Articulatory Binding

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1 The mismatch between phonological and phonetic representations

The division[1] of the stream of speech into a string of discrete segments represents the number of places where contrast between the current speech event and others is possible. Discrete segments may not only be employed to represent phonological contrasts in speech events, however, but also in the plans for actually uttering them. Beyond isomorphism with phonological representations, the appropriateness of discrete segments at some level in the plans speakers employ to produce utterances is demonstrated by the fact that the vast majority of speech errors reorder entire segments rather than parts of segments or features (Shattuck-Hufnagel & Klatt 1979). This speech error evidence does not, however, reveal whether a segment-sized unit is employed at all levels in the plan for producing an utterance, nor what principles govern the coordination of articulators.

Since more than one articulator is moving or otherwise active at any point in time in a speech event, the notion of a segment implies a specification for how these independent movements are coordinated. However, articulatory records of speech events cannot be divided into discrete intervals in which all movement of articulators for each segment begins and ends at the same time, nor can these records be obtained by a simple mapping from discrete underlying phonological segments. The continuous and coarticulatory properties of actual speech events instead make it very unlikely that the plans for producing them consist of nothing more than a string of discrete segments (Öhman 1966, 1967; Fowler 1980; Browman & Goldstein 1985, 1986; but cf. Henke 1966; Keating 1985). Looking up from the

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1. This paper will appear in J. Kingston & M. Beckman (eds.) Papers in Laboratory Phonology I: Between the Grammar and Physics of Speech. Cambridge: Cambridge University Press.

phonetic to the phonological representation, the discrete phonological segment derived from the commutation of contrasting elements is at best covert.

Discreteness has, moreover, gradually disappeared from phonological representations, in two widely-separated steps. The first step broke the segment into a bundle of distinctive features, a move which can be traced back at least to Trubetzkoy (1939). Entire segments are still formally discrete, but they are no longer indivisible atoms. This step necessarily preceded breaking up the feature bundles themselves into linked tiers on which the domain of each feature is independently specified (Goldsmith 1976, Clements 1985, Sagey 1986). Discreteness survives in these models only in the timing units of the skeleta (Clements & Keyser 1983), and even the equation of the timing unit represented by the traditional segment with these timing units is presently in question (McCarthy & Prince 1986). Since the domain of feature specification in nonlinear phonological representations is both larger and smaller than the traditional segment, these representations remove any principled phonological reason to expect to find discrete segments in speech events. Discrete segments cannot be found in speech simply because they are not there in the phonological representation anymore than in the phonetic one. Giving up the idea of the segment as a discrete element in phonological as well as phonetic representations requires some other principles for coordinating articulations, however, since the evidence for such coordination is patent.

The principles of coordination which have been devised so far in nonlinear phonological models are largely formal in nature. They include one-to-one, left-to-right mapping (Goldsmith 1976, Clements & Ford 1979), the projection of P-bearing units (Clements & Sezer 1982), the no-crossing prohibition (Goldsmith 1976, Kenstowicz 1982, Sagey 1986), geminate integrity (Schein & Steriade 1986) or inalterability (Hayes 1986), the obligatory contour principle (Leben 1978, McCarthy 1986), and the shared feature convention (Steriade 1982). Parallel principles for coordinating articulations in the plans speakers employ in producing speech must also be discovered (see Browman & Goldstein 1985, 1986, to appear for other proposals). This paper presents such a phonetic principle of coordination, which constrains when glottal articulations in consonants occur relative to oral ones. I refer to these constraints as "binding".

2 The binding principle

The binding principle is intended to account for two fundamental asymmetries in the distribution of glottal articulations (see Maddieson 1984):

1. Stops are much more likely to contrast for glottal articulations than either fricatives or sonorants, and
2. Glottal articulations in stops are much more frequently realized as modifications of the release of the oral closure than its onset.

The principle attempts to account for these asymmetries in terms of two kinds of phonetic differences between stops and continuants.

First, both the state of the glottis and degree of constriction downstream may affect the pressure of the air inside the oral cavity, and thereby the acoustics of the sound produced. Changes in the size of the glottal aperture and the tension of the folds influence the resistance to air flow through the glottis, and therefore have the control of air flow through the glottis into the oral cavity as their proximate function. In obstruents, the distal function of the changes in glottal resistance which affect glottal air flow is to manipulate intraoral air pressure. The larger the glottal aperture and the lower the fold tension, the more glottal resistance will be reduced, the more air will flow through the glottis, and the more rapidly air pressure will rise in the oral cavity behind the obstruent articulation. This aerodynamic interaction between glottal and supraglottal articulations will be most dramatic in stops since the downstream obstruction of air flow is complete. The amount that intraoral air pressure is elevated behind the stop closure together with the size of the glottal aperture determine the acoustic character of the explosive burst of noise that occurs when the stop is released. Glottal aperture affects the acoustics of the burst both by the aerodynamic means just described and by determining what acoustic coupling there is between supra- and sub-glottal cavities. The acoustic character of the burst therefore at once depends on and cues the state of the glottis.

Second, the release of a stop is acoustically distinct from its onset. A burst of noise is produced at the stop release as a result of the sudden opening of the oral cavity. Because the acoustic character of the burst reflects the size of the pressure buildup behind the obstruction (and acoustic coupling to the subglottal cavity), glottal articulations are expected to be coordinated with that part of the stop rather than its onset. No burst occurs at the release of a continuant's articulation because their obstruction of air flow is not complete. The release of a fricative or sonorant will therefore be the acoustic mirror image of its onset. With a less than complete obstruction, variations in glottal air flow will affect intraoral air pressure less, since the more open the articulation, the less air is trapped behind it. The goal of the glottal articulations which accompany continuant, especially approximant, articulations can therefore be only the proximate modification of the source.[2] Fricatives are actually intermediate between stops and approximants, since their oral aperture is small enough to obstruct air flow, elevate intraoral air pressure, and accelerate flow through the oral constriction enough to create noisy turbulence. This elevation of intraoral air pressure depends upon a sufficiently large glottal aperture; voiceless fricatives exhibit the widest glottal aperture of any voiceless consonant, and even voiced fricatives are produced with a more open glottis than corresponding voiced stops or sonorants (Hirose & Gay 1972, Hirose, Lisker, & Abramson 1972, Collier, Lisker, Hirose, & Ushijima 1979). These larger glottal apertures would also alter the spectrum of the fricative noise by increasing the acoustic coupling between the supra- and sub-glottal cavities. How this coupling influences the acoustics and perception of fricatives cannot be gone into in this paper, beyond noting that all the acoustic effects of the wide aperture will be distributed across much of the fricative interval. Such distirbuted acoustic effects of glottal articulations probably characterize continuants in general, in contrast to stops, where they are confined to moment of the release and the short interval imediately following it. In general terms, the acoustic effects of glottal articulations in stops are disjoint from and follow the acoustic effects of the oral articulations, while in continuants they are much more nearly simultaneous.

The binding principle claims that a glottal articulation is more constrained -- more tightly "bound" -- in when it occurs the more the oral articulation obstructs the flow of air through the vocal tract: a glottal articulation

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2. What is essential here is whether the supraglottal articulation causes pressure to build up above the glottis. The binding principle therefore does not distinguish between nasal and nonnasal sonorants, i.e. between segments in which air is allowed to escape through the nose from those where it escapes through the mouth.

is most tightly bound to a stop, since air flow is completely obstructed by the stop closure, while the lesser obstruction of a fricative or approximant allows the glottal articulation to shift with respect to the oral one. Since degree of obstruction is neither an articulatory nor acoustic continuum -- both the transition from approximation to constriction and from constriction to closure involve crossing of thresholds --, the binding principle partitions segments into distinct manners. Usually just two are distinguished: either stops vs. fricatives and sonorants, i.e. noncontinuants vs. continuants, or stops and fricatives vs. sonorants, i.e. obstruents vs. approximants. The dividing line appears to fall most often between stops and continuants, despite fricatives' dependence for noise production on an adequate glottal air flow.

The binding principle predicts that the timing of oral articulations determines when glottal articulations will occur and that timing depends on the continuancy of the oral articulation. The onsets and offsets of glottal articulations will be more or less synchronized with the onsets and offsets of oral articulations in continuants, but not in stops. In the latter, they will align with the release so as to modify it and the immediately following interval acoustically. Alignment of glottal articulations in stops with the release is apparent in voice onset time (VOT) contrasts, in which adduction of the glottis is timed with respect to the release of the stop. Glottal articulations are also aligned with the stop release in at least two other kinds of stops, breathy voiced stops and ejectives, which do not participate in VOT contrasts. Partial abduction begins with or just before the release of the stop in breathy voiced stops and tight glottal closure combines with reduction of oral volume to produce an intense burst at the release of an ejective. This alignment again has the effect of concentrating the acoustic effects of the glottal articulations in the immediate vicinity of the release.

The next section of this paper addresses the problems that pre-aspirated stops of the sort found in Icelandic present to the claim that glottal articulations bind to a stop's release rather than its closure. It is shown that both in the phonology and phonetics of Icelandic, pre-aspirates are not after all a problem for this aspect of the binding principle. The final part of the paper explores a number of further problems with the binding principle and proposes tentative resolutions of them.

