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The timing of geminate consonants

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In current phonological theory, geminate consonants are distinguished from non-geminates by a difference in units on the timing tier in an autosegmental representation, other features being the same; and while there are geminates of three kinds according to how they arise (tautomorphemic, concatenated, and derived by total assimilation), the representation of all three on the timing tier is the same. The present paper investigates two questions: what exactly is the acoustic difference between geminate and non-geminate consonants (focusing on voiceless stops); and are there acoustic differences between geminates derived from different sources phonologically. We examined two unrelated languages, Bengali and Turkish, and found that the single overriding cue distinguishing geminate from non-geminate stops is the duration of the closure. In Bengali, we examined geminate stops derived from the three different sources and found no significant difference in closure duration. Thus the autosegmental representation of the difference between geminate and non-geminate consonants in terms of a timing difference is vindicated, and we have an acoustic correlate for the timing measure. As a secondary result, we have shown that total assimilation leading to the formation of a geminate constitutes an instance of neutralization that is phonetically complete.

1. Introduction

In this study we investigate some of the timing properties of geminate consonants in two unrelated languages, Turkish and Bengali. Catford (1977, p. 210), noting that phonetically long consonants may be ambisyllabic or tautosyllabic and heteromorphemic or tautomorphemic, proposes to reserve the term "geminate" for tautomorphemic ambisyllabic consonants (cf. also Lehiste, 1970, p. 45). In our study, we do not consider any tautosyllabic long consonants; in fact, for various reasons, our investigation is limited to intervocalic voiceless stops. We are, however, specifically interested in the question whether heteromorphemic long consonants differ significantly from tautomorphemic ones phonetically as well as phonologically. In this paper, we use the term "geminate" to mean a phonetically long consonant, whether tautomorphemic or heteromorphemic.

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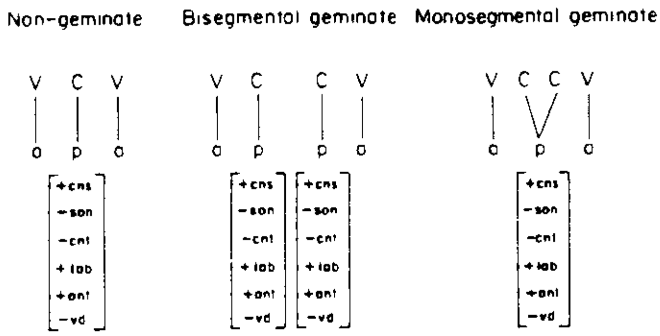

Figure 1. Representations of a non-geminate stop, a bisegmental geminate stop and a monosegmental geminate stop.

It is well established that heteromorphemic and tautomorphemic geminates differ in phonological behavior. Tautomorphemic -rr- in Malayalam becomes [tt] while heteromorphemic -rr- does not: /arr-il/ 'river-LOC' becomes [attil] as against /dur-rani/ 'bad queen', which remains [durrani] (Mohanan & Mohanan, 1984). In Tigrinya, velar stops become fricatives in postvocalic position: /ʔa-kalib/ 'dog plural' > [axalib], while a tautomorphemic geminate remains: /yi-k'abbir/ 'he buries' > [yikkabbir]; but the first part of a heteromorphemic geminate becomes a fricative: /mirak-ka/ 'calf 2sg masc' > [miraxka] (Hayes, 1986, referring to Schein, 1981 and Kenstowicz, 1982).

The representational framework of autosegmental phonology provides a principled account of this differential behavior in terms of the phonological representations assigned to tautomorphemic and heteromorphemic geminates and the ways in which phonological rules may apply to them. In autosegmental phonology, long vowels and geminate consonants are represented as differing from the corresponding short vowels and single consonants in the number of units on the timing (CV) tier (see, for example, Leben, 1980; Clements & Keyser, 1983; Hayes, 1986). This is intended to reflect the fact that the difference between short and long vowels, and between single and geminate consonants, is essentially one of timing, with other features being the same. Those segmental features not directly reflecting timing, or the CV structure, are represented on a separate level, called the melodic tier. Melodic tier and timing tier representations are related by association lines, which indicate which timing position each melodic element corresponds to.

