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Phonetic and Phonological Aspects of Liquid Devoicing in Thai, Hungarian, and American English Stop-Liquid Sequences*

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It is a well-known coarticulatory phenomenon that liquids preceded by voiceless stops tend to devoice partially, e.g. English *clash* /k^{h}læʃ/ → [k^{h}l̥ æʃ]. The purpose of this paper was to investigate acoustically whether devoicing of the liquid following a voiceless stop in the three languages Thai, Hungarian, and American English originates at the planning level, e.g. is phonological, or whether it is phonetic, e.g. occurs as artifact of the implementation process. The study reported here investigated VOT and the amount of devoicing in /pl/, /pR/ (R stands for any rhotic), /kl/, /kR/, and /tR/ sequences with respect to: a) the influence of the position of the relevant sequence with respect to a syllable/morpheme boundary, and b) the effect of speaking rate. 12 subjects participated in this study, 4 subjects per language, 2 females and 2 males. The results show that liquid devoicing exhibits a systematic pattern in English but not in Hungarian or Thai, suggesting that it is phonological in English and phonetic in Hungarian and Thai.

1. Introduction

The current paper investigates the well-known coarticulatory phenomenon that liquids preceded by voiceless stops tend to devoice partially, as illustrated in (1) in the English word *clash*:

(1) /k^{h}læʃ/ → [k^{h}l̥ æʃ]

Many languages exhibit the phenomenon investigated here: a speech sound changes - fully or partially - its phonation type (voiced or voiceless) under the influence of an adjacent sound with an opposite voicing specification. While theoretical phonologists refer to this phenomenon most often as voicing assimilation, phoneticians and experimental phonologists prefer the term laryngeal coarticulation (Ohala, 1993).

Coarticulatory phenomena like the one under investigation here are often called natural processes, since they can be explained in terms of phonetics. If we assume, as for example proposed in Ohala (1993), that the synchronic sound systems of languages often result from cases of fossilized coarticulation, we might expect that in some languages voicing assimilation is a fact of the synchronic sound system and hence part of the phonology, whereas in others it is the result of coarticulation occurring during the phonetic implementation.

To test whether phonetic liquid devoicing is distinguishable from phonological liquid devoicing, the present study investigated the properties of liquid devoicing in three genetically unrelated languages: Thai (Daic), Hungarian (Finno-Ugric), and American English (Indo-European).

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Based on evidence from the acoustic analysis conducted on stop-liquid sequences in the three languages it will be argued that liquid devoicing is phonetic in Hungarian and Thai, but phonological in English.

In order to determine whether liquid devoicing is phonological or phonetic in the investigated languages it is, of course, necessary to find criteria that can determine the phonological versus phonetic status of liquid devoicing. A common experimental paradigm (Lehiste, 1960; Docherty, 1992) is to study the interaction of coarticulation with prosodic/morphological boundaries. In the case of a significant influence of the boundary on the extent of coarticulation it can be concluded that the presence of a higher order grammatical constituent (e.g. a syllable, morpheme or word) determines the phonetic realization of the sound or sound sequence under investigation, and therefore can be considered a phonological phenomenon. Example (2) illustrates the boundary effect on sonorant devoicing in English according to Lehiste (1960):

(2) night-rate [naɪt.ɹeɪt] vs. nitrate [naɪ.tɹ̥eɪt]

Another criterion to determine the phonetic versus phonological status of a given process has been proposed in the work of Keating (1985) who argues that discrete/categorical, contrastive phenomena should be considered phonological, whereas gradient, non-contrastive phenomena should be considered phonetic. While this has been successfully applied to determine the phonetic versus phonological status in studies on nasalization (Cohn, 1993) and on vowel allophony (Choi, 1995), it does not lend itself easily to the investigation of laryngeal coarticulation (for further discussion see below).

A third approach has been used by Solé (1992). She proposes that speaking rate can be used to determine whether a given process should be considered phonetic or phonological. Since speaking rate is under the control of the speaker, it can be seen as a higher-level adjustment. Adjustment of the amount of coarticulation with speaking rate, therefore, indicates systematic control over coarticulation, which suggests that the coarticulatory phenomenon under investigation is phonological rather than phonetic in nature.

Finally, cross-linguistic comparison can shed light onto the phonetic versus phonological status of coarticulation. While research over the last decades has shown that gradient coarticulatory variation may very well be language specific and thus has overthrown the long held belief that gradient changes are universal aspects of speech (for a summary see Farentani and Recasens (1999)), it is still interesting to see which gradient variations occur across different languages and which turn out to be language specific. Even though some gradient phenomena are language specific and, therefore, their phonetic status may be disputable, we may still assume that those coarticulatory gradient phenomena that can be observed cross-linguistically are truly phonetic in nature.

Some of the criteria used in the present study to determine the phonetic versus phonological nature of laryngeal coarticulation in stop - liquid sequences have been used previously (Docherty, 1992; Klatt, 1975); however, the current study differs from these studies in several respects:

- Previous studies were limited to English; the current study investigates also Thai and Hungarian.
- Previous studies included male subjects only; this study includes male and female speakers.
- While Dochertys (1992) study like the current study investigates stop liquid sequences

within and across boundaries, the current study differs in that it also investigates the effect of speaking rate.

- And finally, while previous studies used voice onset time (VOT) alone to study the amount of laryngeal coarticulation in stop-liquid sequences, the current study takes into account the possibility that the amount of devoicing of the liquid is not necessarily equivalent to or correlated with the VOT of the preceding stop. Therefore, the duration of absence of voicing during the liquid was also measured in order to determine the percentage of devoicing of the liquid, since devoicing has to be understood as relative to the total duration of the segment.

2. Distinguishing the Effects of Phonetics from those of Phonology

Coarticulatory / assimilatory phenomena have been the focus of much experimental research over the past 70 years ever since the introduction of experimental techniques into the study of human speech. The results of these studies have informed our understanding of speech production as well as inspired various theories concerning the nature of phonetic and phonological representations (for a comprehensive summary see Hardcaste and Hewlett (1999)). An ever re-occurring issue in the discussion of experimental studies on coarticulation is to what extent coarticulatory phenomena can be regarded as phonetic or phonological, i.e. to what extent is coarticulation a result of the inertia of the articulatory system (Lindblom, 1963, 1990; Öhman, 1966, 1967) as opposed to a feature-spreading process (Daniloff and Hammarberg, 1973; Keating, 1985, 1990) or inherent part of dynamic phonological units (Fowler, 1980; Browman and Goldstein, 1986b).

