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1 Introduction

Recent work has argued that phonology includes grammatical principles and representations that refer to the temporal coordination of gestures (Gafos, 2001, 2002). In this paper, we extend this line of work by arguing that the distribution of phonetically long consonants in English derives from general principles of gestural organization.

In English, clusters of homorganic consonants are attested at morpheme junctures inter-vocalically but not at word edges. This is shown in (1-3).

(1) Juncture geminates

Stem+Suffix	**Prefix+Stem**	**Across words**
vowelless	dissatisfied	big game
meanness	subpolar	Bob# posed a question

(2) Past tense, past participle

	[t]		[d]		[əd]	*
licked	lɪkt	bugged	bʌgd	needed	nidəd	nidd
leashed	liʃt	leaned	lind	carded	kɑrdəd	kɑrdd
kept	kɛpt	buzzed	bʌzd	sounded	saʊndəd	saʊndd

(3) Plural, possessive, 3rd person plural

	[s]		[z]		[əz]	*
pots	pɑts	rugs	rʌgz	houses	haʊzəz	haʊzz
puffs	pʌfs	leaves	livz	judges	dʒʌdʒəz	dʒʌdʒz
kicks	kɪks	rims	rɪmz	roaches	roʊtʃəz	roʊtʃz
Pete's	pits	Doug's	dʌgz	Ross's	rɑsəz	rɑss

We will use the term 'geminates' to refer to the phonetically long consonants such as /ss/ in 'dissatisfied' (also called fake geminates). Geminates surface as a result of word-formation processes, such as prefixation, suffixation, compounding or simply word concatenation. However, as seen in the last columns of (2), (3), geminates are not allowed with the regular past tense suffix /–d/, and also the plural, 3rd person singular and possessive suffix /–z/.

2 Previous Treatments

Depending on the choice of the underlying forms of the suffixes, there are two possible ways of treating the alternations in (2) and (3) above. The first way is to assume that schwa is present underlyingly and then deleted in the cases where its deletion would not create an OCP violation (e.g. Borowsky, 1986). This approach is formalized in (4). The rule deletes a schwa if the two flanking consonants are not identical. Hence, the OCP is active and blocks the syncope rule.

(4) $ə \rightarrow \varnothing / C_i \_\_ C_j \quad i \neq j$

As stated in (4), however, the syncope rule predicts unattested forms. There are many cases where schwa is present between non-identical consonants in English and where (4) does not apply. For example, the rule would target the vowels in the first syllables of words like 'corruption' and 'police', *[krʌpʃn] and *[plis]. Schwa deletion between non-homorganic consonants may apply in English, but only optionally (e.g., hist[ə]ri → hist[Ø]ri).

To improve the syncope analysis, we may constrain the contexts where rule (4) applies. Note that the deleted schwa is stem-internal in *[krʌpʃn] 'corruption', but follows a morpheme boundary in [lɪkt] 'lick#ed'. However, even if we constrain the rule to apply only to schwas preceded by a morpheme boundary, as in (5), the rule would still be too powerful. It would yield forms like *[klinr] 'clean#er', *[klinbl] 'clean#able', *[disbidɪənt] 'disobedient', or *[bɪgst] 'biggest'.

(5) Schwa deletion: $ə \rightarrow \varnothing / C_i \# \_\_ C_j \quad i \neq j$

The conclusion is that schwa deletion is specific to just two suffixes in English, namely /-əz/ and /-əd/. Consequently, under the syncope analysis, the nature of past tense and plural allomorphy is not purely phonological.

The second way of approaching the data in (1), (2) is to assume the underlying specifications for the suffixes to be /-z/, /-d/ and posit a rule of schwa insertion, shown in (6) (Anderson, 1974:58, Yip, 1988:87).

(6) Schwa epenthesis: [nidəd], *[nidd]

$$\varnothing \rightarrow \text{ə} \,/ \begin{bmatrix} +\text{cor} \\ \alpha\text{cont} \\ \beta\text{strid} \end{bmatrix} \_\_\_ \begin{bmatrix} +\text{cor} \\ \alpha\text{cont} \\ \beta\text{strid} \end{bmatrix}$$

For Yip, stridency is the crucial trigger of the rule. Only adjacent segments that are specified for the same value of stridency trigger the epenthesis. For example, the rule does not apply in words 'booths', 'wholly', and 'pinned' (*[buθəs], *[holəlɪ], *[pɪnəd]). In the first case, /θ/ and /s/ do not agree in stridency. In the other two cases, /l/ and /n/ are sonorants, and by assumption these are not specified for stridency at all (Yip, 1988:87).