The autosegmental framework allows for two possible representations for a geminate consonant: the two C elements on the timing tier may each be linked to a feature matrix on the melodic tier, the two feature matrices being identical; or the two C elements may be linked to a single feature matrix on the melodic tier. Following Schein & Steriade (1986), we will refer to these two representations as bisegmental and monosegmental, respectively. Figure 1 illustrates the representations for a non-geminate stop, a bisegmental geminate stop, and a monosegmental geminate stop.

McCarthy (1986) argues that a universal condition (the Obligatory Contour Principle, cf. Leben, 1973, 1978; Goldsmith, 1979; McCarthy, 1979) requires that underlying tautomorphemic geminates be monosegmental in underlying (as well as surface) representation. Heteromorphemic geminates must underlyingly be bisegmental, though McCarthy suggests that these too come to be monosegmental in surface representation as a result of tier conflation. In all cases, the essential difference in representation between geminates and non-geminates, at any level, is the number of units on the timing tier.

Discussions of geminate consonants within the autosegmental framework have not been very explicit about which articulatory or acoustic features this representation

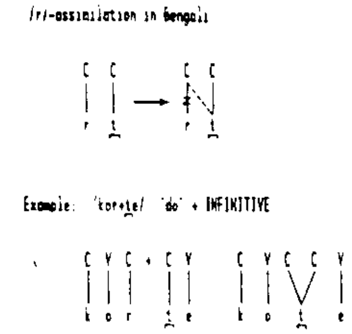

Figure 2. Representation of a geminate stop derived by total assimilation.

is supposed to reflect. It is generally assumed in informal descriptions that what distinguishes geminate from non-geminate consonants acoustically is duration. There are surprisingly few studies, however, aimed at determining experimentally the acoustic correlates of consonant length, and they have not been entirely consistent in the measures taken. Lisker (1974, pp. 2401–2405) discusses the question of acoustic measures corresponding to length in consonants and vowels, and notes that practice has not been uniform or even always explicit. In particular, investigators have not been consistent regarding whether VOT is included as part of the duration of the consonant. Thus, both informal and formal phonological descriptions rely on an impressionistic notion of consonant length, not clearly related to well-defined acoustic cues. One of the purposes of this paper is to establish firmly, for two languages, that the acoustic cue distinguishing geminate from non-geminate stop consonants is in fact a duration measure, specifically the duration of the closure of the stop.

Another question that arises in connection with the phonological representation of geminates is whether geminates that are phonologically derived, either by concatenation of identical consonants across a morpheme boundary or by total assimilation (either across a morpheme boundary or within a morpheme), differ acoustically from underlying geminates, which do not require a process of derivation. Figure 2 illustrates the derivation of a geminate arising from total assimilation.

Phonologically, geminates of these three kinds differ at least in underlying representation, though perhaps not in surface representation; and in any case their "timing" representations at both underlying and surface levels are non-distinct. The autosegmental representation, then, if interpreted straightforwardly, would appear to claim that the three types of geminates should be non-distinct in timing, and hence non-distinct acoustically. On the other hand, geminates derived by total assimilation represent a case of neutralization. Whether or not all instances of phonological neutralization lead to phonetic neutralization is still a matter of debate (cf. Dinnsen, 1985; Lahiri, Schriefers & Kuijpers, 1987). In this light, it is also of interest to us to determine whether geminates of the three different phonological origins are acoustically distinct or not.

In this paper we report on studies designed to determine experimentally differences between geminate and non-geminate voiceless stops in both Turkish and Bengali. In particular, we address the question of whether there is one overriding acoustic cue distinguishing geminate from non-geminate voiceless stops, and whether it is the same cue in both languages. For Bengali, we also investigate whether geminate stops derived by morpheme concatenation or by total assimilation differ from each other or from underlying tautomorphemic geminates.

2. Previous work on geminates

Previous experimental work on geminates has mainly taken the form of perception experiments involving artificial manipulation of the duration of closure. Such studies include investigations of tautomorphemic and heteromorphemic geminate consonants in different languages. No previous study has systematically dealt with both cases in a single language.