While phoneticians and experimental phonologists have paid much attention to questions concerning the relationship between phonetics and phonology, theoretical phonologists have only in the last 15 years started to integrate results of experimental phonetic research into phonological modeling (cf. Steriade (1997, 1999); Kirchner (2001); Hayes et al. (2004) and papers therein). One of the reasons why theoretical phonologists might have been rather reluctant to look to experimental studies for clarification of theoretical issues might be that it is not straightforward how detailed phonetic studies can inform phonological theory. However, studies such as the ones reported in Hayes et al. (2004) have shown that phoneme inventories and frequent cross-linguistic phonotactic restrictions can be explained by making reference to the acoustic and perceptual properties of frequent versus infrequent phonemes or phoneme sequences. Another respect in which detailed phonetic studies can inform phonological theory is by testing the assumptions that different phonological theories make about the nature and organization of phonological units, as suggested for example in Beckman (1999). The results of the study presented here like other studies on coarticulation can shed light on the nature of phonological units involved in articulation. In the following sections three different views about the nature of coarticulation will be reviewed. The predictions made by these different approaches to coarticulation will be laid out and the relevance of these predictions with respect to the current study will be discussed.

2.1. Coarticulation as Result of the Inertia of the Articulatory System

The view that coarticulation is the result of the inertia of the articulatory system is put forward for example in Lindblom's (1990) theory of adaptive variability and Öhman's (1966; 1967) vowel-to-vowel coarticulation model. Both views are on a par with a SPE style phonological model

(Chomsky and Halle, 1968), where coarticulation is defined as adjustments in the "vocal tract shape made in anticipation of a subsequent motion etc." (p. 295) and assumed to originate from the physical properties of speech.

Öhman's (1966) comparative study of Swedish, American English, and Russian VCV utterances was the first to show that gradient aspects of speech can be language specific. hman found that the second formant transitions in the first vowel depend not only on the intervening consonant (a stop), but also on the identity of the transconsonantal vowel, resulting in vowel-to-vowel coarticulation. However, coarticulatory effects were found only in Swedish and American English, not in Russian. hmans model explains this language specific difference as a consequence of the interaction between two simultaneous and conflicting vowel commands on the tongue body during the palatalized consonant in Russian. Crucially, the difference between the languages is not attributed to differences at the planning level, i.e. phonology.

The main tenet of Lindblom's (1990) theory, which was developed to account for vowel reduction, is that the speech mechanism has a tendency to economize effort. Adaptive variability refers to the speakers ability to adapt their production to the demands of the communicative situation; if the situation requires a high degree of phonetic precision, speakers are able to over-articulate but when this high degree of precision is not needed speakers will under-articulate in order to economize articulatory effort. Coarticulation, therefore, plays a central role in this framework, since the continuum from over to under-articulated speech is manifested perceptually as gradual decrease in phonetic contrast, and articulatorily as gradual increase in gestural overlap. If we now generalize Lindbloms framework to all coarticulatory processes, the prediction would be that an increase in gestural overlap in faster speech should be expected if the coarticulatory phenomenon is purely phonetic, i.e. due to the inertia of the speech mechanism; a proportional adjustment of gestural overlap to speaking rate on the other hand should be indicative of a phonological process, i.e. the coarticulatory variability originates at the level of gestural planning. The same line of reasoning underlies the study on nasalization by Solé (1992), mentioned earlier. Since the degree of precision is higher in careful, slow speech than in colloquial, fast speech, we expect the amount of coarticulation to increase with faster speaking rate if the coarticulatory process is purely phonetic. If, however, the coarticulatory process originates at the planning stage, we expect the amount of coarticulation to adjust proportionally to speaking rate. Lindblom's (1990) theory and Solé's (1992) study serve as the basis for the criterion of speaking rate utilized in the present study.

2.2. Coarticulation as Feature Spreading and Feature Based Models

The strict dualism of the view that coarticulation is due to the inertia of the speech mechanism was challenged by Daniloff and Hammarberg (1973), who argued that the sharp distinction between intent and execution would entail that the articulators are unable to carry out the commands as specified. They proposed to assign coarticulation to the phonological component and to view it as a feature spreading process across segments. Daniloff and Hammarberg's (1973) feature spreading theory, however, is somewhat problematic since it fails to account for the gradient nature of coarticulation and the temporal changes during the segment, as pointed out by Farentani and Recasens (1999).

Keating's (1985; 1990) window model of coarticulation overcomes this problem by accounting for coarticulation in a language specific phonetic component. Keating, similar to non-linear phonological frameworks like for example Sagey's (1986) model, assumes that phonological units are timeless, abstract, and with no internal temporal structure, whereas phonetic units are continuous in time and space and possess an internal temporal structure. However, while Sagey assumes that the phonetic representation resembles the phonological representation in terms of the feature-geometric architecture, Keating proposes the window as the phonetic unit of representation. A window is formed by the range of values associated with the physical realization of a feature. For each articulatory or acoustic dimension, a window has its own duration and width representing the possible physical values that a target can take. The window width, in turn, depends on the output from the phonological component. If a feature is specified in the phonology, the window associated with this feature will be narrow and allow no or little contextual variation. If, however, a feature is unspecified in the phonology, the corresponding window will be wide and allow large contextual variation.

If we now want to apply the window model to the case of laryngeal coarticulation in stop-liquid sequences, we encounter the following problem. The notion of temporal gradience typically employed in a window model type approach such as for example Cohn (1993) is not applicable in the case of voicing, since at any given point in time voicing is either present, i.e. the vocal folds vibrate, or not present, i.e., the vocal folds dont vibrate. Even though voicing comes in different phonation types, such as modal, creaky, and breathy voicing, we do not find a gradual change over time. Therefore, the current study does not further draw on the window model of coarticulation.

2.3. Coarticulation in Co-production Models

The main criticism of feature-based models is that they need a translation process that renders the abstract, static and timeless phonological units into articulatory movements. In this translation process, the speech plan provides the spatial targets, while a 'central clock' specifies the temporal order in which the articulators have to move. Co-production models Fowler (1980); Browman and Goldstein (1986b, 1992); Fowler and Saltzman (1993) overcome this dichotomy by integrating the time program into the speech plan.