Yip does not explicitly discuss how adjacent identical strident consonants as in 'dissimilar' should be treated. However, in Yip's formulation of schwa epenthesis, rule (6) is restricted to apply only within the domain of a coda. Therefore, schwa is epenthesized only if the adjacent consonants would form a coda cluster. Since in an intervocalic context (VCCV), the two consonants belong to different syllables, it follows that schwa epenthesis does not apply in forms such as 'dissimilar'.

3 Experiment

Note that for Yip (1988), the vocalic element in 'needed' is actually not a schwa but a high front lax vowel [ɪ] but even if it were a schwa, it is assumed that it would also have specific phonetic features: indeed, Browman and Goldstein (1992) have argued that lexical schwas as in 'pand[ə]' are specified for an actual gestural target. An alternative hypothesis to Yip's vowel epenthetic analysis, however, is that the epenthetic schwa is not specified for an actual gestural target but rather is the surface consequence of a specific timing relation between two consonants (Browman and Goldstein, 1989, 1992). In the gestural model, a vowel-like element can arise from the timing of two consonantal gestures without having an actual vocalic target. If this hypothesis is correct, then there are two types of English schwas: schwas with an actual vocalic target as in 'pand[ə]' versus targetless schwas as in 'need[ə]d'. Experimental work by one of the authors compares schwa vowels in these two different contexts (Smorodinsky, 2002).

Articulatory data were collected from three speakers of American English (AS, ER and ET) using an electromagnetic midsagittal articulometer, a device that can provide data on movement of coils placed on the surface of the tongue (Perkell et al., 1992). The vertical (Y) and the horizontal (X) movements of the coils placed on the tongue tip (TT) and tongue dorsum (TD) were analyzed: TDY, TTY, TDX and TTX.

The stimuli were embedded in a common environment "$V_1C_1\leftrightarrow C_2V_2$" where V_1 and V_2 were identical (eight different vowels were used, five front and three back) and where C_1 and C_2 were tongue tip gestures. For example, "If needed even once" (past tense schwa) versus "If Needa'd even known" (lexical schwa).

The hypothesis for the targetlessness of the past tense schwas makes two testable predictions. First, if the tongue dorsum is assumed to be controlled continuously by vowels having targets (e.g. Öhman, 1966), the tongue dorsum coil position during a schwa in the targetless schwa tokens should not differ significantly from the tongue dorsum position during the flanking vowels V_1 and V_2. A greater effect of V_1 and V_2 on targetless schwas was thus expected compared to lexical schwas, for which the tongue dorsum was expected to move away from V_1 toward a target for schwa (for example, if V_1 is a high vowel, the tongue dorsum would lower to achieve a target for schwa but it would raise if V_1 is a low vowel).

Second, the intergestural timing, defined here as the interval in time between C_1 and C_2 target achievement, has been shown by Cho (2001) to be sensitive to morphological and phonological structure. In this case, the intergestural timing was expected to be less variable for past tense schwas than lexical schwas: if past tense schwas are the result of a direct gestural timing relation between two tongue tip gestures, then this relation is expected to be more stable than in the case where the two gestures are separated by a vowel. This is because in the latter case the CVC sequence involves two coordination relations, CV and VC, and thus the two consonants are not directly coordinated with each other (see Browman and Goldstein, 2001; Gafos, 2002 for details).

Even though no systematic qualitative differences were found between the two types of schwas and both schwas were heavily context-dependent (which was to be expected since any vowel in this position, especially a schwa, would be heavily coarticulated with surrounding vowels, see e.g., Magen, 1997), the tongue position during past tense schwas was found to be more context dependent than during lexical schwas. Specifically, with respect to the first prediction, a greater effect of vowel context during past tense schwas than during lexical schwas was observed in the vertical dimension of TD movement (TDY) for all three subjects. An ANOVA revealed a significant interaction between vowel context and schwa type ($p<.05$) for subject AS, and a significant interaction was also found for Subject ER in TTY ($p<.01$), TDX ($p<.01$) and TTX ($p<.05$) (see

Smorodinsky, 2002 for a full description). Correlations between schwa (two values, S_1 and S_2) and the surrounding vowels (V_1 and V_2) were also calculated. This yielded 12 pairs: four pairs (V_1/S_1, V_1/S_2, V_2/S_1, V_2/S_2) for each of the three subjects. For TDY, tongue position was systematically more correlated with tongue position of the surrounding vowels for past tense schwas than for lexical schwas. This was the case for all three subjects, and a paired-sign test for all 12 pairs was significant ($p<.001$). A similar result was obtained for the TTY coil for two subjects (ER and AS).