Lisker (1958) measured closure durations for short and long voiceless stops in Italian, Swedish, Marathi and Telugu. He found variation depending on length and speed of utterance, but the long stops were generally of greater duration than the short ones. In a perception experiment, two recorded Marathi words (*matə* 'mind' and *mattə* 'drunk') were artificially manipulated to increase the closure duration of the first and decrease the closure duration of the second in 20 ms steps. For the Marathi speaker who produced the original test items, the artificial stimuli produced from original *matə* passed to being perceived as *mattə* when the closure duration increased from 140 to 160 ms; the stimuli from original *mattə* passed to being perceived as *matə* when the closure duration decreased from 140 to 120 ms. Lisker concluded that cues other than duration of closure produced only about a 20 ms shift in the boundary value between /t/ and /tt/. He did not speculate on what the other cues might be.

Several other studies have employed some version of the incremental variation technique to localize the perceptual boundary between short and long (or single and double) consonants. Pickett & Decker (1960) artificially lengthened the closure duration of the /p/ in the word *topic* to cause the stop to sound double. Their results showed that /p/-closures longer than 250 ms in normal rate of utterance were judged as double consonants by English-speaking subjects. Obrecht (1965) used artificially manipulated stimuli to localize the perceptual boundary between geminate and non-geminate consonants in Arabic. Varying the closure duration for intervocalic /b/, duration of the nasal resonance for intervocalic /n/, and duration of frication noise for initial /ṣ/, he determined that the perceptual boundaries were between 140–160 ms for /b/–/bb/ and /ṣ/–/ṣṣ/ contrasts, and 90–110 ms for /n/–/nn/. Obrecht concluded that duration is a strong cue in discriminating between geminate and non-geminate consonants in Arabic. Repp (1978, 1983), by systematically varying the closure interval of synthetic VCV stimuli, showed that more than 200 ms of silence was needed for English-speaking subjects to perceive the stop as a geminate rather than a single consonant.

These studies have established that duration of closure is a significant cue in the perception of single versus geminate consonants. However, as Maddieson (1985) reports, several studies on vowel duration indicate that vowels preceding geminate consonants tend to be shorter than those preceding single consonants. Thus, there appears to be a possibility that vowel duration may interact significantly with closure duration in differentiating geminates from single consonants. Similarly, differences in VOT might provide a significant cue. No study has systematically investigated the role of possible cues other than closure duration in the perception of single and geminate consonants.

3. New experiments

To study the acoustic features of geminates we first investigated geminate stops in Turkish, comparing geminate and non-geminate stop consonants in similar environments. Turkish has tautomorphemic geminates, heteromorphemic geminates derived by assimilation, and geminates resulting from the concatenation of homorganic consonants across morpheme boundaries. In this first experiment we did not distinguish between these types. Because heteromorphemic geminates are relatively rare in modern standard Turkish, direct comparisons between the types at the same point of articulation are hard to find in sufficient numbers.

We contrasted intervocalic voiceless geminate and non-geminate stops. Besides duration of stop closure, we took two other measures: length of the preceding vowel, and VOT following the release. Since words with a geminate consonant have the structure (C)VC.CV(C), the first syllable is closed. Given the overall tendency of vowels to be shorter in a closed syllable, the length of the vowel in the first syllable could be a potential cue for a geminate consonant. Similarly, a difference in VOT could turn out to be significant as an acoustic difference between geminates and non-geminates.

3.1. *Production*

Three paid male subjects were asked to read 18 pairs of Turkish words three times in a different randomized sequence. The words are listed in the Appendix. All the subjects were native speakers of Turkish who also spoke some Dutch and very little English. Each word was written out on a separate index card and the subjects were asked to read at a normal rate of utterance. Twenty of these words were in minimal pairs differing only in their intervocalic consonants. The other words were not in minimal pairs, but they were in near minimal pairs, in which the preceding and following vowels were the same and the stress patterns were identical. The consonants examined were [t] *vs.* [t:] and [k] *vs.* [k:], because the language provides the maximum number of contrasts between geminates and non-geminates in voiceless stops at these places of articulation.