According to co-production models, the amount of coarticulation depends on the degree to which the temporally overlapping gestures share articulators. For example, we find a minimal degree of coarticulation in a /VbV/ sequence, where the vocalic and consonantal constriction gestures involve two independent articulators, the tongue body and the lips respectively, and one common articulator, the jaw. However, in the sequence /VgV/, we find a high degree of coarticulation induced by coproduction, since the vocalic and the consonantal gestures share both the tongue body and the jaw. The general idea of coproduction models, then, is that gestures 'blend their impact on the common articulator, which can result in several possible outcomes.

In a sequence of two identical gestures, coproduction models predict that the outcome is a composite movement, e.g. a 'melting together of the two movements into a single one, which, however, is greater in extent than any single movement by itself. In other words; a summation of the two gestures takes place. This prediction is supported by a study of laryngeal abduction/adduction movements in sequences of two voiceless consonants (Munhall and Löfqvist, 1992). Munhall and Lfqvist report that two distinct glottal abduction movements were observed at slow speaking rates, whereas single movements with increased amplitude were found at moderate and fast speaking rates.

In a sequence of two gestures that impose conflicting demands on the same articulator, coproduction models make two controversial proposals. Earlier work by Bell-Berti and Harris (1981) proposed that the gestural conflict can be resolved at the planning level by delaying the onset of the competing gesture so that the ongoing goal can be achieved. Fowler and Saltzman (1993), on the other hand, proposed that no changes at the planning level may be needed. Instead, they proposed that any given gesture has its own characteristic degree of ‘blending strength, where blending strength is a concept introduced to capture the relation between coarticulatory resistance and coarticulatory aggression. If gestural overlap occurs between a stronger and a weaker gesture, the stronger gesture tends to suppress the weaker one and to affect the common articulator more. If, however, the two conflicting gestures are of similar blending strength, the outcome tends to be an averaging of the two gestures. This proposal resembles very much the view that coarticulation is due to the inertia of the speech mechanism put forward by Lindblom’s (1990) theory of adaptive variability and Öhman’s (1966; 1967) vowel-to-vowel coarticulation model described above. And as outlined in the previous section, Fowler and Saltzman’s (1993) proposal predicts - just as Lindblom (1990) - that an increase in speaking rate has a magnifying effect on gestural overlap, if the phenomenon does not originate at the planning level; i.e. is phonetic. Therefore, every process, which is not magnified with increase in speaking rate, but adjusts proportionally with speaking rate should be considered a planned event.

For the phenomenon under investigation in the current study, liquid devoicing in stop-liquid sequences, coproduction models would predict that if VOT or devoicing of the liquid adjusts proportionally with speaking rate, liquid devoicing originates at the level of gestural planning and results from a rule specifying the overlap of a single glottal gesture with two oral gestures (Browman and Goldstein, 1986a).

3. Investigating Laryngeal Coarticulation

3.1. Research Question and Hypotheses

This experiment was designed to investigate laryngeal coarticulation in stop-liquid sequences in three genetically unrelated languages: Thai (Daic), Hungarian (Finno-Ugric), and American English (Indoeuropean). The stop-liquid sequences were investigated in two environments: in sequences within the onset of a syllable (henceforth tautosyllabic condition) and in sequences across syllable boundaries (henceforth heterosyllabic condition). The experiment was limited to the liquids /l/ and /R/ [1] and did not include the two other members of the natural class of approximants /w/ and /j/ because the phonotactics of Thai and Hungarian do not allow for the construction of a systematic set of stimuli containing /w/ and /j/. Thai does not permit /j/ to follow a stop in complex onsets, and /w/ occurs only in complex onsets with /k(h)/, but not with /t(h)/ or /p(h)/ (Henderson, 1970). The phoneme inventory of Hungarian does not contain the phoneme /w/ at all (Siptár and Törkenczy, 2000).

In order to investigate laryngeal coarticulation in stop-liquid sequences, two voicing timing parameters were studied: (a) voice onset time (VOT) and (b) percentage of devoicing of the liquid.

[1] R stand for any rhotic independent of its exact phonetic realization in the three languages.

While the VOT is an inherent part of the stop consonant, the amount of devoicing of the liquid, i.e. the percentage of absence of voicing during the duration of the liquid, can be seen as a property of the liquid. Why make the distinction between these two parameters? It has been argued in the phonetic literature (Klatt, 1975) as well as in the phonological literature (Steriade, 1997, 1999) that the function of the partial devoicing of the liquid is to provide a phonetic cue for the voicing category (voiceless aspirated versus voiced or voiceless unaspirated) of the stop preceding the liquid. And while there is no question that the devoicing of the liquid is caused by the preceding voiceless stop, the question arises whether the liquid is merely a result of the VOT pattern of the stop or whether liquid devoicing is best understood as a property of the whole stop-liquid sequence. The two parameters were studied in the tautosyllabic and heterosyllabic condition in conjunction with (i) speaking rate, and (ii) place of articulation of the stop consonant. This design intends to answer the following research questions:

1. Does the VOT and/or percentage of devoicing of the liquid in the tautosyllabic sequences differ from VOT and/or duration of absence of voicing during the liquid in the heterosyllabic sequences? In other words; is liquid devoicing influenced by the presence of a higher-order grammatical constituent, such as syllable or morpheme boundary?

2. Does the VOT and/or percentage of devoicing of the liquid adjust proportionally with speaking rate in the (i) tautosyllabic condition; (ii) in the heterosyllabic condition; or (iii) in both? In other words; does the coarticulation originate at the level of gestural planning or is it due to the inertia of the speech mechanism?

3. Does the onset of voicing (= end of VOT) occur around a consistent point of time during the liquid in the two conditions? In other words; is the window (see Section 2) for the timing of the offset of the laryngeal gesture wide or narrow?

4. Finally, in what respect do the three languages Thai, Hungarian, and English pattern similarly, and in what respects are they different?

Research questions (1) through (3) are aimed at distinguishing whether liquid devoicing in the three languages should be considered phonetic or phonological based on the predictions made by the different models of coarticulation summarized in Section 2. Research question (4) engenders a variety of hypotheses, for example differences between the languages might be caused by the differences in the phonetic category to which the stops and liquids in each language belong. Although in all three languages the same stop-liquid sequences are investigated, certain differences exist in the phonetic categories to which these stops and liquids belong across the languages. The rhotic in Thai and Hungarian is the alveolar trill /r/, while it is the alveolar approximant /ɹ/ in American English. In American English the stops are voiceless aspirated, in Thai and Hungarian they are voiceless unaspirated with the Hungarian stops being more aspirated than the stops in Thai.[2] We would expect that there is a strong correlation between the amount of aspiration and the amount of devoicing in the liquid. Therefore, we expect liquids to devoice most in American English, less in Hungarian, and least in Thai.