In addition, the tongue position during past tense schwas was significantly correlated with the tongue position of the surrounding vowels ($p<.05$) while this correlation was not significant for the lexical schwas (for ET, the correlations were not significant for either schwa type). Moreover, for subject ER, the differences between the correlation coefficients for past tense and lexical schwas were significant at the 5% level. In the horizontal dimension (TDX and TTX), the results were mixed (see Smorodinsky, 2002 for a full description of these results).

With respect to the second prediction, the standard deviations of the measured intergestural timing values were smaller for past tense schwas than for lexical schwas; for subject ER 26 vs. 32, for AS 17 vs. 20, and for ET 19 vs. 21. Despite the fact that the Levene’s statistic was not significant ($p>.05$), the observed tendency supports the tested hypothesis.

These results thus offer converging evidence for the targetlessness of the vocalic element in the past tense allomorph (-ed) as in ‘needed’. This was concluded based on two types of evidence: the past tense schwa tongue position was more vowel context dependent than that for the lexical schwa, and intergestural timing of the two tongue tip gestures was less variable for past tense schwas than for lexical schwas.

4 Analysis

We attribute the presence of geminates word-medially versus their absence word-finally to differences in temporal coordination between the two contexts. Our proposal aims to account directly for the phonetic targetlessness of schwa and also to account for certain facts about the durational variation of geminates. Thus, we offer a unified treatment of a larger set of data than previous accounts.

In our account, we combine the theory of gestural representations (Browman and Goldstein, 1989, 2001) with a constraint-based theory of grammar (Prince and Smolensky, 1993). The basic units of phonological representation are dynamically defined gestures and their temporal relations. Figure (1) is a schematic of a gesture, with its temporal landmarks. The life of the gesture begins at the onset of the movement of the articulator(s). Target identifies the time point when the articulator reaches the target constriction (in our case, the coronal constriction of the tongue, observed in TT). This begins the hold phase until the constriction is actively released. C-center is the temporal midpoint between the target and the release. By release-offset, the gesture loses its active control over the articulator and any additional movement is either passive, or controlled by another gesture.

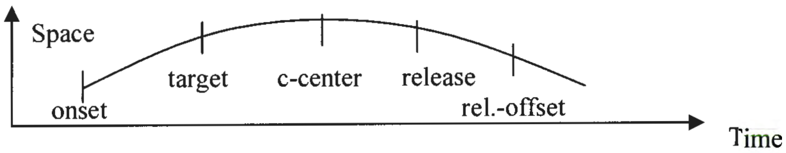


Figure 1: Spatio-temporal realization of a gesture.

Gafos (2002) argued that temporal relations among gestures are directly manipulated by the phonological grammar of (a dialect of) Moroccan Arabic. These relations are expressed through Optimality Theoretic alignment constraints referring to temporal landmarks. To extend this framework in English, we begin by noting that two non-identical consonants in English CC sequences are produced in 'close transition': "...the articulatory stricture for the second consonant is formed before the stricture for the first is released" (Catford, 1988:117). This is shown in Figure (2).

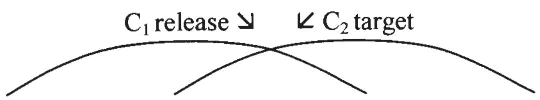


Figure 2: Close transition between two non-identical consonantal gestures.

We model this temporal relation with the OT constraint CC-COORD(INATION), shown in (7).