The words were recorded on a Nagra 4.2 tape recorder with an AKG microphone. All stimuli were then digitized using a 10 kHz sampling rate with a 5 kHz low pass filter setting. Measurements were made using a waveform editor at the Max-Planck speech laboratory. For each of the 324 words, the duration of the preceding vowel was measured from the onset of the vocalic formant structure to the beginning of the closure; the duration of the closure was measured from the offset of the preceding vowel up to the onset of the burst; and the voice onset time was measured from the onset of the burst to the onset of the vocalic formant structure of the following vowel.

The mean durations (in ms) of each measurement across all speakers are shown in Fig. 3.

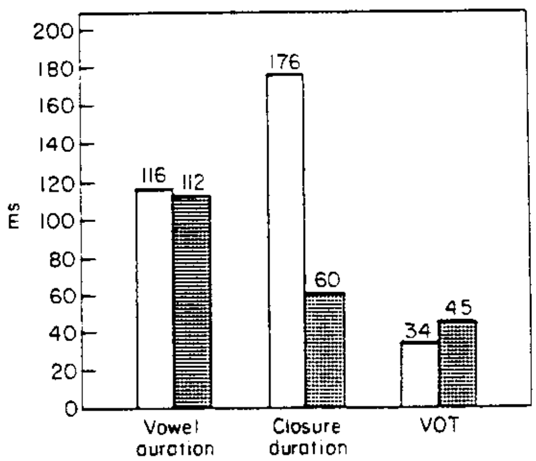

Figure 3. Mean measures of the duration of the preceding vowel, duration of closure, and the VOT of Turkish geminate (□) and non-geminate (▨) stops.

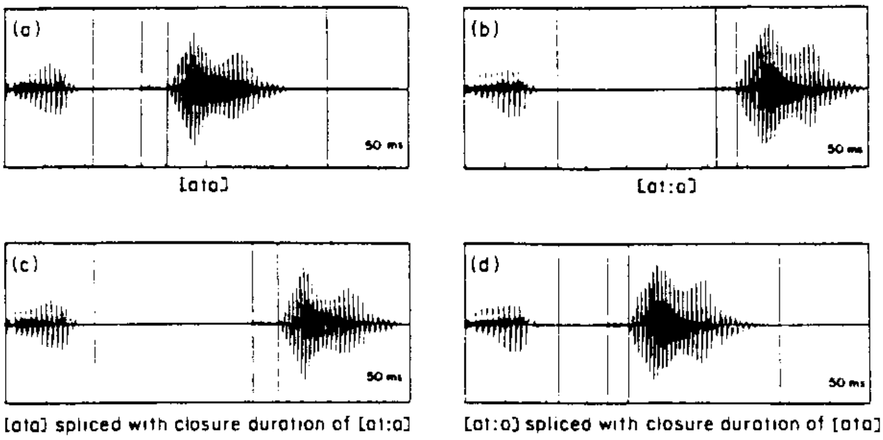

Figure 4. Sample waveforms of Turkish geminate and non-geminate original and cross-spliced stops: (a) and (b), waveforms of the Turkish words [ata] and [at:a], respectively; (c) and (d), waveforms of the cross-spliced versions of these words where the closure durations of the two words have been interchanged keeping everything else constant.

As Fig. 3 indicates, the duration of the preceding vowel varies very little, and a t-test on the means showed no overall significant effect ($p = 0.163$). Although the overall difference in VOT was only 11 ms, a t-test on the means showed a significant effect ($p < 0.001$). This was an overall effect; the difference was not significant for every speaker.

The closure duration shows a dramatic difference, the average duration for geminate stops being almost three times the duration of the non-geminate stops. A t-test on the means of course showed a significant overall effect ($p < 0.0001$).

3.2. *Perception*

We know from earlier studies that increasing the silent interval of the closure of synthetic stimuli does change the percept of consonants both in languages having tautomorphemic geminates and in languages which have double consonants over a word or phrase boundary. In our production study of Turkish stops, we find that there is not only a significant difference in the closure duration, but also in the VOT. To examine the saliency of the closure duration we next performed a perception experiment not by incrementally increasing the silent interval, but by cross-splicing the closure duration of the geminate and non-geminate consonants, keeping everything else constant. Sample waveforms of original and cross-spliced stimuli are given in Fig. 4.