[2]While Thai also has voiceless aspirated stops, these could not be used in the current study since they occur only in syllable-initial position. Therefore, no words with voiceless aspirated stops followed by a liquid across a syllable boundary exist in Thai.

3.2. Elicitation Materials

For all three languages a list of ten words was prepared containing each of the stop-liquid sequence /pR/, /pl/, /tR/, /kR/, and /kl/ once in the tautosyllabic and once in the heterosyllabic condition. Since none of the three languages allow tautosyllabic /tl/ sequences, this sequence type could not be investigated causing an asymmetry in the data set. While this general design applies to all three languages, there were some differences between the shape of the words on the three lists due to different prosodic and morphological constraints in each language.

For English, all words were disyllabic and carried primary stress on the first syllable. While all words with the stop-liquid sequence in the tautosyllabic condition were monomorphemic, the words in the heterosyllabic condition were compound words and the syllable boundary for all these words coincides with the morpheme boundary. In English the default syllabification is that the stop-liquid sequence is syllabified as onset. The only way to enforce a different syllabification, such as the stop in coda position and the liquid in the onset of the following syllable, is by imposing a morpheme boundary on the sequence, since contrastive syllabification does not exist in English (nor has it been reported for any other language). The words were designed such that the tautosyllabic sequence occurred in the onset of the second syllable, and for the heterosyllabic sequence, the stop occurred in the coda of the first and the liquid in the onset of the second syllable. This entails that the tautosyllabic sequence has to occur in the unstressed syllable, which has been shown to shorten the VOT of stops in stop-/l/ sequences (Docherty, 1992). This choice seemed, however, unavoidable in order to control for stress. Docherty (1992), for example, designed his word lists so that the tautosyllabic stop-sonorant sequences occurred in a stressed syllable, but couldnt maintain control over stress in the heterosyllabic sequences due to a lack of a large number of unstressed prefixes in English.

For Hungarian, the words consisted of either four or five syllables, however, the number of syllables was kept consistent for any given sequence type in tautosyllabic and heterosyllabic condition. In other words, while the two words containing tautosyllabic /tr/ and /pr/ may differ in the number of syllables. The words containing tautosyllabic /tr/ and heterosyllabic /t.r/ will never differ in the number of syllables. Just as for the English words, all Hungarian words carried primary stress on the first syllable and the relevant stop-liquid sequence occurred in the onset of the second syllable for the tautosyllabic condition and for the heterosyllabic condition the stop occurred in the coda of the first syllable and the liquid in the onset of the second syllable. However unlike English the default syllabification for Hungarian is to syllabify stop-liquid sequences with the stop in coda position and the liquid in the onset of the following syllable. The stop-liquid sequence in Hungarian is only syllabified into a single onset if it occurs word- or morpheme initially (Siptár and Törkenczy, 2000). For example, in the monomorphemic word for makrame /mɔk.rɔ.meː/ the syllable boundary falls between the /k/ and the /r/, whereas in the word for fake crystal /aːl.kris.ta^j/ the /kr/ sequence is forced into the onset of the second syllable since the morpheme boundary falls between the morphemes /aːl/ fake and /kris.ta^j/ crystal.

For Thai, all words are compound words and consisted of two syllables. This is due to the fact that polysyllabic monomorphemic words are extremely rare in Thai; therefore, it is also impossible to say which syllabification of stop-liquid sequences would be the default case. Just like in English and Hungarian, the sequences occurred in the onset of the second syllable for the tautosyllabic condition and for the heterosyllabic condition the stop occurred in the coda of the first and the liquid in the onset of the second syllable. However, unlike English and Hungarian, Thai is not a stress language but has lexical tone. Although it was attempted to control for the tone, this control could not be maintained throughout the word list. While the majority of words had a rising tone, one word had a falling tone and two had a rising-falling contour tone. This asymmetry in the data set was kept in mind, but anticipating the results no effect of the tone on VOT or duration of voicelessness during the liquid could be seen.

3.3. Participants and Data Collection

Overall 12 subjects participated in this experiment; four subjects per language, two male and two female subjects each. All subjects were between 20 and 40 years old. The American English speakers were speakers of the Mid-Western dialect of American English with the exception of one male talker, who grew up in California, but has been living in the Mid-West for several years.

The Thai speakers were all from the Southern part of Thailand and were students in the United States. They all had been here for less than 5 years.

The Hungarian speakers were all from the greater Budapest area. Two of the four speakers were students in the United States who had lived here for less than two years. The other two speakers were visitors from Hungary who spent their summer vacation here.

The participants were instructed to read each of the ten words, which were randomly ordered, at three different speaking rates. The first time, speakers were asked to read the word in isolation and to enunciate very carefully. The second time, speakers were asked to read the word in a carrier sentence at normal speaking rate. The carrier sentences for each language were:

English:	I say again.
Hungarian:	Azt mondata ugye?
	‘He said , didn’t he?’
Thai:	Kham níi ʔáan wâa rɯɯpláaw?
	‘This word is pronounced , isn’t it?’

The third time the participants were asked to read the word again in the carrier sentence, but this time as fast as they could. Overall, 360 utterances were produced by the speakers, 120 per language, 30 per participant, ten at each speaking rate. All utterances were recorded using a Marantz tape recorder.

3.4. Acoustic Analysis

The recorded data were digitized at a sampling rate of 22.05 kHz and analyzed using the speech software PRAAT (Boersma and Weenink, 2008). The analysis procedure involved displaying the speech waveform and a wideband spectrogram. The waveform was used to measure the length of VOT starting at the offset of the stop closure (i.e. beginning of release burst) to the onset of voicing as evidenced by strong periodicity (or regular vertical striations in the spectrogram).