3 The problem of pre-aspirates

3.1 Introduction

3.1.1 The oral-glottal schedule in pre-aspirated stops

Icelandic has a class of stops which are traditionally called "pre-aspirated," since the glottis opens before the oral closure is made, producing a preceding interval of noise. Pre-aspirates are markedly rarer in the world's languages, at least as a contrasting type, than the common post-aspirates. Contrary to the prediction of the binding principle, this early abduction of the glottis may be bound to the onset of the oral closure, in contrast to the post-aspirated stops in which abduction is bound to the release of the closure. Since Icelandic also has post-aspirated stops, a contrast appears to exist in this language between stops whose glottal abduction binds to the stop closure and those where it binds to the release.

In Icelandic pre-aspirated stops (Petursson 1972, 1976, Thrainsson 1978, Lőfqvist & Yoshioka 1981b, Chasaide p.c.), the glottis begins to open during the preceding vowel, partially devoicing it. Pre-aspiration generally has the timbre of that vowel. There is some uncertainty about when peak glottal opening is reached and when the folds are again adducted, however. Lőfqvist and Yoshioka's data indicate a small glottal opening that peaks before the stop closure, with adduction coinciding with the beginning of the stop closure, while both Petursson's and Chasaide's data show a much larger peak opening that is aligned to the closure, with adduction not occurring until the stop is released or even somewhat after. Pre-aspirated stops in Lőfqvist and Yoshioka's data invert the order of glottal and oral articulations found in breathy voiced stops such as occur in Hindi, in which the glottal opening (largely) follows the release of the oral closure (Kagaya & Hirose 1975, Benguerel & Bhatia 1980), while the pre-aspirates observed by Petursson and Chasaide are the mirror image -- relative to the stop closure and release -- of post-aspirates, in which the glottis begins to open at the onset of the oral closure, reaches peak opening at release, and is only adducted noticeably later. In either case, the timing of glottal abduction relative to the oral closure in pre-aspirates contrasts with that found in another stop type in which the opening of the glottis is likely to be bound to the release of the closure, either breathy voiced or post-aspirated stops.

3.1.2 The phonology of pre-aspiration in Icelandic

Pre-aspiration in Icelandic (Garnes 1976, Thráinsson 1978), and perhaps in the other languages in which it is found, arises only from underlying clusters and not from single segments. On the surface, pre-aspirated stops contrast with unaspirated geminate or single stops between vowels and with post-aspirated stops, but before nasals or laterals the contrast is only between pre-aspirates and single unaspirated stops. The syllable boundary falls after the stop in the latter sort of clusters. Even when they occur alone, Icelandic pre-aspirates all retain one quite overt property of surface heterosyllablic clusters: only short vowels may precede them, which also indicates that they close the preceding syllable. On the other hand, vowels are long before post-aspirates in this language, whether occurring alone or followed by a glide or rhotic. Post-aspirates and clusters beginning with them must therefore belong only to the following syllable.

In all dialects, pre-aspirates arise from underlying geminate aspirates, but the sources of pre-aspiration or a close analogue of it are by no means restricted to those. In Southern Icelandic dialects, underlying clusters of a voiced fricative, nasal, lateral, or rhotic preceding an underlying aspirated stop are typically realized with the first segment is voiceless and the second unaspirated. In Northern dialects, a more restricted set of consonants undergoes devoicing before underlying aspirates. In both sets of dialects, when the first consonant devoices, the second is underlyingly aspirated, i.e. [+ spread], and when the first consonant remains voiced on the surface, the following stop is invariably post-aspirated. Since devoicing of the first segment co-occurs with an obligatory absence of post-aspiration on the stop, it represents the shift of the [+ spread] specification to the first segment from the stop.

Furthermore, in most dialects the first stop in heterorganic clusters of stops where the second is underlyingly aspirated is realized as the corresponding voiceless fricative, and again, if the stop spirantizes, the second may not be post-aspirated. Since voiceless fricatives demand a very wide glottal aperture to elevate air flow through the glottis sufficiently to produce turbulence downstream through the oral constriction, this realization can also be seen as a shift of [+ spread] to the first element of the cluster. Finally, as in many other languages, Icelandic stops do not contrast for aspiration after /s/, a segment which demands at least as wide a glottal aperture as the other voiceless fricatives.

In general terms, not only may just one segment bear a [+ spread] specification in surface forms, but only one segment in the cluster needs to (or can) be specified as [+ spread] in underlying forms. In all these cases, underlying specification of the second member of the cluster as [+ spread] is phonetically realized as a property of the first rather than the second element of the cluster by a quite general procedure in the language. In all dialects, clusters in which the final stop is underlyingly [+ spread] contrast with others in which the final stop is not [+ spread]. In the latter sort of cluster, the preceding consonant remains voiced uniformly.

Since it arises only in clusters whose second member is [+ spread], pre-aspiration cannot contrast directly with post-aspiration. The latter arises only when an underlying [+ spread] stop occurs in absolute initial position in word or directly after a vowel. Generalizing, pre-aspiration arises in syllable codas in heterosyllabic clusters whose second member is [+ spread] as a result of a shift of this specification to the preceding coda. On the other hand, post-aspiration is only found in singleton [+ spread] stops or those which are the first member of a tautosyllabic cluster, i.e. in onsets rather than codas. Formulaically, /aC.p^{h}a/ is realized as [aC^h.pa], while /aa.p^h(C)a/ undergoes no change. The failure of pre-aspirates to ever contrast directly with post-aspirates within morphemes in Icelandic eliminates them as a problem for the binding principle, at least insofar as the phonology of the language is concerned. (The analysis outlined above is a generalization of Thrâinsson's (1978). I am indebted to Donca Steriade for making the significance of devoicing in the initial segments of clusters ending in [+ spread] stops clear to me.)

3.2 Pre-aspirates as a test of the binding principle in the phonetic component: The covarying durations of glottal abduction and flanking oral articulations

3.2.1 Introduction

An experiment was designed to determine whether the abduction of the glottis is still after all part of the same articulatory unit as the following stop closure in pre-aspirated stops, since there is no a priori reason why the units of articulation should be identical to underlying ones. If pre-aspiration is coordinated with the following stop rather than the preceding vowel, then glottal articulations must be allowed to bind phonetically to the closure as well as the release in stops, despite the absence of any event as salient as the release burst at the beginning of the closure.

This experiment assumes that if two articulations are coordinated with one another, their individual durations will covary across global changes in segment duration, due to changes in rate or prosodic context, i.e. coordinated articulations should exhibit relational invariance (Tuller & Kelso, 1984). Specifically, if abduction of the glottis is coordinated with an adjacent or overlapping oral articulation, then the duration of abduction should covary with that of the oral articulation. If the binding principle is correct, then the duration of an abduction which overlaps the release of a stop closure, as in post-aspirated stops, should correlate positively with the duration of the closure, but no necessary correlation should be observed when abduction does not overlap the release, as in pre-aspirated stops. Pre-aspiration may instead be coordinated with the preceding vowel and its duration might covary with the duration of that segment. Alternatively, glottal abduction in pre-aspirated stops may be coordinated with no oral articulation. The binding principle does not distinguish between the two possibilities.

3.2.2 Methods

A single female speaker of Icelandic was recorded producing words containing medial pre- and post-aspirated stops under conditions that would change segment durations. Since the binding principle predicts coordination of glottal abduction with the preceding stop, specifcally its burst, in post-aspirated stops, covariation of the durations of oral and glottal articulations in them can be compared with that in pre-aspirated stops. Medial breathy-voiced and post-aspirated stops were also recorded from a single female speaker of Hindi under similar conditions. Since abduction overlaps or follows the stop release in both breathy voiced and post-aspirated stops, these Hindi data provide an additional test of the positive prediction of the binding principle that abduction will be coordinated with a release burst that it overlaps temporally.

All tokens in both languages were produced medially in short frame sentences, with the sentences read in a different, random order for each repetition. The Icelandic speaker produced a variety of real words containing pre- and post-aspirated stops between the first, stressed syllable and the second. (Lexical stress occurs obligatorily on the first syllable in Icelandic words.) The Hindi speaker produced nonsense words of the shape [a___a] or [a___apa] with the stops in the blanks. In alternate readings, the Icelandic speaker put focus on the test word itself or on the immediately preceding word. Segments are expected to be longer in words in focus than in those not in focus, particularly in the vicinity of the stressed syllable. Final lengthening would lead one to expect longer segments in the Hindi words where only one syllable follows the stop than when two do. Both of these manipulations, though they are quite different from one another, should therefore affect the duration of the stops, and their component articulations. In addition, for both languages, each way of reading the words was produced at self-selected moderate and fast rates. This orthogonal variation in rate will also affect segment duration, though more globally than focus or the number of following syllables. Multiple repetitions of each utterance type were collected from each speaker under each condition.

The utterances were digitized at 10 kHz and measurements made from the waveform displays, rather than articulatory records, to the closest millisecond. Three intervals were measured in each case:

1. The duration of audible glottal abduction,
2. The duration of the flanking vowel plus the duration of audible glottal abduction, and
3. The duration of the flanking oral closure plus the duration of audible glottal abduction.

The interval of glottal abduction was taken to be the stretch of noise between the vowel and oral closure, except for pre-aspiration in Icelandic, where this interval included a breathy interval at the end of the preceding vowel as well as a following interval of noise before the stop closure. This interval is that portion of the actual abduction of the glottis which is audible; since in all cases the flanking stop closure overlaps some part of the abduction, the interval measured is only part of the total duration of the abductory gesture. The vowel was identified as that stretch where the waveform was intense, clearly periodic, and with the asymmetric periods characteristic of modal voice. The oral closure was identified as that interval of greatly reduced amplitude or silence between vowels.