Of the 18 pairs of stimuli used for the production experiment, there were 10 minimal pairs. We chose these 10 pairs of words spoken by the second speaker for the perception test. For each stimulus the closure duration was extracted and substituted into the other member of the minimal pair. Thus we had in all 40 stimuli: 10 original geminates, 10 original non-geminates, and 20 artificial stimuli made from the 20 originals by cross-splicing the closure durations. There were 20 different Turkish words which were used as fillers.

The 20 original test words were randomized with the fillers in one block and the 20 cross-spliced words were randomized with the fillers in a second block. Two test tapes were made. On the first tape, the original stimuli and the fillers were recorded first, followed by the cross-spliced stimuli (and fillers). On the second tape the order was

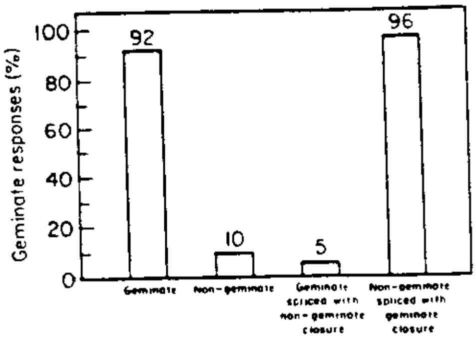

Figure 5. Results of the perception experiment (free choice) with original and cross-spliced stimuli.

reversed. The inter-stimuli interval was 4 s, with a 6 s interval after every block of 10 stimuli. There was no gap between the original stimuli and the cross-spliced stimuli, so we assume that the subjects were not aware of any difference in the order of presentation of the original and the cross-spliced stimuli. There were also 10 practice-items at the beginning of each tape.

Five native speakers of Turkish listened to each tape. The subjects were asked to listen to each word and write down what they heard. They were told that each word they heard was a real word of Turkish. After they had done this test they were asked to do a forced choice test where the minimal pairs had been written out on the answer sheets. The same tapes were used and the subjects were told to ignore the filler items. There was no significant difference in the results. The results of the free-choice experiment are given in Fig. 5.

The results in Fig. 5 clearly show that the closure duration is perceptually a significant cue in distinguishing geminate and non-geminate consonants. All other factors remaining constant, cross-splicing the duration of stop closures succeeded in changing the percept of the geminates to non-geminates and vice-versa.

Since the difference in VOT was also significant in the production data we decided to check and see whether this measure could be as strong a cue as the duration of closure. Given the magnitude of the difference in closure duration between geminates and non-geminates, and the fact that cross-splicing this portion succeeded in overriding all other cues, cross-splicing the VOT alone seemed unlikely to change the percept of the consonants. Nevertheless, we interchanged the VOT of the same pairs of words we used for the previous experiment and ran a pilot study with two subjects. The effect was essentially nil. Except for one token, responses to the manipulated stimuli did not differ from those to the original.

4. Underlying and derived geminates

Surface geminates, as we mentioned earlier, arise from three different sources with (initially at least) three different phonological representations. Underlying tautomorphemic geminates are represented initially (and thereafter) as two timing slots associated with a single melodic segment, i.e. as monosegmental. Heteromorphemic geminates may arise by concatenation of identical consonants at a morpheme boundary and have (initially) two timing slots each associated with a melodic segment. A third source of geminates is by total assimilation.

It has been argued (e.g. Halle & Vergnaud, 1980; Steriade, 1982; Hayes, 1986) that total assimilation involves the spread of the features of one segment onto the other, creating a structure with two timing slots linked to a single melodic element (i.e. a monosegmental representation). McCarthy (1986) has argued that through tier conflation the geminates arising by concatenation of identical segments also come to have a representation with two timing slots linked to a single melodic segment (a monosegmental representation). Thus, if these arguments are accepted, all geminates, no matter what their source, should be monosegmental in surface representation.