In addition to measuring VOT, the duration of absence of voicing during the liquid was determined. In order to measure the duration of absence of voicing during the liquid, it was necessary to determine the overall length of the liquid. The offset of the liquid in the current study was determined by the same criteria for segmentation as first described in Peterson and Lehiste (1960) classic study on the duration of vowel nuclei. For /l/, the end of the steady portion of the typical formant values for /l/ (see below) was taken as offset of /l/. For /R/, the low third formant was the best indicator. The point at which the frequency movements of the third formant started to increase served as offset of /R/.[3]

Determining the onset of the liquids was somewhat difficult, since the acoustic landmarks indicating the presence of the liquid after a voiceless stop consonant are not as clear as those for liquid-vowel transitions. For /R/, the presence of a low F3 was used again as acoustic landmark for determining its starting point. Determining the starting point for /l/ was more complex and made use of the locus model (Delattre et al., 1955). The formant transition patterns of the first and second formant after the release of voiced stops are easily visible in a spectrogram and have been well described (Delattre et al., 1955). The same formant transition patterns can be found after the release of voiceless stops (Johnson, 1997; Stevens, 2000), however, they are not as easily visible, since the formants are not excited by vocal fold vibration, but similar to the formants visible in /h/ sounds - by the air stream leaving the oral cavity after the release. According to the locus model, the hypothetical starting frequency of F2 for bilabial stops is around 720 Hz, for alveolar stops around 1,800 Hz, and for velar stops around 3,000 Hz. However, since the release portion of a stop is a movement rather than a posture, the information about the place of articulation contained in the release portion is seen in formant movements rather than in particular formant values. Making use of the locus model, we can infer the formant movement for F2 because we can calculate the typical formant values for /l/ (F1 ca. 530 Hz, F2 ca. 1,600 Hz, and F3 2,650 Hz and an anti-formant around 2,125 Hz) using a tube model (Johnson, 1997). The formant transition in the release portion of /p/ before /l/, therefore, is rising from the hypothesized F2 locus value 720 Hz for /p/ to the F2 value of 1,600 Hz for /l/. The end of this rising formant transition in the second formant was taken as the beginning of /l/. The formant transition in the release portion after /k/ before /l/ is a falling one, starting at the hypothesized F2 locus value of 3,000 Hz for /k/ falling to the F2 value of 1,600 Hz for /l/. The end of this falling formant transition in the F2 was taken as the beginning of the /l/.

Using the acoustic landmarks described above, the following measurements on each utterance were taken: VOT (as described above); duration of liquid (as described above); duration of absence of voicing during the liquid (= time from onset of liquid to the offset of VOT); duration of the sequence from release burst to the offset of liquid; and finally, the percentage of voicelessness during the liquid and during the stop-liquid sequence as a whole was calculated. On the obtained values an ANOVA was carried out and tested for significant effects of the independent variables: boundary condition (within versus across boundary), place of articulation and speaking rate on the dependent variables: VOT and amount of devoicing during the liquid.

4. Results

4.1. VOT and Devoicing in Tautosyllabic and Heterosyllabic Sequences

The first research question was concerned with whether the syllable / morpheme boundary had a significant influence on the two parameters: VOT and devoicing.

[3]Note, that it was possible to use the third formant as reliable acoustic cue for the current study, since the only two rhotics contained in the data here were alveolar approximants (American English) and alveolar trills (Thai and Hungarian) which both have been found to display a low third formant (Lindau, 1985). Other rhotics, such as uvular /R/ sounds are different in that they have a relatively high third formant.

4.1.1. English

For English, the VOT in the tautosyllabic condition tended to be longer than in the heterosyllabic condition, but the difference was not significant (F = 3.8; p = .1473) when averaged across all subjects. However, a highly significant interaction between syllable condition and place of articulation of the stop was found (F = 13.3; p = .0002), suggesting that whether or not the VOT differed with the occurrence of the sequence across versus within a syllable boundary depended on the stop consonant in the sequence. While VOT differed significantly for /ɹ/ versus /t.ɹ/ (p = .03) and for /kl/ versus /k.l/ (p = .02), it differed marginally for /pl/ versus /p.l/ (p = .09) and not at all for /kɹ/ versus /k.ɹ/ (p = .33) and /pɹ/ versus /p.textturnr/ (p = .11). This result is surprising, since we had expected that all the stop-liquid sequences would pattern together since they form a coherent group phonologically (voiceless stop plus liquid). At this point no explanation for this result can be offered.

If we turn now to the parameter of devoicing, we find that liquids devoice significantly more in the tautosyllabic condition than they do in the heterosyllabic condition (F = 51.14; p = .0056). The percentage of devoicing differed significantly for all stop-liquid sequences in the two conditions: /kl/ versus /k.l/ (p = .03), /pl/ versus /p.l/ (p = .05), /kɹ/ versus /k.ɹ/ (p = .05), /ttextturnr/ versus /t.textturnr/ (p = .005), and /pɹ/ versus /p.textturnr/ (p = .04). This is illustrated in Figure 1:

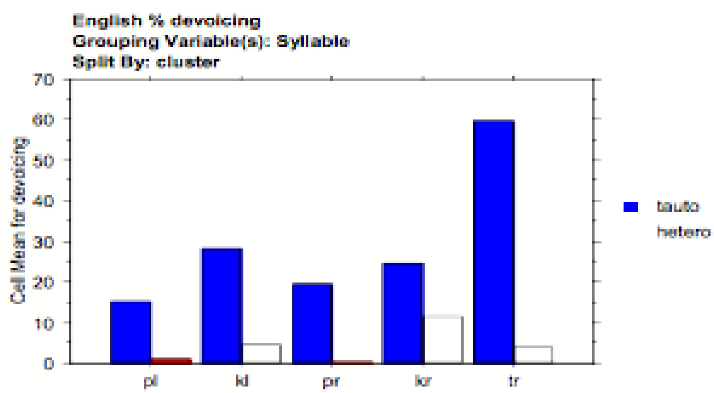

Figure 1: Difference of VOT in heterosyllabic and tautosyllabic stop-liquid clusters.

The results for English suggest that the presence of a syllable /morpheme boundary affects the liquid and the VOT in similar ways. However, the liquid is affected more consistently than the VOT.

4.1.2. Hungarian

For Hungarian no significant difference in the length of VOT in tautosyllabic versus heterosyllabic stop-liquid sequences was found (F = 1.8; p = .27). If we turn to the percentage of devoicing in the liquids, we find a tendency for the liquids in the tautosyllabic condition to devoice more than for those in the heterosyllabic condition. However, the difference in the percentage of devoicing between the liquid in the two conditions was for the most part not significant (F = 5.67; p = .14). The only stop-liquid sequence for which the percentage of devoicing in the liquid was marginally different was /k.l/ versus /kl/ (p = .06). The pattern of the effect of the syllable / morpheme boundary on the percentage of devoicing in the liquid in Hungarian appear similar to those found in the English data. However, unlike in English, the effect is not statistically significant.