The question immediately arises whether acoustic records can be used in this way to measure the duration of articulatory events. This question is especially pertinent here since that part of glottal abduction which overlaps with the oral closure cannot be observed directly in an acoustic record. However, I have assumed that changes in the duration of the observable part of the glottal abduction outside the interval of the oral closure will be in proportion to changes in its total duration. If this is true, measuring the observable part would reveal the same relative changes as measuring the entire interval of abduction.

3.2.3 Analysis

Correlations were calculated between the duration of audible glottal abduction and the acoustic durations of each of the flanking oral articulations combined with the duration of audible glottal abduction for each of the two stop types in the two languages. Correlations tend to be positive, often quite strongly so, when an interval is correlated with a larger interval which includes itself, but the portion of the obtained correlation which is due simply to this inclusion can be calculated and the significance of the difference between these obtained and expected correlations determined (Cohen & Cohen 1983, Munhall 1985). If the obtained correlation is significantly larger than the expected value, then the durations of the two articulations can be assumed to be positively correlated, while if the obtained correlation is significantly smaller, then the two intervals are negatively correlated. Correlations that are more positive than expected are taken here to indicate coordination between the two articulations. These part-whole correlations avoid the negative bias which arises from errors locating the boundary when correlating the durations of adjacent intervals (Ohala & Lyberg 1976).

3.2.4 Results

Figures 1a-d illustrate the relationship between the duration of audible glottal abduction and the acoustic durations of the adjacent consonant and vowel articulations for each of the stop types, pooled across all conditions.

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Figures 1a-d about here.

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In each of these figures, the duration of glottal abduction, i.e. pre-aspiration, post-aspiration, or breathy-voice, is plotted on the vertical axis against the durations of both the flanking oral articulations, the vowel (in open squares) and stop closure (in filled squares), on the horizontal axis. The duration of each of the oral articulations on the horizontal axis is the combined acoustic duration of that oral articulation and glottal abduction since the correlations are part-whole. Regression lines for abduction by vowel and abduction by closure are plotted separately in each figure, and the formulae of each of these regression lines are given at the top of each figure, together with the observed correlations. As expected, all the correlations are positive, some quite strongly so. The obtained and expected correlations with indications of significant differences, if any, pooled across conditions (as plotted in the figures) are listed in table 1 below, for the two different rates in table 2, and for the two different focus positions (Icelandic) or two different numbers of following syllables (Hindi) contexts in table 3:

	Icelandic		Hindi	
	Preaspirated	Postaspirated	Breathy voice	Postaspirated
Overall:				
n=	187	78	48	48
AxC	.800 > (.598)	.616 = (.619)	.827 = (.735)	.797 > (.634)
AxV	.917 > (.848)	.728 > (.381)	.383 = (.572)	.670 = (.708)

Table 1: Part-whole correlation between glottal abduction and adjacent closure or vowel duration: observed (expected), all data pooled. n is the number of tokens of each type; different n's are given for all the tokens of each stop type pooled for each condition. "AxC" indicates correlation between abduction and adjacent closure, "AxV" between abduction and adjacent vowel. ">" indicates the observed correlation is significantly ($p < .05$ or better) positive compared to the expected value, "<" that it is significantly negative, and "=" that there is no significant difference. The same conventions are used in all the other tables.

	Icelandic		Hindi	
	Preaspirated	Postaspirated	Breathy voice	Postaspirated
Rate:				
Slow:				
n=	94	39	24	24
AxC	.674 = (.561)	.554 = (.663)	.770 = (.825)	.851 = (.833)
AxV	.891 > (.806)	.762 > (.394)	.068 < (.569)	.684 = (.763)
Fast:				
n=	93	39	24	24
AxC	.705 = (.684)	.678 = (.748)	.817 = (.810)	.760 = (.746)
AxV	.855 = (.812)	.632 = (.544)	.337 = (.543)	.521 = (.719)

Table 2: Part-whole correlation between glottal abduction and adjacent closure or vowel duration: observed (expected), condition: rate.

	Icelandic		Hindi	
	Preaspirated	Postaspirated	Breathy voice	Postaspirated
Focus:			Number of syllables:	
In focus:			a_a:	
n=	93	40	24	24
AxC	.821 > (.627)	.574 = (.597)	.821 = (.652)	.850 = (.689)
AxV	.942 = (.921)	.696 > (.376)	.301 = (.424)	.745 = (.747)
Not in focus:			a_apa:	
n=	94	38	24	24
AxC	.710 > (.544)	.641 = (.692)	.845 = (.840)	.730 = (.658)
AxV	.871 = (.827)	.741 > (.396)	.784 > (.531)	.732 = (.854)

Table 3: Part-whole correlation between glottal abduction and adjacent closure or vowel duration: observed (expected), condition: focus (Icelandic) and number of syllables (Hindi).

3.2.5 Discussion

The binding principle predicts no positive correlation between the durations of glottal abduction and the FOLLOWING stop closure in Icelandic pre-aspirates but just such a positive correlation between the durations of abduction and the PRECEDING closure for the other three stop types: Hindi breathy voiced and Hindi and Icelandic post-aspirated stops. Nearly complementary predictions are made regarding correlation between the durations of abduction and the adjacent vowel; no positive correlation is expected for stop types other than the Icelandic pre-aspirates, which may exhibit such a correlation as a result of coordination between the opening of the glottis and the articulation of the preceding vowel. Alternatively, abduction of the glottis in Icelandic pre-aspirates may not be coordinated with either of the two flanking oral articulations. The binding principle does not require that glottal articulations be coordinated with oral ones, but instead predicts how they will be coordinated if they are.

As table 1 shows, for all the data pooled, correlations between pre-aspiration and BOTH flanking oral articulations were significantly more positive than expected. The observed correlation of .800 between abduction and the following closure is significantly more positive than the expected .598, and the observed correlation between abduction and the preceding vowel is also significantly more positive than expected: .917 vs. .848. Significantly positive correlations are also observed between abduction and the following vowel in Icelandic post-aspirated stops, but not between abduction and the preceding closure. In post-aspirated stops in Hindi, however, the correlation between abduction and the preceding closure is significantly more positive than expected. The Hindi breathy voiced stops exhibit no significant correlation between abduction and either the preceding closure or the following vowel. Even so, the difference between the observed and expected correlations for abduction with preceding closure in Hindi breathy voiced stops is in the same direction as for the Hindi post-aspirated stops. The correlations between abduction and the following vowel, on the other hand, are in the opposite, negative direction, though for neither type of stop are they significant.

Tables 2 and 3 show that, with one exception, the difference between observed and expected correlations observed in each condition separately do not differ in DIRECTION from those obtained when all the data were pooled. The exception is that significantly positive correlation between abduction and the following vowel in Hindi breathy voiced stops when followed by two syllables (table 3), which is otherwise consistently negative with respect to the expected correlation. The same pattern of SIGNIFICANT differences was not always found, however, in each of the conditions as when all the data were pooled. Though in the same direction as in other conditions, no significant differences between observed and expected correlations were obtained for any of the stops at the fast rate; elsewhere, however, at least some of the differences are significant. One consistent and troublesome result is that no significant difference in either direction was found between abduction and the preceding closure for Icelandic post-aspirated stops in any of the experimental conditions. This failure is especially worrisome since post-aspirated stops in Icelandic do show significantly positive correlations between abduction and the following VOWEL in three out of four conditions, and in the fourth the difference between observed and expected correlations is in the same direction. Also, the near absence of significantly positive correlations for both of the Hindi stops in any of the conditions reveals generally weak covariation between the duration of abduction and that of either of the flanking oral articulations in this language. Finally, the significantly positive correlation between abduction and the preceding closure obtained for the Hindi post-aspirated stops when all the data were pooled is not found in any of the conditions taken separately.

If all correlations which differ from the expected value in one direction are considered, not just those which are significant, then the binding principle fails in two ways in Icelandic:

1. Pre-aspiration correlates positively with the following closure, but
2. Post-aspiration does not correlate positively with the preceding closure.

This pattern of results is exactly the opposite of what was predicted by the binding principle. For both pre- and post-aspirated stops, abduction correlates positively with the flanking vowel, which is neither predicted nor excluded by the binding principle. The Hindi data weakly support the binding principle, on the other hand; both breathy voice and post-aspiration correlate positively with the preceding closure but either do not correlate or correlate negatively with the following vowel.

What these data reveal is an essential difference between the two languages, rather than between stops which differ in the order of the glottal and oral articulations. By this measure in Icelandic, glottal abduction appears to be coordinated with the adjacent vowel and for pre-aspiration also with the following oral closure, while in Hindi, glottal abduction is coordinated with the preceding oral closure but not the following vowel. The relatively small number of significant correlations suggests one of two things: either this method of evaluating coordination is too coarse, perhaps because abduction is only measured partially, or that coordination between glottal and oral articulations, where it does exist, does not exhibit strong relational invariance.

The most troubling results are the double failure of the binding principle in Icelandic: the absence of the predicted positive correlation of abduction with the preceding closure in post-aspirated stops and the presence of the excluded positive correlation of abduction with the following closure in the preaspirated stops. In the next section, the coordination between glottal and oral articulations that this latter positive correlation appears to indicate is shown instead to be an illusion. The failure of the binding principle with respect to the Icelandic post-aspirates remains genuine, however, unless it can be shown that relational invariance is not an appropriate measure of coordination.