We are interested in the question whether there is any acoustical difference between geminates of different origins. If, for example, heteromorphemic and tautomorphemic geminates turn out to differ in length, that would argue against their having identical surface representations and would also cast doubt on the interpretation of the slots on the CV-tier as "timing" elements. (Unless, of course, they are sufficiently abstract timing elements, and then the question is again what relation they have to observable timing properties.) Since geminates derived by total assimilation present a case of phonological neutralization, we are also interested in this question because of its relevance to the conjecture of Dinnsen (1985) that phonological neutralization does not necessarily give rise to phonetic neutralization. Consequently we might expect these assimilation-derived geminates to differ acoustically from underlying geminates, and, presumably, from geminates arising by direct concatenation without assimilation.

In order to investigate these questions, we examined Bengali, which has geminates of all three types in greater abundance than Turkish, where direct contrasts at the same place of articulation were somewhat difficult to find.
Examples:

underlying:	/pat̪:a/	→	[pat̪:a]	'whereabouts'
concatenated:	/pat̪+t̪e/	→	[pat̪:e]	'spread out' infinitive
assimilated:	/kor+t̪e/	→	[kot̪:e]	'do' infinitive

Cf. /kor+i/ → [kori] 'do' 1st pers sing. The productive postlexical phonological rule involved in the last example affects /r/, assimilating it totally to a following coronal stop. For a thorough description of Bengali phonology and morphology see Chatterjee (1975).

4.1. *Method*

Three native speakers of Bengali read 24 words, 12 containing geminate consonants and 12 containing only non-geminates. Of the 12 containing geminates, there were four of each type—underlying, concatenated and assimilated. Each speaker read the words three times in a different random order. The words are listed in the Appendix. As in the Turkish experiment, we took three measures: duration of the closure, duration of the preceding vowel, and VOT. The results are given in Figs. 6 and 7.

4.2. *Results*

As in Turkish, the closure duration is significantly different ($p = 0.000$) between geminates and non-geminates. The difference between the means is almost exactly the same as in Turkish (about 120 ms), but since both geminates and non-geminates are longer in Bengali than in Turkish, the relative difference is less, geminates being about twice as

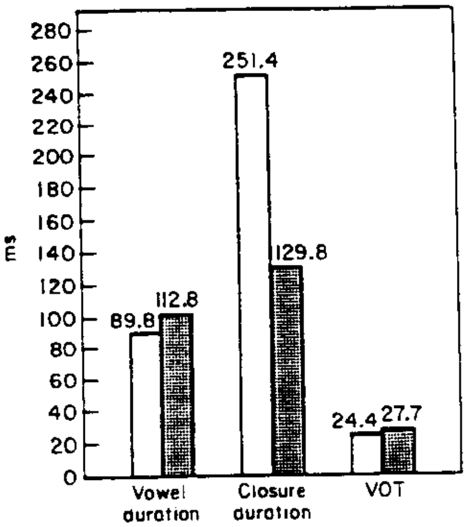

Figure 6. Mean measures of the duration of the preceding vowel, duration of closure, and the VOT of Bengali geminate (□) and non-geminate (▩) stops.

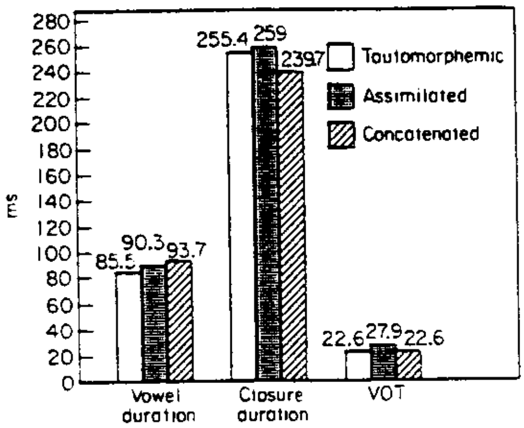

Figure 7. Mean measures of the duration of the preceding vowel, duration of closure and the VOT of tautomorphemic, assimilated and concatenated geminates in Bengali.

long as single stops in Bengali as opposed to about three times as long in Turkish. The mean difference in vowel duration is marginally significant overall ($p = 0.002$), though (as was the case with VOT in Turkish) not significant for every speaker. There is no significant difference in the VOT.