4.1.3. Thai

If we now turn to Thai, we find that the VOT in stop-liquid sequences within a syllable onset does not differ significantly from the VOT in sequences across syllable boundaries (p = .79). If any tendency is discernible, it is the inverse tendency observed for Hungarian and English: the VOT in the heterosyllabic condition tends to be somewhat longer than the VOT in the tautosyllabic condition. This tendency, however, seems to be limited to sequences containing the liquid /r/.

A look at the percentage of devoicing in the liquid shows that the tendency observed in the distribution of VOT is also apparent in the amount of devoicing of the liquid. The liquids in the heterosyllabic condition tended to devoice more than in the tautosyllabic condition, with exception of those liquids following the stop /p/. However, this tendency again was not statistically significant (p = .297). The results for Thai seem to suggest that the presence of a syllable / morpheme boundary affects VOT and the percentage of devoicing of the liquid in a similar, but in a rather idiosyncratic way. The effect on both, VOT and percentage of devoicing of the liquid is not statistically significant.

4.1.4. Discussion

This section investigated the effect of a syllable/morpheme boundary on VOT and on the amount of devoicing in the liquid. The results are summarized in Table 1:

	VOT	%Devoicing
English	marginally	yes
Hungarian	no	marginally
Thai	no	no

Table 1: Effect of syllable/morpheme boundary on VOT and % devoicing.

The results for the three languages show that the VOT is not significantly affected by the presence of a syllable / morpheme boundary in any of the three languages. This result is consistent with results previously reported for English, as for example by Docherty (1992) who found that it was not the mean length of the VOT that distinguished syllable internal stop sonorant sequences from sequences across a syllable boundary as for example suggested in Kahn (1976). The only difference between stop sonorant sequences within and across syllable boundaries that Docherty (1992) found was a tendency for stops with a long VOT to occur more frequently in syllable onsets.

The percentage of devoicing of the liquid, on the other hand, was significantly different in English. The liquids that occurred in a complex onset following a stop consonant were significantly more devoiced than those that occurred as single onset consonant following a stop consonant in the preceding syllable coda. While we find the same tendency in the Hungarian data, the Hungarian liquids in the tautosyllabic condition were not significantly different from those in the heterosyllabic condition. Finally, we found that the Thai data did not show any systematic effect of the syllable boundary on the percentage of devoicing in the liquid.

The English results show that the presence of a syllable / morpheme boundary affects the liquid more than the VOT, which is more closely linked to the stop consonant. This suggests that the difference between tautosyllabic and heterosyllabic stop-liquid sequences lies in the alignment of laryngeal and supralaryngeal gestures rather than in a difference of the magnitude of the laryngeal feature alone. While a single laryngeal gesture seems to overlap with two oral gestures in tautosyllabic stop-liquid sequences, the laryngeal gesture seems to be aligned with the oral gesture of the stop in heterosyllabic stop-liquid sequences. The fact that the difference between tautosyllabic and heterosyllabic sequences is statistically significant in English, but not in Hungarian seems to suggest that a phonological rule governing the gestural overlap is active in English, but only developing or marginally present in Hungarian. The Thai data does not suggest the presence of any such rule in Thai phonology.

4.2. Adjustment of VOT and Devoicing with Speaking Rate

The second research question was concerned with whether or not VOT and / or devoicing adjust with speaking rate. The results discussed above showed some interaction between the tautosyllabic versus heterosyllabic condition for all three languages. In addition, an interaction between speaking rate and VOT as well as the amount of devoicing in the liquid was found in the data. The question of whether VOT and devoicing adjust with speaking rate was established for each condition, tautosyllabic and heterosyllabic, separately. Speaking rate was measured as duration of the stop liquid sequence. Figure 2 illustrates that the mean duration of the sequence was considerably longer at the slow and medium speaking rate compared to the fast speaking rate in English and Thai, and that all three speaking rates were significantly different in Hungarian.

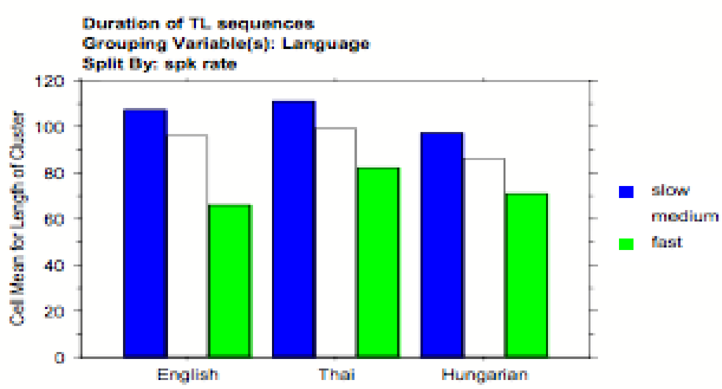

Figure 2: Mean duration of stop-liquid sequences in slow, medium, and fast speech.

For English the duration of the stop-liquid sequences at the fast speaking rate (mean = 66 ms, SD = 20) was significantly shorter (p ¡ .0001) than at the medium (mean = 96 ms, SD = 32) or slow (mean = 107, SD = 34) speaking rate. The duration of the sequence in Thai was also significantly shorter (p = .03) at the fast speaking rate (mean = 83 ms, SD = 24) compared to the medium (mean = 99, SD = 33) and the slow (mean = 111, SD = 43) speaking rate. In Hungarian the duration of the sequence was significantly different for all three speaking rates. The sequence at the fast speaking rate (mean = 71 ms, SD = 18) was significantly shorter (p = .0007) than at medium speaking rate (mean = 86 ms, SD = 18), which, in turn, was significantly shorter (p = .009) than at the slow speaking rate (mean = 97 ms, SD = 21).

4.2.1. English

In the English data, we find a significant interaction between VOT and speaking rate in both the tautosyllabic (F = 17.5; p = .0031) and the heterosyllabic condition (F = 10.2; p = .0117). The VOT in both conditions was proportionally shorter at the fast speaking rate compared to medium and slow speaking rate, indicating that the VOT adjusts to speaking rate. As mentioned in the previous section, the medium and slow speaking rate were not significantly different from each other in the mean duration of the stopliquid sequence. However, in the tautosyllabic condition, where stop and liquid form a complex onset, we find a stronger linear correlation of the VOT with the length of the stop-liquid sequence (Pearsons r = .740) than in the heterosyllabic condition (Pearsons r = .590).

