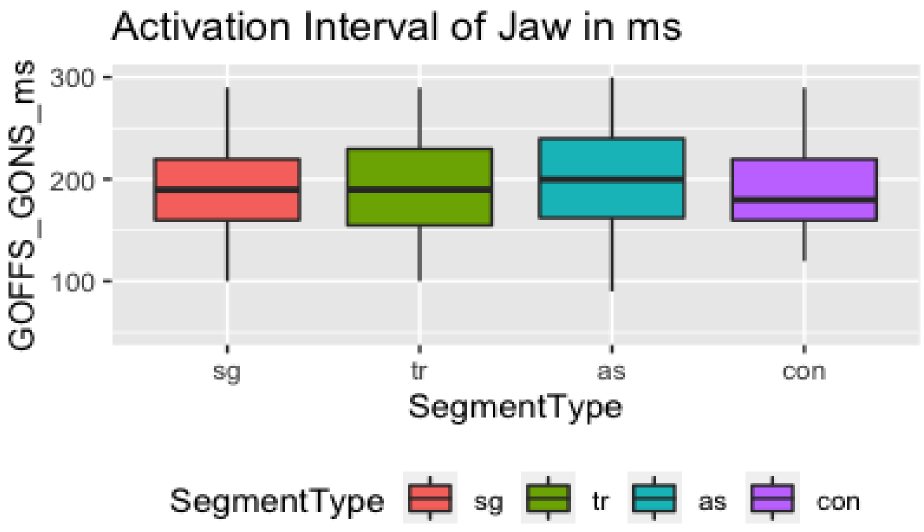

Figure 18. Jaw activation intervals across segment conditions for all four subjects.

Displacement values of the Jaw also did not show any significant results with true geminates comparison with assimilated geminates(*t* value= -0.067, *p* value=0.946) and with concatenated geminates (*t* value=0.340, *p* value= 0.734). The activation intervals of Jaw were also compared between the three geminate types. No significant effect was seen for true geminate and assimilated geminate comparison (*t* value= 1.099, *p* value= 0.2724) and no significant effect was seen for the comparison of true and concatenated geminates (*t* value= -0.070, *p* value=0.944).

5. Discussion

The comparison of Tongue blade gestures for the geminate types with the singletons showed that there is a significant effect of peak velocity when compared to assimilated geminates where assimilated geminates have higher peak velocity than singletons, while true geminates and concatenated geminates pattern together and they are found to be lower peak velocity than that of the singletons, although this difference was not significant. The result from true and concatenated geminates compared to singletons patterns similarly with the observation of Löfqvist where the Tongue Blade gestures in geminates were found to have slower speed. The fact that the assimilated geminates are faster in speed, shows that they do not pattern like the other geminates. This may indicate that there may be an influence of a rhotic on the overall sequence. Rhotics in Bengali have been previously described as approximant-like (ud Dowla Khan, 2010) or like a tap articulation (Dasgupta, 2003). Although the specific findings were not perfectly in-line with the hypothesis surrounding the presence of a rhotic gesture which was expected to be approximant-like, they are nonetheless consistent with the presence of a rhotic gesture which is like a tap articulation. According to an articulatory investigation of rhotics in a related language, Tamil, taps were found to have higher peak velocity than other rhotic types. It has also been reported that rhotics in Bengali can be realized as taps when they are before dental stops (Dasgupta, 2003). This points to the fact that the assimilated geminates maybe articulated with higher gestural stiffness, a pattern seen in Tamil taps that had higher peak velocity than other types of coronals (Narayanan *et. al.,* 1999). The Tamil study reported high constriction formation peak velocity for taps compared to dental stops. Since the assimilated geminates have higher peak velocity despite the similar displacement measures, this could mean that the assimilated geminates are articulated with a tap in the initial part of the gesture. Since there is evidence of a tap-like rhotic initiation in assimilated geminates, this result supports the prediction that the assimilated geminates are not completely neutralized.

Hence, this finding shows that the prediction of Distinctive Feature Theory, that all articulatory parameters of the assimilated geminates will be identical to that of the true geminates, does not hold true for the current data from Bengali. Although the acoustic investigations by Lahiri and Hankamer (1988) supported the Distinctive Feature Theory, i.e. the acoustic measurements did not show any significant differences between the phonetic manifestations of assimilated vs true geminates, articulatorily the assimilated geminates have different phonetic manifestations from true geminates. The current findings however support the prediction of the Articulatory Phonology theory that the rhotic and the dental stop gestures could have different degrees of overlap, so even when they sound similar, articulatorily they can still be non-identical.