(7) CC-COORD: Align the release of C_1 with the target of C_2

Based on the experimental results discussed in section 3, we propose that the vocal element in the final cluster of [nidᵊd] results from an 'open transition' between the two [d] gestures rather than from an active vowel gesture. That is, the temporal relation between the two Cs is such that the onset of the second C gesture occurs at the release offset of the first C gesture. This is schematized in Figure (3). The dotted line shows a period of no constriction between the release of the first and the target of the second gesture, representing the transitional schwa. The vertical bold line highlights the temporal coordination of the two relevant landmarks: C_1 release offset to C_2 onset. This is a distinct coordination relation from the default, close transition of CC-COORD in (7).

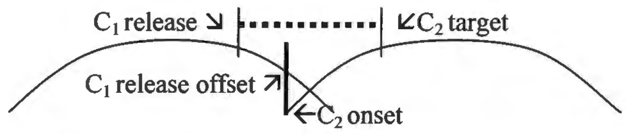


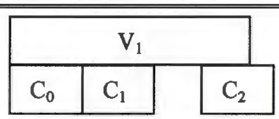
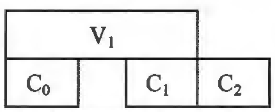
Figure (3) Open transition between two identical consonantal gestures.

The reason why a distinct coordination relation is employed in a cluster of identical consonants is clear. If close transition were to be employed, it would result in a violation of the gestural version of the OCP. The OCP is a well-established general principle of phonology (Leben, 1973; McCarthy, 1986). The gestural version of the OCP as an OT constraint is given in (8) below (Gafos, 2002).

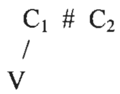
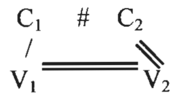
(8) OCP: Overlapping (oral) identical gestures are prohibited.

For two juxtaposed identical consonants, the constraints CC-COORD and OCP are in conflict. This is shown in tableau (9). The boxes represent gestures, as described in Figures (1-3). Candidate (9b) employs the default coordination between the two final Cs, but violates the OCP. To avoid the OCP violation, the two Cs are distanced in time (they are coordinated with an open transition) as shown in candidate (9a). Hence, OCP >> CC-COORD.

(9) Close transition is avoided, OCP >> CC-COORD

bus+z		OCP	CC-COORD
☞a. bʌsəz			*
b. bʌsz		*!	

Next we turn to the question of why 'epenthesis' is not attested word-internally. The coordination geometry between vowels and consonants word-internally is crucially different from that of the word-final context. The schemas in (10a,b) depict the coordination relations present in the two relevant contexts. In (10a), a bare consonant suffix denoted as C_2 (e.g. /-z/, /-d/) is attached to a stem ending in a VC sequence ('#' is the morpheme boundary). In (10b), a vowelled suffix, denoted as C_2V_2, is attached to a stem ending in a VC sequence. The line linking V and C_1 in (10a) shows a VC-type coordination relation between a vowel nucleus and its subsequent tautosyllabic consonant. This is the same relation as that between V_1 and C_1 in (10b).

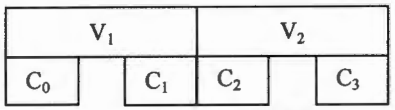
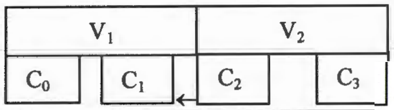
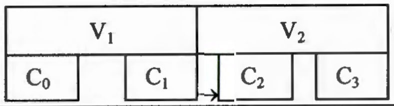
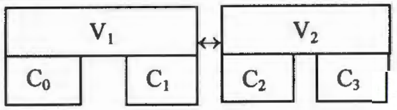
(10) a.  b. 

The presence of the V_2 in (10b) implies two additional coordination relations, one between C_2 and V_2 and another between V_1 and V_2 (both shown in double lines). The first is a CV-type coordination relation applying between an onset consonant and its tautosyllabic vowel. The second is a VV-type relation between vowels of consecutive syllables. Following Öhman (1966) and Fowler (1983), we assume that vowels in consecutive syllables overlap with each other. We express this requirement as the coordination constraint in (11). The set of coordination constraints is summarized below (based on Gafos, 2002 and Browman and Goldstein, 2001).

(11) VV-COORD: Align the release offset of the first vowel to the onset of the second vowel (Adjacent vowel gestures are contiguous).
(12) CV-COORD: Align the c-center of the consonant gesture with the onset of the vowel gesture.
(13) VC-COORD: Align the release of the vowel gesture with the target of the consonant gesture.