3.3 Breathiness and noise: the two components of pre-aspiration in Icelandic

3.3.1 Introduction and methods

A closer look at pre-aspiration reveals that the coordination with the following oral closure is illusory. As illustrated by the waveform of the transition from a vowel to a pre-aspirated stop (in the word stökkur "brittle, nom. masc.") in figure 2a, preaspiration has two components: a breathy interval followed by an interval of noise.

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Figure 2 about here.

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The breathy interval was identified as that where the shape of a glottal period changed from asymmetric to sinusoidal, while noise was simply that interval where the waveform no longer appeared periodic; both intervals could be identified consistently by eye. Breathy voicing is a product of partial abduction of the folds, which increases air flow through the glottis sufficiently to produce noise and also increases the negative slope of the spectrum of the glottal wave. Compared to modal voice, in which the higher harmonics are more intense than the first, in breathy voice, a shortening of the closed phase of the glottal cycle relative to the open phase produces a source spectrum in which the first harmonic is more intense than higher harmonics (Bickley 1982, Ladefoged 1982). The more intense first harmonic produces the characteristic nearly sinusoidal shape of the waveform. This initial partial abduction is not great enough to extinguish voicing, however. That only happens somewhat later, when the vocal folds become too far apart to vibrate any longer and only noise is produced. Vocal fold vibration thus ceases substantially before the beginning of the following oral closure. Of the two components of pre-aspiration, Chasaide (1986) has argued that it is the breathy interval and not the noise which is the most salient cue to identifying a stop as pre-aspirated in Icelandic and Scots Gaelic.

The waveform in figure 2a is for a token in focus spoken at a moderate rate, i.e. under conditions when segment durations are expected to be longest. Figure 2b is the waveform for an out-of-focus token of the same word spoken quickly, i.e. one in which segment durations are expected to be shortest. This comparison shows that the duration of the noisy component is reduced much more drastically than the duration of the breathy component, a consistent feature of these data. The difference between these two waveforms is in fact characteristic of the effects of varying rate or focus location; the breathy component remains essentially inert while the noisy component changes in proportion to changes in other segment durations. Changes in the durations of the two components of pre-aspiration were examined quantitatively in the data collected from the Icelandic speaker and the changes in their individual durations compared to changes in the total duration of pre-aspiration, the duration of the preceding vowel, and the following stop closure, again via part-whole correlations.

3.3.2 Results

The breathy component varies in duration much less than does the noisy component, across the experimental conditions. The noisy component itself varies in the expected direction, being markedly shorter at fast than slow rates and when the word is not in focus than when it is. Figures 3a-c illustrate the relationship of the duration of the breathy and noisy components to the total duration of pre-aspiration, the duration of the preceding vowel plus pre-aspiration, and the duration of the following closure plus pre-aspiration for all the data pooled.

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Figures 3a-c about here.

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The results of correlating the durations of the breathy and noisy components to each of these intervals are compared with expected values in tables 4-6. These are again part-whole correlations.

			Breathiness	Noise
Overall:	n =	188	-.202 < (.247)	.929 > (.878)
Rate:				
Slow:	n =	94	-.471 < (.298)	.922 > (.827)
Fast:	n =	94	-.108 < (.318)	.884 = (.855)
Focus:				
Yes:	n =	93	-.018 < (.217)	.963 > (.900)
No:	n =	95	.339 = (.365)	.780 = (.721)

Table 4: Part-whole correlations between breathy and noisy components of preaspiration and total duration of preaspiration: observed (expected).

			Breathiness	Noise
Overall:	n =	188	-.004 < (.370)	.915 = (.929)
Rate:				
Slow:	n =	93	-.230 < (.404)	.898 = (.915)
Fast:	n =	95	.082 < (.423)	.885 = (.906)
Focus:				
Yes:	n =	94	.127 = (.273)	.958 = (.962)
No:	n =	94	.446 = (.487)	.861 = (.874)

Table 5: Part-whole correlations between breathy and noisy components of preaspiration and duration of preceding vowel: observed (expected).

			Breathiness	Noise
Overall:	n =	187	.047 < (.215)	.706 > (.614)
Rate:				
Slow:	n =	94	.077 = (.251)	.579 = (.605)
Fast:	n =	93	.000 < (.299)	.624 = (.669)
Focus:				
Yes:	n =	93	.087 = (.147)	.796 > (.618)
No:	n =	94	.459 > (.240)	.527 = (.432)

Table 6: Part-whole correlations between breathy and noisy components of preaspiration and duration of following closure: observed (expected).

The duration of the breathy component correlates negatively with the total duration of pre-aspiration (table 4) when all the data are pooled and when correlations are calculated for each condition separately. The observed correlation for the noisy component, on the other hand, is nowhere significantly different from the expected value. The correlation between the breathy component and the preceding vowel (table 5) is also significantly negative overall and in all conditions, except that where the word was not in focus. Even there, the observed correlation is less than the expected value. On the other hand, the correlation between the noisy component and the preceding vowel is significantly positive in the overall correlation and the two conditions where a longer vowel is expected: at the slow rate and when the word was in focus. (For both components, the nonsignificant correlations are in the same direction compared to the expected values as the significant ones.) Finally, the breathy component exhibits a significant negative correlation with the following stop closure (table 6) overall and in the two conditions when a shorter closure was expected (again, the nonsignificant correlations are in the same direction). The correlation of the noisy component is significantly positive overall and when the word was in focus; otherwise, the observed correlations are not significantly different from the expected values (here, no consistent direction is evident in the nonsignificant correlations).

3.3.3 Discussion

Since the part-whole correlations between the noisy component and pre-aspiration were nowhere significantly more positive than expected, the noisy component can be identified as the single significant component of the measured duration of pre-aspiration. On the other hand, the breathy component must be independent of pre-aspiration duration, since its duration correlates negatively. With respect to the flanking oral articulations, a similar pattern emerges; the breathy component tends to correlate negatively with each of them, while the noisy component either exhibits no correlation or a positive correlation. More generally, the duration of the breathy component stays the same or increases slightly as the other articulations get shorter, while the duration of the noisy component varies proportionally in the same direction as the other articulations. These facts allow a different interpretation of the apparent positive correlation between the duration of pre-aspiration and that of the following closure, which removes the problem these Icelandic data presented to the binding principle.

Figure 4a schematically represents the timing of the oral and glottal articulations which will produce the waveform in figure 2a (cf. Petursson 1976). As sketched in figure 4, at faster rates or when the word is not in focus (cf. figure 2b), the interval between the two successive oral articulations is shortened; the closure occurs earlier than at slower rates or in focus. This earlier closure overlaps more of the interval of wide glottal abduction which produces the noisy component of pre-aspiration and thereby shortens the interval during which it is audible. Since this noisy interval is the principal component of pre-aspiration, this rate- or focus-induced variation in the amount of overlap produces the observed positive correlation between pre-aspiration and the following closure. However, since the oral articulation is simply sliding with respect to the glottal one, that positive correlation does not indicate coordination between the two after all. Instead the timing of the glottal articulation remains more or less unchanged as the interval between the oral articulations varies, with the closure overlapping more or less of the interval of wide glottal aperture which produces the noisy component of pre-aspiration. However, slight lengthening of the breathy component at the same time that the noisy component is being shortened indicates that the schedule of the glottal articulation is not entirely invariant. At faster rates or out of focus, the small abduction which produces breathiness occurs earlier with respect to the end of the vowel articulation and the transition to the wider abduction which produces noise alone takes longer. What is significant here is that the timing of the glottal articulation is being adjusted with respect to the preceding vowel, though it apparently is not adjusted with respect to the following consonant.

The complementary variation between the two components of pre-aspiration suggests that they may trade off perceptually in conveying the fact that the stop is pre-aspirated. With the longer breathy interval, pre-aspiration is anticipated to greater extent in shorter vowels, perhaps to ensure that some minimum interval of non-modal phonation occurs, while with longer vowels, the upcoming oral closure is also later, so a longer noisy component will occur. These data from production thus do not conflict entirely with Chasaide's claim that breathiness is more important than noise for identifying a pre-aspirated stop. They instead suggest that the relative importance of the two components, as measured by their relative durations, varies in a complementary way with the acoustic duration of flanking oral articulations.

This account of Icelandic pre-aspirates supports the suggestion of Browman and Goldstein (to appear) that apparent assimilations and deletions which occur in casual speech arise simply from an acoustically obscuring overlap of the movement of one articulator -- the apparently assimilated or omitted articulation -- by the sliding movement of another over it, rather than being a product of actually substituting or omitting articulatory gestures. In their view, the shift from a careful to a casual speech style changes the relative timing of articulatory gestures but not their shape or occurrence. It is not at all surprising that this suggestion should generalize to the effects of varying rate and focus location in these Icelandic data, since the differences between casual and careful speech undoubtedly parallel those between fast and moderate rates of speaking or between a word out of focus and one in focus.