In order to assess the influence of speaking rate on the amount of devoicing of the liquid, the absolute duration of absence of voicing in ms during the liquid was taken (rather than the percentage) to determine whether the amount of devoicing differed significantly across the three speaking rates. This was done because the percentage of devoicing is a relative measurement that neutralizes the effect of speaking rate which expresses a proportion rather than an absolute value. We find that the amount of devoicing as expressed in the duration of absence of voicing during the liquid differs significantly in the tautosyllabic condition (F = 22.945; p = .0064) indicating that the amount of devoicing does adjust to speaking rate. In the heterosyllabic condition, however, we find that the amount of devoicing of the liquid does not differ significantly across the different speaking rates (p = .2228). Figure 3 illustrates these results:

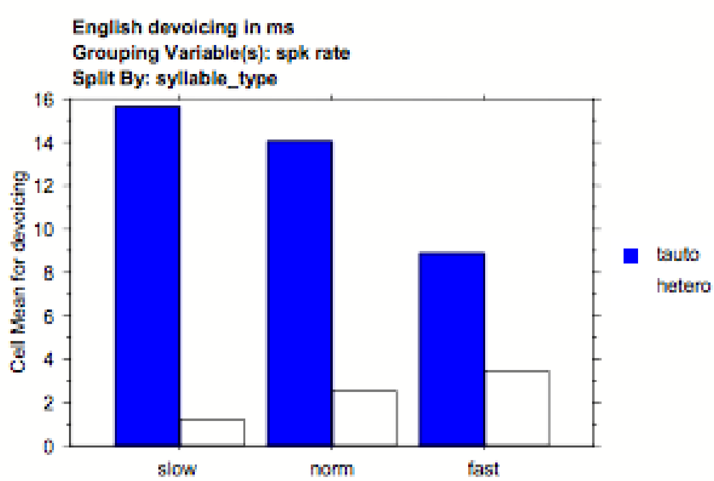

Figure 3: Effect of speaking rate on devoicing of the liquid in English.

The results show that in English the VOT as well as devoicing of the liquid interact with speaking rate. However, while the VOT adjusts to speaking rate in the tautosyllabic as well as in the heterosyllabic condition, the duration of devoicing during the liquid adjusts to speaking rate only in the tautosyllabic condition.

4.2.2. Hungarian

For Hungarian, the VOT at the three different speaking rates is not significantly different in the tautosyllabic condition (p = .3554). However, we do find a significant difference between the VOT at fast and slow speaking rate (F = 9.009; p = .0102) in the stop-liquid sequences across syllable boundary suggesting that the VOT adjusts to speaking rate in the heterosyllabic condition. The VOT for the three speaking rates in the tautosyllabic and heterosyllabic condition are shown in Figure 4:

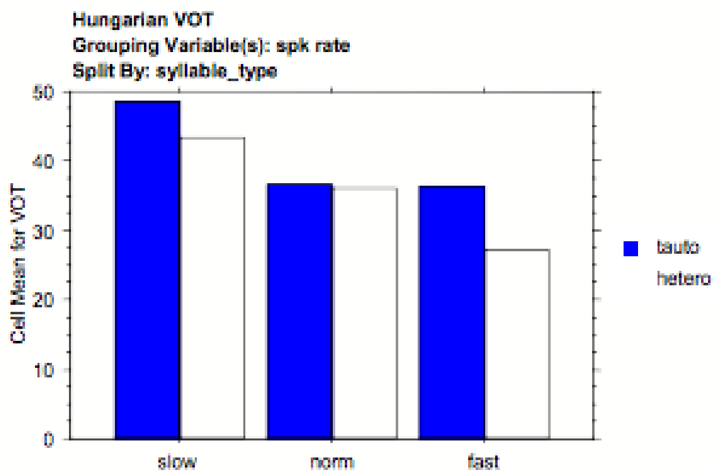

Figure 4: Effect of speaking rate on VOT in Hungarian.

If we now turn to the duration of voicelessness during the liquid, we find that the amount of devoicing does not adjust to speaking rate in either the tautosyllabic (p = .1314) or in the heterosyllabic condition (p = .2198).

4.2.3. Thai

For the Thai stopliquid sequences in the tautosyllabic condition, the VOT does not differ significantly across the three speaking rates (p = .2015). Similar to Hungarian, we do find a tendency for the VOT in the heterosyllabic condition to adjust with speaking rate (F = 12.732; p = .0184). These results are illustrated in Figure 5:

The duration of devoicing during the liquid again like Hungarian - does not adjust to speaking rate in Thai, as it does not differ significantly across the three speaking rates in either the tautosyllabic (p = .5867) or the heterosyllabic condition (p = .2349).

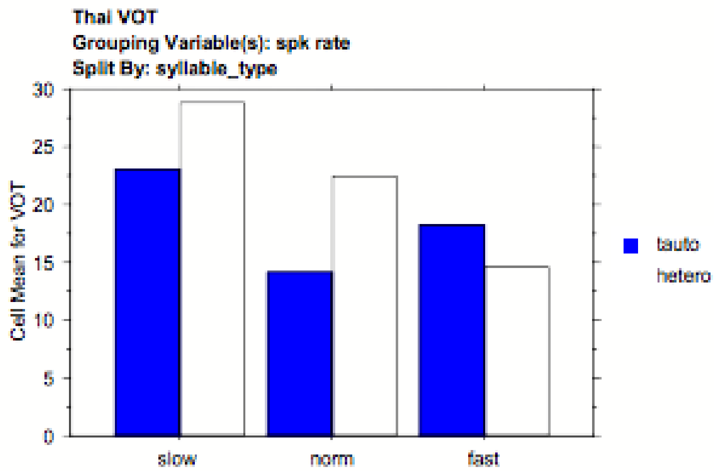

Figure 5: Effect of speaking rate on VOT in Thai.

4.2.4. Discussion

In this section we have examined whether or not the VOT and/or the amount of devoicing of the liquid adjusts to speaking rate in the three languages under investigation. The results are summarized in Table 2:

	VOT		Devoicing of liquid	
	tautosyllabic	heterosyllabic	tautosyllabic	heterosyllabic
English	yes	yes	yes	no
Hungarian	no	yes	no	no
Thai	no	yes	no	no

Table 2: Adjustment of VOT and devoicing of liquid to speaking rate.