We are now in a position to derive the presence of inter-vocalic geminates. The tableau in (14) shows that intervocalic geminates are forced by the requirements of the additional coordination constraints abbreviated below as VC, CV, and VV. Candidate (14a) employs the default CC-COORD relation but violates the OCP. To avoid the OCP violation, the two Cs in the remaining candidates (14b-d) shift apart in time resulting in open transition. However, every possible strategy to achieve open transition, shift C_1 left, shift C_2 right or shift V_1 and V_2 apart, violates a top-ranked alignment constraint (VC-, CV-, or VV-COORD respectively).

(14) Violation of the OCP intervocalically

[min nəs] (mean+ness)	VC	CV	VV	OCP	CC
a. ☞ 				*!	
b. 	*!				*
c. 		*!			*
d. 			*!		*

To summarize, we argued that word-finally the OCP dictates a specific coordination plan between two identical consonants C_1 and C_2, where the C_2 shifts away from C_1 (see next section for the relevant notion of identity). This results in a targetless schwa between the two consonants. Word-medially, the OCP is violated to satisfy the additional coordination requirements present in the VC_1C_2V context. The C_2 gesture cannot shift away from the C_1 without violating VV-, VC-, or CV-coordination.

5 Defining Identity in the Gestural OCP

In this section, we refine the statement of the gestural OCP by taking into account different kinds of homorganic consonants and the role of sonority.

The OCP must force an open transition between consonants that do not have exactly the same place of articulation, e.g. 'bushes' [buʃᵊs], *[buʃs]. Yip (1988) deals with such forms by the requirement of identity in stridency. We argue that such data do not warrant a revision of the OCP. The definition in (8) requires 'identity' in gestures. We say that two gestures g_1 and g_2 are identical iff they employ the same <u>articulator</u> and the same values for the constriction degree (CD) tract-variable (see Gafos, 2002 and Yip, 1988). For example, the oral TT gestures of /t/ and /d/ are identical, but the oral TT gestures of /t/ and /s/ are not since the CD value for /t/ is [closure], but for /s/ it is [critical]. To return to the example in 'bushes', the oral gestures for /ʃ/, /s/ are identical with respect to the OCP since they both require the same articulator, Tongue Blade, and have the same CD value, [critical]. Hence, the OCP is triggered when /ʃ/ and /s/ gestures are combined, and forces the open transition.

However, the OCP is not triggered in cases like 'booths' [buθs] as can be seen by the lack of an open transition, *[buθᵊs]. To account for this, we assume that /θ/ is articulated with the Tongue Tip, and /s/ is articulated with the Tongue Blade. Hence, the OCP is not violated in [θs] sequences and the default close transition emerges. The effects captured by Yip's identity requirement for [±strident] follow from the gestural OCP.

Next, consider the fact that identical oral gestures of segments with different sonority do not trigger the OCP: 'leaned' [lind], *[linᵊd]. Therefore, the sonority profile of the adjacent segments (that these gestures are part of) is relevant for the calculation of identity. In the gestural model, sonority is defined as the degree of vocal-tract opening computed over a hierarchically structured set of vocal tract tubes. The basic idea is that the supralaryngeal gestures for sonorants like /n/ or /l/ include an open constriction in the nasal or oral-lateral part of the vocal tract. On the other hand, the supralaryngeal gestures for /t/ and /d/ do not have such an open constriction. As a result, the computed constriction degrees for /n/ and /d/ at the supralaryngeal node are different, and consequently [nd] clusters do not violate the OCP. For a detailed description, see Browman and Goldstein (1989:135–42) and Gafos (2001). The revised OCP is formulated below. The same statement of the OCP applies to Moroccan Arabic (Gafos, 2002) and Imdlawn Tashlhiyt Berber (Dell and Elmedlaoui, 1996).

(15) OCP: Overlapping (oral) identical gestures with the same supralaryngeal constriction degree are prohibited.

Finally, consider the data in (16) showing a situation where the plural suffix /-z/ and the possessive /-z/ are adjacent. In this case, the OCP violation is avoided via fusion of the two morphemes.

(16) The buses' [bʌsəz] tires went off. *[bʌsəzəz]
Johns' [dʒɑnz] noses are crooked. *[dʒɑnzəz]

To account for the fusion cases, we adopt Yip's (1995) treatment of haplology. Yip proposes the constraint MORPHDIS that requires distinct realizations of different morphemes. She shows that ranking the OCP above this constraint (OCP >> MORPHDIS) prohibits adjacent realizations of different morphemes with identical phonological content. As a result, these adjacent, phonologically-identical morphemes fuse into one that carries the semantics of both, thus violating MORPHDIS.