There was a significant difference between the tongue blade gestures for true geminates vs concatenated geminates' activation intervals where concatenated geminates were slightly longer in duration than true geminates. While no significant differences were found between concatenated and true geminates for peak velocity and displacement measures, the activation interval for concatenated geminates when compared to true geminates were found to be significant. This indicates that the concatenated geminates have longer duration than true geminates. This could be an effect of the morpheme boundary because it was predicted by previous studies that morpheme boundaries have an effect on the timing relations of consonant sequences across the morpheme boundary (Keating, 1990). The phase window model (Byrd, 1994) suggests that one way of allowing variability in timing is through allowing a range of possible timing relationships. The model predicts that within the same morpheme the timing window allowed for variability is much shorter while the timing window spanning across two morphemes has a wider timing window. Zsiga (1997, p 268) also points out that timing relation between gestures becomes less stable as they go higher in the prosodic hierarchy (segment, syllable, word, phrase), which means that within a same morpheme, two segments are more closely coarticulated, but across the morpheme boundary they are less tightly coarticulated. More overlap is expected in more tightly coarticulated sequences and less overlap is expected in less tightly coarticulated sequences, which could increase the timing of a sequence. Since the concatenated geminates are two identical gestures, this longer duration of the overall sequence could be because of lesser overlap between the gestures because the timing window is larger to allow for more variability. Additionally, it was also reported by previous studies which investigated dissimilar consonant sequences (Cho, 2005) that the consonant-consonant phase timing is longer for sequences involving consonants across a morpheme boundary. Cho (2005) studied Korean consonant sequences with one set having a morpheme boundary vs another without a morpheme boundary. They observed that there was a significant effect of word internal morpheme boundary in homophonous word pairs such as "pani" vs "pan-i". They found that the words involving a morpheme boundary had different phonetic manifestations, i.e. their intergestural timing was longer which showed that they were sensitive to the morpheme boundary allowing for more room for variability. Although the study on Korean compared the timing relations using the C-Centre effect, the intergestural variability indicated in sequences with morpheme boundaries was more, i.e. they were reflective of the phase window model's prediction that sequences across boundaries show greater variability. The current study does not investigate a CV sequence using the C-Centre effect, but the longer duration of the concatenated geminates compared to true geminates indicates an effect of the morpheme boundary which introduces some timing variability. Nonetheless, from the results it is clear that the morpheme boundary information is not completely erased as predicted by the Tier Conflation theory and Bracket Erasures theory, morphological information is still encoded in the articulatory manifestation of the concatenated geminates.

Peak velocity and displacement values of concatenated geminates were not significantly different from that of true geminates. This could be due to the fact that when the first stop attains its target, the second one begins from the same position. Due to an overlap between the two dental stops, there is no release of the first segment, as that is overlapped by the second part of the sequence which is the same stop. Hence the tongue blade velocity and displacement is not different from what is seen for true geminates. This unreleased closure gesture when overlapped by the following stop's closure gesture may make the concatenated geminates also be interpreted as one long gesture instead of two gestures, however, interpreting them as two gestures instead of one single geminate gesture in this case may be more appropriate. This is because the activation interval is significantly higher from true geminates, confirming the difference between the nature of the two kinds of geminates and that concatenated geminates have more timing variability.

The results also show no difference in peak velocity between singletons and true geminates, and singletons and concatenated geminates contrary to what has been reported in previous results. This result is like the results seen in Japanese bilabial geminates (Löfqvist, 2005), where singletons and geminates did not have any difference in peak velocity. However, the Japanese geminates were significantly different from singletons in terms of displacement of lip gestures. For Japanese (Löfqvist, 2005) it was concluded that the speakers control the position of the virtual target when the peak velocity of the lower lips were same for both singletons and geminates, but the displacement of the geminates were higher. The study also concluded that the speakers control the timing of when the target is reached. From the current results from Bengali, true geminates and the concatenated geminates rely more on the difference in activation duration to set them apart from singletons and not on the peak velocity and displacement of the Tongue blade. The true and concatenated geminate gestures are activated for longer durations than the singletons.

Additionally, results also show that concatenated geminates are more similar to true geminates in terms of peak velocity than assimilated geminates. This is also indicative of the different articulatory nature of the assimilated geminates. The assimilated geminates being higher in peak velocity compared to both true and concatenated geminates, confirms the hypothesis that there can be a remaining rhotic gesture imparting an effect on the peak velocity of the overall gesture of the assimilated geminates. Since both concatenated and true geminates do not have a rhotic component in the sequences, they do not have the higher velocity. What these findings tell us about the overall phonological status of the geminates is that both concatenated and assimilated geminates are not identical to true geminates in their phonetic manifestation, contrary to what Distinctive Feature Theory predicts, hence the feature spreading analysis of the assimilated geminates and tier conflation analysis of the concatenated geminates, may not be sufficient to account for the articulatory nature of these sequences.

6. Conclusion

In conclusion, the findings of this study do not support the predictions of the Distinctive Feature Theory because in both the comparisons, assimilated vs true geminates and concatenated vs true geminates, there are differences in the phonetic manifestations. Assimilated geminates show evidence of incomplete neutralization where traces of the rhotic articulation remain, this supports the predictions of articulatory phonology and concatenated geminates show variability in timing compared to true geminates which also support the predictions of articulatory phonology. While perceptually both the derived geminates may sound similar to the true geminates, the gestures show different phonetic manifestations. Further investigation of the gestures may reveal how the acoustic similarities occur in the acoustic data while the articulatory gestures reveal that the derived geminates are non-identical to the true geminates. Furthermore, learning more about the nature of the rhotics would help understand the nature of the assimilated geminates. As for the geminate and singleton comparison, the geminate pattern is similar to the Japanese geminates in that they are slower in velocity than the singletons. However, the Japanese geminates also show higher displacement values, which indicate a different virtual target of the geminates. However, the Bengali true geminates were not significantly different from the singletons in displacement measures, which points to the fact that they probably have the same displacement but are differentiated mainly by their activation interval measures.

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Conflict of interest

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