When we compared the three different kinds of geminates, we found absolutely no acoustic differences. A three way ANOVA, with utterances as the random variable, shows no significant differences in any of the three measures (vowel duration, $F(2, 4) = 0.1800$, $p = 0.8417$; closure duration, $F(2, 4) = 0.4721$, $p = 0.6545$; VOT, $F(2, 4) = 2.3410$, $p = 0.2723$).

5. Conclusion

We have established that in the two languages studied, Turkish and Bengali, the critical acoustic feature distinguishing geminate from non-geminate stops is the duration of the closure. A cross-splicing experiment in Turkish demonstrated the perceptual saliency of the difference in duration of closure and showed that it overrides all other cues. While the other acoustic measures were sometimes significant (VOT in Turkish, vowel duration in Bengali), they were not found significant for all speakers, and neither was significant overall for both languages.[1]

We have also shown that in Bengali, there is no significant acoustic difference between geminates of different origins. Tautomorphemic and heteromorphemic geminates are indistinguishable acoustically and geminates derived by total assimilation are indistinguishable from other types of geminates. A consequence of this last observation is that in this case at least phonological neutralization leads to phonetic neutralization.

These results provide support for the autosegmental representation of geminates as differing from non-geminates in timing, and for an interpretation of that representation according to which the relevant timing measure is the duration of the closure, at least for voiceless stops. Also supported is the assignment of identical timing representations to all kinds of geminates, since it has been found that they do not differ from each other acoustically.

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[1]John Ohala has suggested that we should test this result further by constructing stimuli with incremental variation in the duration of consonant closure (by manipulation of original non-geminates) and decremental variation (by manipulation of original geminates) and have subjects identify them (adopting the method used by Lisker, 1957, 1958: see also Elugbe & Hombert, 1975). Failure of the two ID functions to coincide would betray the existence of cues other than length, whereas if the functions were found to coincide it would be firmly established that length of closure is the only significant cue. This experiment is under way.

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Appendix

Turkish

Non-geminate		Geminate	
ata	horse-DAT	at:a	horse-LOC
atɯ	horse-ACC	at:ɯ	throw-PAST
batɯ	west	bat:ɯ	sink-PAST
dɛmɛtɛ	bunch-DAT	dɛmɛt:ɛ	bunch-LOC
ɛtɛ	meat-DAT	ɛt:ɛ	meat-LOC
ɛti	meat-ACC	ɛt:i	do-PAST
ota	grass-DAT	ot:a	grass-LOC
sa:te	clock-DAT	sa:t:ɛ	clock-LOC
jata	Yacht-DAT	jat:a	yacht-LOC
jatɯ	yacht-ACC	jat:ɯ	lie down-PAST
akɯ	white-ACC	hak:ɯ	right-ACC
batar	sink-AOR	bat:anijɛ	blanket
čatal	fork	hat:a	line-LOC
dikɛn	thorn	sik:ɛ	Dervish's cap
lɛkɛ	spot	mɛk:ɛ	Mecca
oka	arrow-DAT	ok:a	(a measure of weight)
rakɛt	raquet	tak:ɛ	skull-cap
sakal	beard	bak:al	grocer

Bengali

Non-geminates		Geminates	
		Underlying	
gɔt̪o	past event	pat̪:a	whereabouts
lɔt̪a	creeper	gõt̪:a	thrust
bat̪i	lamp	ʃat̪:a	able
got̪i	progress	mɔt̪:o	inebriate; mad
pat̪a	leaf	Concatenated	
põt̪a	to plant; plinth	pat̪+t̪e > pat̪:e	spread, INF
mat̪a	mother	pũt̪+t̪e > pũt̪:e	bury, INF
hot̪e	from; possibly	gãt̪+t̪e > gãt̪:e	string, INF
pat̪i	small; petty	t̪at̪+t̪e > t̪at̪:e	heat, INF
pũt̪i	bead	Assimilated	
gãt̪i	pickaxe	gɔrt̪o > gɔt̪:o	hole
t̪at̪ano	to heat	kɔrt̪a > kɔt̪:a	master
		kart̪ik > kat̪:ik	seventh month
		b^hort̪i > b^hot̪:i	full