3.4 Summary

The Icelandic data appeared at first to cast serious doubt on the binding principle in two ways. First, pre-aspiration correlated positively with the following stop closure, and, second, post-aspiration did not correlate with the preceding stop closure. In both kinds of stops, furthermore, the duration of audible abduction of the glottis correlated positively with the adjacent vowel. However, as closer examination of the variation of duration in the two components of pre-aspiration has shown, there is no actual coordination between glottal abduction and the following oral closure in Icelandic pre-aspirates, at least as reflected in relational invariance. Instead, the relative timing of the two flanking oral articulations vary with respect to one another, occurring closer together at faster rates or out of focus. This variation changes the duration of the audible interval of noise in pre-aspiration without affecting the duration of the breathy component proportionally because the oral closure overlaps more or less of the interval of wide glottal abduction that produces the noisy component. Since the noisy component is the principal component of pre-aspiration, this variation in the amount of overlap of glottal abduction by the oral closure leads to an APPARENT covariation between the durations of pre-aspiration and the following oral closure, suggesting coordination of the two articulations. The more correct view is that the glottal articulation is not coordinated at all with the following oral closure. Its coordination with the preceding vowel, on the other hand, tends towards invariance, though there is evidence of a small deceleration of glottal abduction at fast rates and out of focus. The Icelandic pre-aspirates do not therefore pose a problem for the binding principle in the phonetics any more than in the phonology.

The Hindi data turned out much closer to the predictions of the binding principle in that in both breathy voiced and post-aspirated stops, glottal abduction only correlates positively with the preceding stop closure.

The post-aspirates of Icelandic remain problematic, since they failed to show even the slightest sign of covariation in duration between glottal abduction and the preceding oral closure of the sort predicted by the binding principle.

4 Binding sites: Predictions of the binding principle and problems

The single ballistic opening of the glottis which occurs in the production of single voiceless consonants could bind either to the beginning or the end of the oral constriction. In fricatives, the beginning and end of the oral constriction are acoustically symmetric -- and the glottal abduction is simply intended to produce a sufficient and continuous flow of air --, so the binding principle can choose one or the other as the favored binding site. In stops, on the other hand, these sites are asymmetric: the dramatic reduction in amplitude at the stop closure is quite different from the burst of noise at the release, and the binding principle predicts that the opening of the glottis binds to the release, because it is the acoustic character of the burst which the glottal articulation is intended to modify.

Observations of the timing of glottal abduction in single consonants and in clusters appear to indicate, however, that glottal articulations are not always timed with respect to oral ones in ways predicted by the binding principle -- stops show coordination of glottal articulations with the closure as well as the release and fricatives exhibit more restrictive timing of glottal articulations than expected:

1. Glottal abduction is coordinated with the closure rather than the release of the stop in voiceless unaspirated stops, and with the beginning of the constriction in voiceless fricatives;

2. As a corollary, the binding principle predicts that glottal articulations will bind to the stop in a cluster of a stop and a fricative (regardless of their order) and to the last stop in a cluster of stops, because often only the last is audibly released. However, the manner of the first rather than the last obstruent in a cluster, i.e. whether it is a continuant, generally determines when the peak glottal opening will occur, despite the first segment's frequent lack of an audible release, whether becasue it's a fricative or becasue it's a non-final stop. In some languages, furthermore, peak opening velocity occurs at the same time relative to the onset of the cluster articulation for clusters beginning with stops as well as fricatives, implying that the closure rather than the release is the general binding point for glottal articulations in consonants of both manners in clusters; and

3. Closure durations in aspirated stops vary inversely across languages with the duration of aspiration, implying that the timing of glottal abduction is relatively invariant, instead of shifting to stay close to the oral release.

The second and third problems are elaborated below; see Louis Goldstein's commentary for much more extensive discussion of aspects of the first two problems.

Considering the speaker's ACOUSTIC goals unsurprisingly resolves the first of the problems for the binding principle. Binding the peak opening in aspirated stops to the oral closure instead does yield a reliable contrast in how their bursts sound compared with those of unaspirated stops. Since the glottis is adducted by the time the stop is released in voiceless unaspirated stops, abduction serves only to ensure an absence of vocal fold vibration during the closure and will not positively modify the acoustics of the burst and what follows. The weak burst of unaspirated stops may be acoustically neutral, i.e. phonetically underspecified and lacking in any unique acoustic signature, in contrast to the positively modified burst of aspirated and some other kinds of stops (such as ejectives) in which the glottal articulation is coordinated with the release. Unaspirated stops cannot, of course, be treated as underspecified in ARTICULATION, since their successful production is only possible if the abduction of the glottis is scheduled so as to be complete at or before the stop is released. If the burst is acoustically neutral in unaspirated stops, however, then the binding principle, or a restricted form of it would not constrain when the glottal articulation occurs. This restricted form of the binding principle applies not to all stops but only to those in which the timing of the glottal articulation is controlled so as to positively alter the acoustics of the burst.

There is some further evidence that the timing of glottal articulations is acoustically less crucial in unaspirated stops. Flege (1982) has shown that the timing of **AD**duction in the voiceless unaspirated realizations of utterance initial [+voice] stops in English does not predict the onset of vocal fold vibration. Some speakers who occasionally or always produce voiceless unaspirated stops in this position always adduct the folds substantially before the stop release, but, nonetheless, there is no voicing until the stop is released. Unlike these stops in English, voiceless unaspirated stops in most of the other languages discussed here are the principal rather than just an optional allophone of the one of the types of stops in the language. Furthermore, in none of these languages is there any variation in the timing of abduction and consequently adduction in their unaspirated stops. These differences in the timing of glottal abduction between the unaspirated stops of these languages and of languages such as English are acoustically irrelevant, however, at least insofar as the acoustics of the burst is concerned, since the glottis is adducted in all of them at the stop release.

The markedly different aerodynamic requirements of fricatives, especially sibilants, suggest that the relative timing of their glottal articulation is governed by quite different considerations than apply to stops. Both the early peak glottal opening and its large size in voiceless fricatives yields the high glottal air flow and hence high oral air flow needed to produce noisy turbulence. Noise also characterizes aspirated stops, but unlike in fricatives this noise occurs late in the articulation of the segment rather than early.[3] These aerodynamic requirements downstream thus demand a different, earlier timing of glottal abduction relative to the oral constriction in fricatives than stops.

Clusters of voiceless obstruents present a picture quite like that of single segments. Löfqvist and Yoshioka (1981a) compared the size and velocity of the glottal opening in single obstruents and obstruent clusters in which just a single opening occurred for three languages, Swedish, Japanese, and Icelandic.[4] In all three, peak opening was earlier in fricatives than stops, and in clusters beginning with fricatives than stops. English is similar (Yoshioka, Löfqvist, & Hirose 1981). In all four languages, the manner of the initial obstruent in the cluster, i.e. whether it was a continuant or not, determines the timing of the glottal gesture. These timing

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3. Voiceless fricatives can be divided (coarsely) into a frication portion followed by an aspiration portion. It is, however, uncertain whether the transition from frication to aspiration is a product of relaxation of the oral constriction, reducing oral air flow directly, or of adduction of the glottis, reducing oral air flow through reduction of glottal air flow. If the latter is the source of this asymmetry, then voiceless fricatives are the articulatory complement of aspirated stops, at least in the relative timing of their oral and glottal articulations. If voiced fricatives are similarly asymmetric, then they are the articulatory complement of voiced stops, in which typically the first part is voiced, but the later portion may exhibit devoicing.

4. The obstruent clusters examined in Japanese included strings derived by devoicing of an intervening vowel. Vowel devoicing is the only means by which "clusters" whose members differ in continuancy may be obtained in this language. These appeared to exhibit the same temporal coordination between oral and glottal articulations as underlying clusters, which in Japanese consist only of geminates, i.e. consonants with the same specification for continuancy (and place).

patterns disconfirm the predictions of the binding principle in two ways. First, it is the first rather than the last member of the cluster which determines when peak glottal opening occurs and, second, stops occurring later in the cluster do not attract abduction to their releases, away from a preceding fricative.

These four languages also resemble one another in that the opening velocity of the glottis is consistently slower for sequences beginning with stops than fricatives. Furthermore, peak velocity is reached at the same time relative to the preceding end of voicing for all sequences beginning with the same manner of consonant. The slower velocity of abduction in stops undoubtedly accounts for their later peak opening compared to fricatives. However, peak velocity does not necessarily occur at the same time relative to voicing offset for stop as fricative initial sequences in all the languages.

The velocity peak is reached at the same time for both stop and fricative initial clusters in Japanese and Swedish, but Swedish differs from Japanese in having a broader velocity peak in its stops than in its fricatives, while both stops and fricatives have a similar narrow velocity peak in Japanese. In Icelandic, on the other hand, the peak opening velocity peak is uniformly later for stops than fricatives. Lower opening velocity alone accounts for the later peak opening in stops than fricatives in Japanese, but in Swedish stops the sustained velocity peak leads to a larger as well as later abduction, and in Icelandic, the later peak velocity in stops compared to fricatives augments the effect of stops' lower velocity of opening in delaying when peak glottal opening occurs. Despite the lack of agreement in the timing of glottal articulations among these languages, these data are a problem for the binding principle since for all three languages the velocity peak is controlled for stops as well as fricatives relative to the beginning of the consonant's articulation, not its release. These data suggest that the peak glottal opening in stops only appears to coordinated with the release because it is later than in fricatives.