The fact that the VOT in English adjusts with speaking rate is not surprising, since it has been shown before that the VOT in aspirated voiceless stops in stop-vowel sequences is longer at a slow speaking rate and shorter at a fast speaking rate, while voiceless unaspirated or voiced stops have not been found to exhibit such an adjustment (Miller et al., 1986). However, the result that the voiceless unaspirated stops in Thai and Hungarian also show adjustment to speaking rate when occurring as the last consonant in a syllable coda is surprising. Previous studies that investigated the effect of speaking rate on voiceless unaspirated stops in Thai (and also French) such as Kessinger and Blumstein (1997) only looked at syllable initial stop consonants and found - consistent with the current study that the VOT of voiceless unaspirated stops does not adjust to speaking rate. A possible explanation for this behavior of syllable final unaspirated voiceless stops in Thai may lie in the fact that syllable initially the unaspirated voiceless stops in Thai may contrast with aspirated voiceless stops, whereas syllable final stops in Thai do not contrast in either voicing nor aspiration (Henderson, 1970). A similar explanation for Hungarian, however, is not at hand, since Hungarian does not contain voiceless aspirated stops in its phoneme inventory.

As far as the importance of the adjustment of VOT to speaking rate for laryngeal coarticulation is concerned, it seems that the observed VOT pattern are solely a property of the stop consonant and do not seem to contribute to the devoicing of the liquid since they have also been observed in stop-vowel sequences as mentioned above and they occur independent of liquid devoicing as seen in the data discussed here. Therefore, the observed VOT pattern cannot contribute much to the answer of the research question of whether laryngeal coarticulation adjusts to speaking rate. The results presented above show that devoicing of the liquid adjusts proportionally to speaking rate only in the English tautosyllabic condition, indicating that devoicing in that condition originates at the level of gestural planning, and, therefore, should be considered phonological in English, but not in Hungarian or Thai.

4.3. Language Specific Differences and Similarities

One respect in which the three languages differ is the phonetic category of the stop consonants. While English voiceless stops are classified as aspirated stops, the Hungarian voiceless stops have been claimed to be unaspirated (Gósy, 2001). The Thai stops used in the current study were also voiceless unaspirated. This classification corresponds to some degree with the VOT values obtained from the three languages in the current study. Averaging across all subjects and utterances for each language, we find that the VOT in English is significantly longer than in Thai (p ¡ .0001). However, although the VOT in Hungarian tended to be somewhat shorter than in English, the difference between the English and Hungarian VOTs was only marginally statistically significant (p = .07). The difference between Hungarian and Thai on the other hand was statistically significant ($p < .0001$). This suggests that Hungarian stops should be categorized phonemically as aspirated rather than unaspirated stops.

The expectation stated earlier was that the VOT would be correlated with the amount of liquid devoicing. However, once again, we find that VOT does not predict very well how much devoicing to expect. While the VOT in Hungarian stops was only marginally shorter than the VOT in English stops, the amount of devoicing in Hungarian liquids following a voiceless stop is significantly greater (p = .03) than in English. The overall percentage of devoicing in Thai is significantly less than either English (p = .001) or Hungarian (p = .0001).

The other difference in phoneme identity lay in the difference between the rhotics: trilled /r/ for Hungarian and Thai, and the alveolar approximant /ɹ/ in English. However, the overall difference in VOT and percentage of devoicing in the liquids for the three languages, as well as the languages specific differences with respect to the influence of the presence of a boundary and speaking rate observed above are confounding factors that render a general comparison of the difference between the two types of rhotics impossible.

5. Discussion and Conclusion

The study reported in this paper investigated the devoicing of liquids in voiceless stop-liquid sequences in Thai, Hungarian, and English. More specifically, the study investigated whether liquid devoicing is influenced by the presence of a syllable or morpheme boundary between the voiceless stop and the liquid, and whether it adjusts to speaking rate. The results showed that the VOT was marginally influenced by a boundary in English, but not at all in Hungarian and Thai. The amount of devoicing, on the other hand, was significantly influenced by the presence of a boundary in English, marginally influenced in Hungarian, and not at all in Thai. Furthermore, the results indicated that for sequences in the onset of a syllable the VOT adjusted to speaking rate only in English; however, across syllable boundaries the VOT adjusted in all three languages. The effect that speaking rate had on the amount of devoicing was very similar for the tautosyllabic condition in that only in English the amount of devoicing adjusted to speaking rate. In the heterosyllabic condition, however, the amount of devoicing in the liquid did not adjust to speaking rate for any of the three languages. This mismatch in the patterning of VOT and devoicing shows that the devoicing of liquids in voiceless stop-liquid sequences does not correlate with the VOT of the voiceless stop. While the VOT seems to be the primary phonetic cue for the categorization of the stop as voiceless aspirated or voiceless unaspirated in all three languages, the function of liquid devoicing liquid seems to differ in the three languages.

In English the amount of devoicing in the liquid seems to provide the phonetic cue for the syllable position of the stop, syllable initial versus syllable final. In Hungarian liquid devoicing differs only marginally, and, therefore, might not be a very strong cue for syllable position. In Thai, the amount of devoicing in the liquid following a voiceless unaspirated stop does not provide a phonetic cue for syllable position of the stop. This suggests that liquid devoicing is phonological in English as it is sensitive to the presence of a syllable/morpheme boundary, and adjusts to speaking rate in the tautosyllabic condition. Hungarian is only marginally sensitive to the presence of a syllable/morpheme boundary, and does not show adjustment to speaking rate of liquid devoicing, indicating that liquid devoicing is much less planned than in English. Finally, there is no planned liquid devoicing in Thai as no systematic patterns of devoicing were revealed in this study.

The differences between the devoicing patterns found in the three languages can be explained in terms of the gestural organization as follows: liquid devoicing in English can be seen - as suggested by Browman and Goldstein (1986a) as originating from a rule that specifies gestural overlap of the laryngeal gesture (open glottis) with the oral gestures for the stop and the liquid. For Thai, the timing of the laryngeal gesture is specified to end simultaneously with the oral gesture of the stop consonant. However, for Hungarian, no specific rule for the temporal alignment of laryngeal and oral gestures is discernible. One suggestion might be that Hungarian is developing a system similar to the one found in English, however, no substantial proof for this hypothesis can be offered without further investigation.

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