To incorporate Yip's account of haplology into our proposal, consider the tableau in (17). The ranking OCP >> CC-COORD has been already established in (9) above. The crucial forms that determine the ranking of CC-COORD and MORPHDIS are in (17a-b). Candidate (17b) avoids the OCP violation by realizing both suffixes with open transition, hence violating CC-COORD twice. Candidate (17a) employs fusion, which avoids one violation of the CC -COORD but violates MORPHDIS. Since (17a) is the output, the ranking that accounts for the data in (16) is OCP >> CC-COORD >> MORPHDIS. Our extension of Yip's (1995) theory would only be that the relevant type of the OCP in this case is the gestural OCP, defined in (15).

(17) Phonologically identical adjacent morphemes fuse

bus+$z_{Pl.}$+$z_{Poss.}$	OCP	CC-COORD	MORPHDIS
☞a. bʌsəz$_{Pl.+Poss.}$		*	*
b. bʌsəzəz		**!	
c. bʌszz	*!*		

6 Extension: Duration of Geminates across Words

It has been observed that geminates across words may have various acoustic realizations. On the one hand, Ladefoged (1993:94) formulates an allophonic rule where a consonant shortens when followed by an identical consonant across a word boundary, e.g. 'to[p p]ost'. On the other hand, the strength of the prosodic boundary also determines the acoustic length of consonants adjacent to that boundary: the stronger the boundary, the longer are the consonants (Turk and Shattuck Hufnagel, 2000; Wightman et al., 1992; Byrd et al., 2000). This means that the duration of a [pp] sequence across an intonational phrase boundary ('Po[p, p]osing a question, stood up') is longer than across a simple word boundary ('to[p p]ost').

We propose that the observed durational variation is a direct consequence of the degree of gestural overlap in the different contexts. Shortening as in 'top post' is a lawful consequence of CC-COORD in (7). Two overlapping gestures in close transition result in a shorter total closure duration than if the same gestures are juxtaposed; no allophonic rule is necessary. Lengthening in $VC_i\#C_iV$ is a result of decreased stiffness of the gestures in the vicinity of strong prosodic boundaries (Byrd et al., 2000). Figure (4) shows the acoustic duration of the geminate across a weak boundary (duration is denoted by the arrow), for some value of stiffness k.

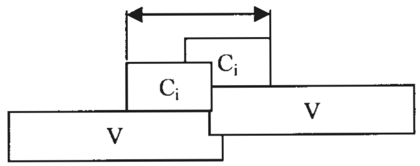


Figure 4: Gestures in a $VC_i\#C_iV$ with stiffness k.

In the context of a strong prosodic boundary (Figure 5), the stiffness of the gestures is decreased. This means slower movement of the articulators, and consequently longer total closure durations. Importantly, we do not have to assume that the coordination relationships between gestures are different under different tempo conditions.[1]

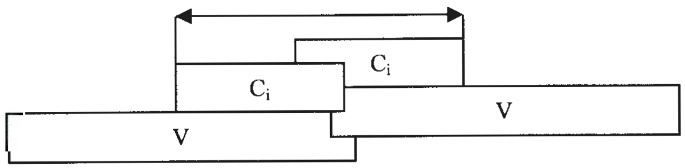


Figure 5: Gestures of the same sequence $VC_i\#C_iV$ with identical coordinations but different stiffness m, where m < k.

7 Conclusion

We proposed a gestural analysis for the distribution of "geminates" in English. The primitives of our analysis are dynamically defined gestures and constraints on their temporal coordination. Temporal relationships between dynamically defined gestures have the status of phonological constraints entering the grammar of a language. The observed effects—schwa

[1]Although normally produced without it, a release (shown with a '/') is optional in sentences like 'Pop, / posing a question, stood up'. The strongest prosodic boundary may indeed require a pause. In other words, the increased strength of the boundary may prevent adjacent vowels from establishing any temporal relation with each other across words.

epenthesis word-finally, "gemination" word-medially, and acoustic length variation under different prosodic conditions—receive a unified treatment.

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