Other kinds of clusters of voiceless obstruents may exhibit multiple openings of the glottis, with partial adduction between them, for each segment that requires a high glottal air flow to produce noise (Löfqvist & Yoshioka 1981a,b, Yoshioka, Löfqvist, & Hirose 1981, 1982). Multiple openings are controlled somewhat differently than single ones. Single openings in single segments and clusters are produced by the posterior cricoarytenoids and the interarytenoids contracting reciprocally in a classical antagonist pattern: contracting the posterior cricoarytenoids opens the glottis and then contracting the interarytenoids closes it; activity in the interarytenoids is suppressed when the posterior cricoarytenoids are active and vice versa. However, in clusters where the glottis opens more than once, activity is almost entirely suppressed in the interarytenoids throughout the cluster. The glottis either opens and closes with a waxing and waning of activity in the posterior cricoarytenoids alone or the small adductions come from slight increases in interarytenoid activity. These data are also problematic for the binding principle since the principle predicts the consolidation of all glottal gestures in a cluster into a single one, bound to the last stop in the cluster, rather than multiple openings. Consolidation in such clusters is evident only in the near total suppression of adductory activity in the interarytenoids.

According to the binding principle, if the release of a consonant articulation produces a salient acoustic event, such as a burst, a glottal articulation will bind to the release because the state of the glottis determines the release's acoustic character. Since in clusters of stops often only the final stop in stop clusters is audibly released, the binding principle predicts tight coordination with this last stop but not with nonfinal stops in such clusters. (By "final", I mean here the last stop in a cluster preceding a vowel or sonorant; in word final stop clusters, the last stop is often unreleased as well.) The latter are, in many languages, often not audibly released. The neutralization of contrasts in glottal articulations in nonfinal members of stop clusters which also occurs in many languages could be a product of the failure of a potential glottal articulation to bind to those members because they are not fortunate enough to be released audibly.

The binding principle predicts that in obstruent clusters of mixed continuancy the stop rather than the fricative will determine when the peak glottal opening will occur because only the stop is released with a burst. That an initial fricative controls the timing of the glottal opening in fricative plus stop clusters is a real problem for the binding principle, despite the fact that a temporal compromise occurs between the two segments, as indicated by the shift of the peak glottal opening to a point later than it would occur in the fricative alone. This comprimise is not sufficient, however, to prevent the neutralization of the aspiration contrast in the following stop. In fact, glottal abduction in voiceless obstruent clusters with just a single glottal opening is generally earlier in clusters beginning with fricatives than in those beginning with stops. This is true regardless of the manner of the following obstruent. That the manner of the first rather than the last obstruent in a cluster determines when the peak glottal opening will occur clearly conflicts with the predictions of the binding principle.

On the other hand, these differences between clusters beginning with fricatives and those beginning with stops may be an artifact. In all the data available on the timing of glottal articulations in obstruent clusters beginning with a fricative, that fricative is a sibilant. Sibilants are the noisiest of fricatives and they also have strong peaks in their spectra. In their high intensity and clear timbre, sibilants grossly resemble vowels, and these two properties make them detectable and identifiable at the syllable periphery. Producing such intense, spectrally distinct noise demands, in addition to a sufficiently small oral aperture to produce turbulence (Stevens 1971, Shadle 1985), a large enough glottal aperture to produce a high glottal air flow. Sibilants may therefore be exempt from the constraints imposed by the binding principle since their requirements for a high glottal air flow probably exceed those of stops.

Browman and Goldstein (1986) also suggest that sibilant plus stop clusters are a special case, though in their view this is because sequential oral articulations are incorporated into the domain of a single opening of the glottis, rather than because of the demand for high glottal air flow to produce high oral air flow by the sibilant. Though all voiceless fricatives may require a large glottal aperture and be expected to incorporate a following stop, non-sibilant fricatives do not generally occur external to stops in syllables. Since only sibilants and not all fricatives, much less all continuants, are incorporated with following stops within single glottal gestures, this coordinative structure, with the loss of an aspiration contrast in the stop it produces, cannot be generalized to other sequences of a continuant followed by a stop.

Turning now to the third problem, Hutters (1985) presents evidence from five languages that the duration of aspiration varies inversely with the duration of the stop closure, apparently because the stop is released before peak glottal opening is reached in the languages with shorter closures, Danish and Hindi, but not until after peak glottal opening in the languages with longer closures, Swedish, English, and Icelandic. These data indicate that the glottal gesture is ballistic and relatively invariant in its timing across these five languages. The timing of the oral closure instead varies cross-linguistically and certainly does not appear to dictate when the peak glottal opening will occur. If the timing of the glottal gesture is roughly invariant in all five languages, the length of the aspiration interval depends on when the oral release occurs relative to the glottal gesture, rather than the glottal gesture being timed with respect to the oral one. This suggestion acquires further support from Hutters' Danish data, in which the interval from the onset of the oral closure to peak glottal opening is nearly constant for stops differing in place of articulation, even though closure and aspiration durations vary inversely across places of articulation. The explanation for these differences cannot be found in the phonologies of these languages, since Icelandic and Danish employ aspiration in quite parallel ways to distinguish their two classes of stops from one another, as do Swedish and English.

Closure durations also differ systematically between aspirated and unaspirated stops, being longer in the latter than the former. The duration of closure in an unaspirated stop is in fact approximately equal to the closure plus aspiration interval of an aspirated stop (Hutters 1985, also Weismer 1980). In English, the duration of constriction in voiceless fricatives is also approximately equal to the duration of closure in unaspirated stops (Weismer 1980), but both the timing of the gesture and its magnitude must be specified because there is an early and large peak in voiceless fricatives compared to the early but small peak in voiceless unaspirated stops and to the late and large peak in voiceless aspirated ones. The two kinds of stops still cannot be produced with the same abductory gesture since the peak opening is much larger in the aspirated than unaspirated stops. It is also not possible to specify velocity alone, since that would not predict the differences in the size of the opening between aspirated and unaspirated stops.

Finally, the fact that closure durations vary across languages in aspirated stops with complementary variation in the duration of aspiration does not mean that glottal articulations are not bound to oral ones. So long as the peak glottal opening occurs at some constant interval from the oral release, then it can be said to be bound to it. The binding principle does not require that this interval be the same for all languages. Significant counterevidence would be a demonstration that closure duration could vary in a single language without proportional variation in the timing of the peak glottal opening. In this connection, we might appeal to a difference between macro-binding, the pattern of covariation in the timing of one autonomous articulation with respect to another, and micro-binding, a specification that the bound articulation occur at a constant interval from the event to which it binds, here, peak glottal opening with respect to the stop release (the distinction is Ohala's, p.c.).

5 Conclusion

The binding principle claims glottal articulations will bind more tightly to oral ones in stops than in continuants and that a glottal articulation would be coordinated with the release of the oral articulation because in that way the release would be shaped acoustically by the glottal articulation and thus convey the nature of that glottal articulation. Support for the first part of the principle has not been presented in this paper, and it will be taken up elsewhere.

The second part of the principle was tested first against data from Icelandic and Hindi. One problem, the possibility of binding of glottal abduction to the onset of a following stop closure in the pre-aspirates in Icelandic was shown to be only apparent problem. Since pre-aspiration is a generally a phonetic property of heterosyllabic clusters ending in an underlying [+ spread] stop -- through a shift of the glottal abduction to the first member of the cluster --, while post-aspiration arises only when such stops occur singly or in tautosyllabic clusters, pre- and post-aspiration may never contrast in the phonology of Icelandic. The apparent coordination of the glottal opening with the following oral closure was shown to be artifact of variation in the amount of overlap between the oral closure and the interval when the glottis was completely abducted; no relational invariance between glottal abduction and oral closure was actually found. The absence of evidence of coordination between glottal abduction and the preceding closure in Icelandic post-aspirates remains unresolved. The data from Hindi more closely followed the predictions of the binding principle, but this suggested a difference in coordination schedules between the two languages rather than the contrast between stops of different types predicted by the binding principle.

The unresolved problems may not expose weaknesses of the binding principle so much as they reflect difficulties in determining the tightness of binding. In particular, measuring covariation in duration may not accurately reveal how or what events are coordinated with one another. This would be especially likely if it were not the onset and offsets of articulations which are coordinated but rather something like their peak displacements. The evidence reviewed above suggests that it is peak opening of the glottis which exhibits invariance with respect to some part of the oral articulation it accompanies. Unless abduction were strictly ballistic, coordination of peak opening with the stop release would probably not be clearly observable in measurements of covariation in duration.

Implicit in the traditional matrices of features employed until recently to represent the component articulations of segments is the claim that each articulatory gesture begins and ends simultaneously. The glottal and oral articulations of unaspirated stops and voiceless fricatives actually exhibit just this pattern of coordination, glottal abduction beginning at nearly the same time as the oral closure of constriction is complete and adduction being complete at the point when the closure or constriction is released. Furthermore, peak glottal opening is coordinated in unaspirated stops and fricatives with the onset of closure or constriction. Voiceless fricatives and aspirated stops contrast in the timing of glottal abduction, a difference which is perhaps best expressed in terms of contrasts in opening velocity, the fricatives being produced with much rapider opening than the stops. Abduction in aspirated stops is, furthermore, coordinated with the release of the stop; it varies in when it occurs with respect to the onset of closure, but not with respect to the release.

The explanatory power of the binding principle arises from the fact that the contrast between aspirated stops on the one hand and voiceless fricatives or unaspirated stops on the other depends on TIMING differences. These timing differences are what is controlled in conveying these contrasts; their results are a markedly different acoustic quality between the burst and the brief interval after it in aspirated and unaspirated stops or between the early noise of fricatives compared to late noise in aspirated stops. The binding principle assures that these acoustic differences exist.

Most troublesome in the long run for the binding principle is the fact that the timing of glottal abduction in voiceless obstruent clusters is determined by the manner of the initial rather than the final obstruent. The difficulty, of course, arises from the fact that that obstruent's release may not be acoustically signalled by a salient, transient event such as a burst. The more general problem for the binding principle posed by such data is that it suggests that glottal and oral articulations are scheduled with respect to the beginning of the articulatory unit rather than looking ahead to its end, despite the possibility that no audible release may occur in the middle of the cluster to convey the state of the glottis. The difficulty presented by these data is only reduced somewhat by the fact that in all the clusters beginning with fricatives, the fricative is a sibilant, which demands such a large glottal aperture that it may override the binding principle. This raises the question of how this principle applies in a grammar.

Considering stops alone, the binding principle may be limited to single stops and not extend to clusters of stops. Rather than enforcing a consolidation of glottal gestures into a single gesture aligned with the audible release of a final stop in a cluster, the glottal gesture of each stop may bind to its release, whether or not it is audible. (Only when the cluster contains a word boundary are there separate openings; otherwise, it appears that only a single glottal abduction occurs.) If the possibility of an audible release, rather than its actual occurrence, is sufficient to determine when glottal abduction occurs, then the binding principle only determines the schedule of articulation within the domain of a single segment, even if that segment forms part of a larger articulatory unit, as it does in a cluster of voiceless stops in which the separate glottal opening gestures of each member appear to have been consolidated into a single opening. The schedule of glottal articulations remains what it would be if the segment occurred alone.[5] This result closely resembles Browman and Goldstein's (1986) demonstration that the movement of the lower lip in bilabial articulations is the same for [p], [b], [m] and [mb], [mp], i.e. whether the accompanying soft palate articulation is single or double. The acoustic result which the binding principle is intended to assure, a burst positively modified by the glottal articulation bound to it, is apparently dispensable in clusters, perhaps because the glottal articulation is predictable within most clusters in the languages investigated (I had originally hoped that the binding principle would provide an account of this predictability). Restricting the binding principle to single consonants shows that neither it nor other constraints are solely

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5. Strictly speaking, this is not true, since as the evidence of sibilant plus stop clusters shows the peak in the glottal abduction occurs at the boundary between the sibilant and stop articulations, a shift to a later point compared to the fricative occurring alone.

responsible for determining when glottal articulations occur relative to oral ones in consonants. Coordination arises instead out of a combination of constraints.

Acknowledgments

What follows has been much improved by the concerted efforts of readers of earlier versions, alphabetically: Mary Beckman, Ailbhe Ni Chasaide, Nick Clements, Louis Goldstein, Johanna Nichols, John Ohala, Donca Steriade, and Kenneth Stevens; you, the reader, should be grateful for their efforts. Kim Silverman's advice regarding the statistical treatment of these data was invaluable. I am also grateful to the speakers of Icelandic and Hindi whose speech is described here, Gudrun Thorhallsdottir and Veneeta Srivastav. Final responsiblity for everything here remains, of course, with me. The work reported in the section on preaspirates was carried out in the Phonetics Laboratory in the Department of Modern Languages and Linguistics at Cornell University with support from the College of Arts and Sciences.

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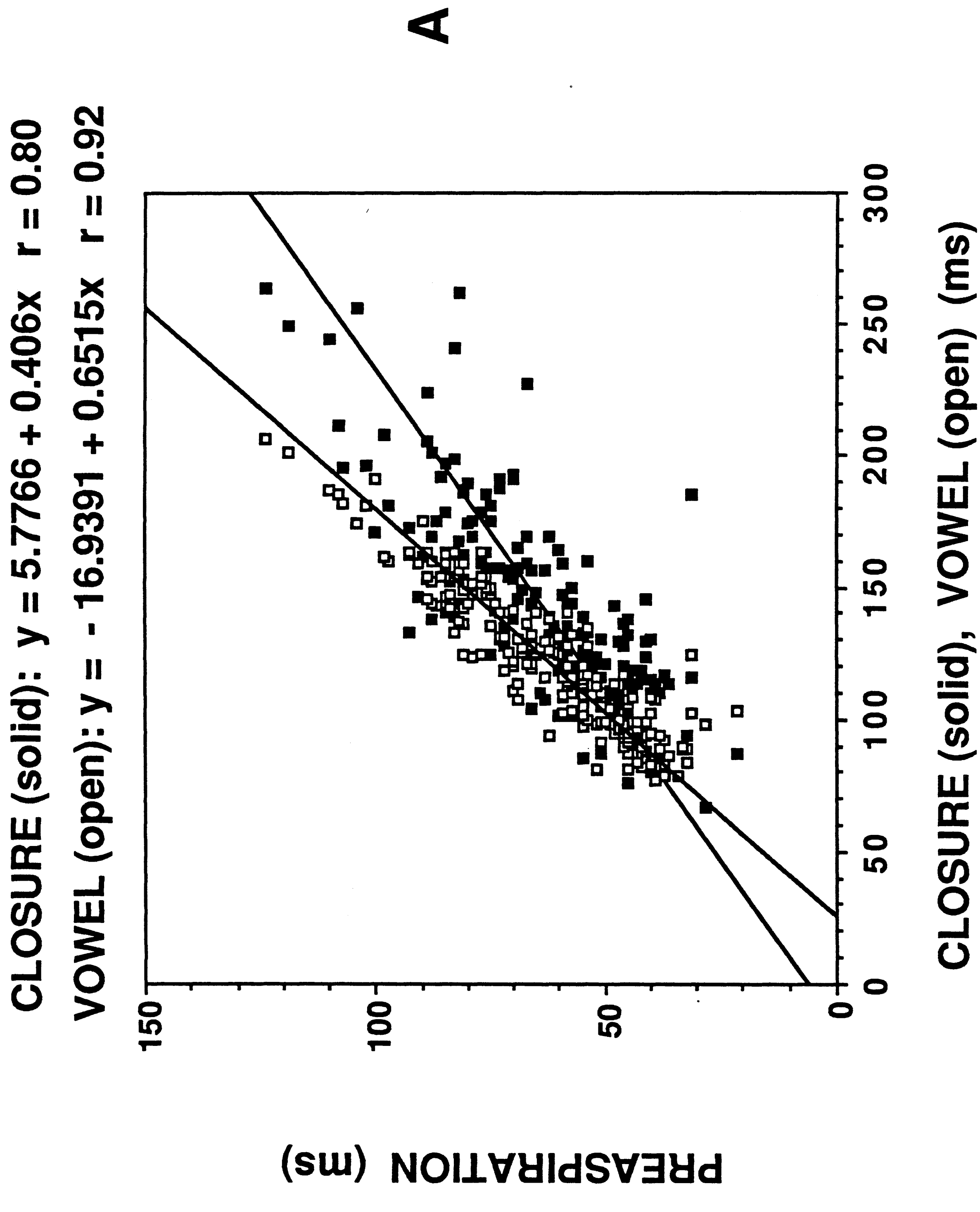
Figure Legends

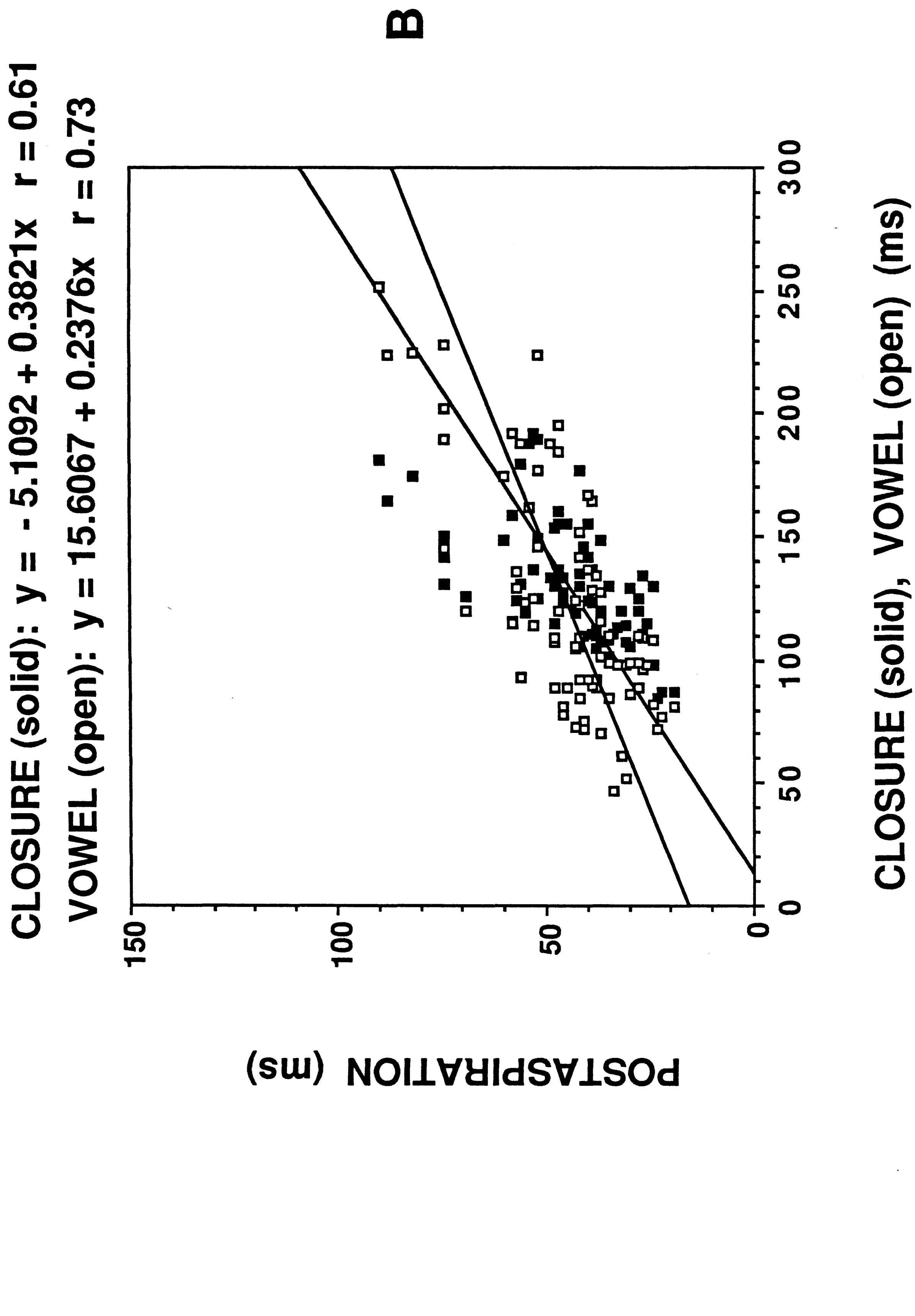
Figure 1: Correlation plots for durations of glottal abduction with the adjacent closure and vowel for all data pooled: a) Icelandic pre-aspirated stops; b) Icelandic post-aspirated stops; c) Hindi breathy voiced stops; d) Hindi post-aspirated stops.

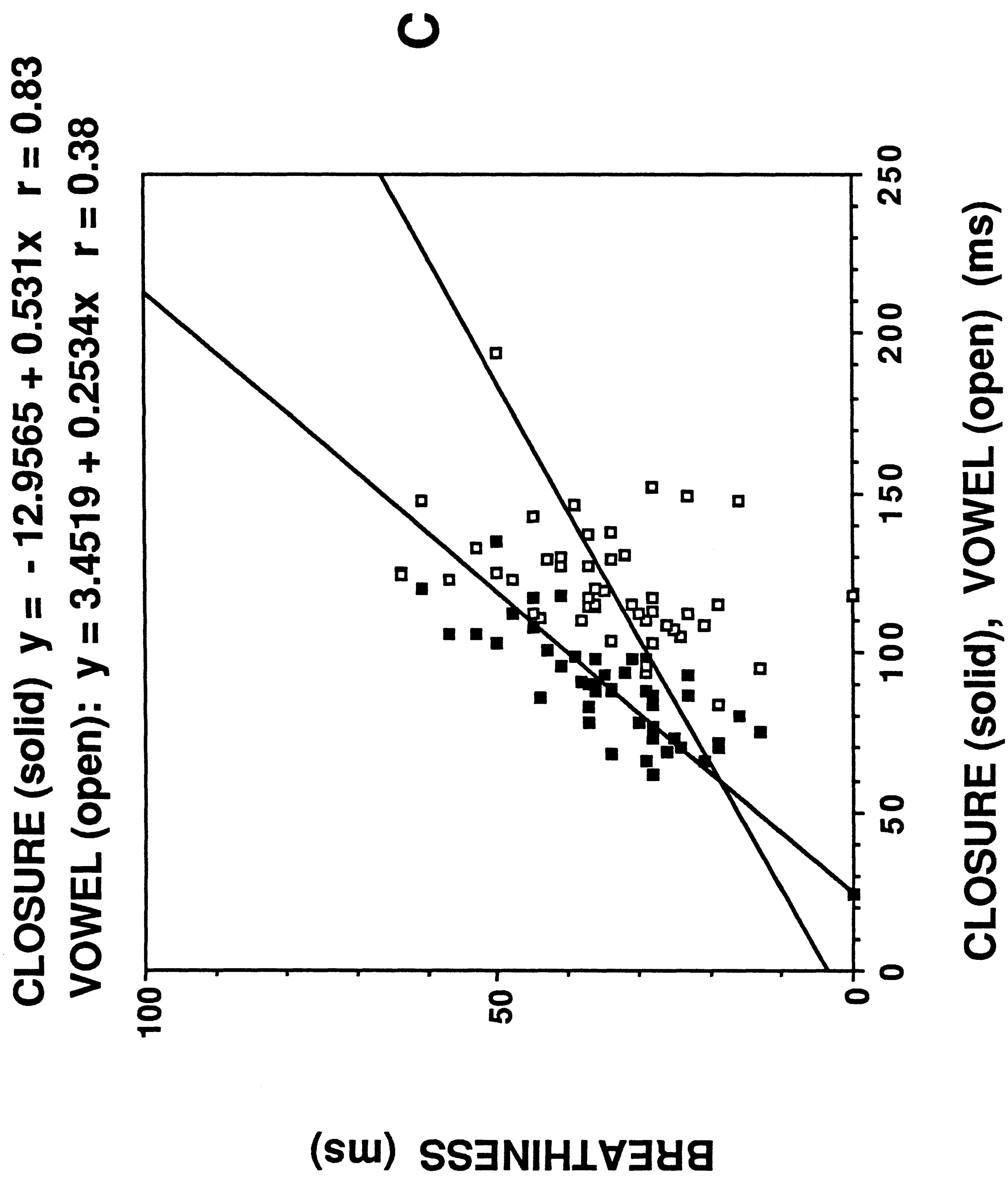
Figure 2: Waveforms of the end of a vowel before a preaspirated stop: a) in the word stökkur "brittle, nom. masc." spoken in focus at a moderate rate and b) of the same word, but out of focus at a fast rate. Note the marked reduction in the duration of noisy component, compared to the inertness of the breathy component.

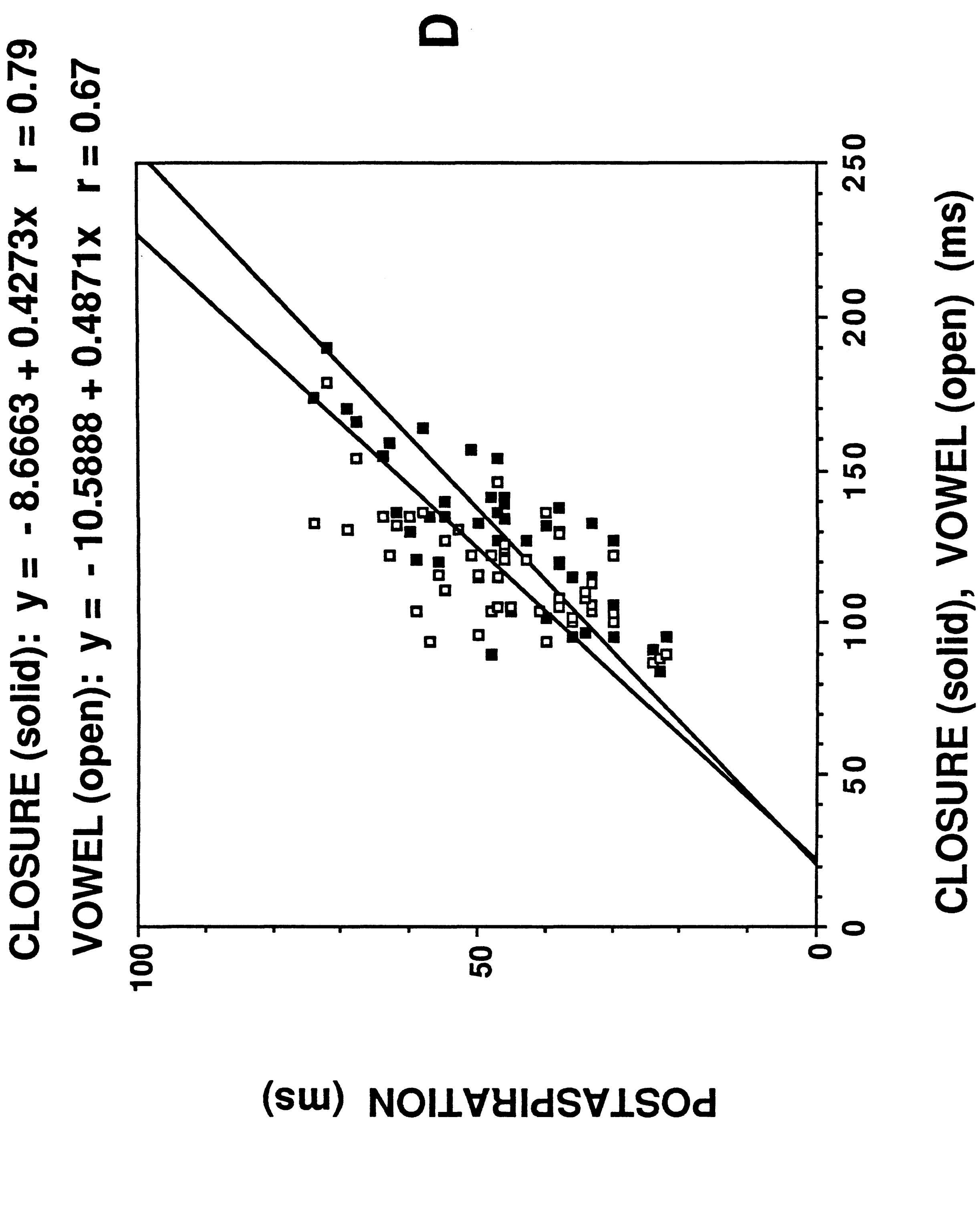
Figure 3: Correlation of duration of breathy and noisy components with total duration of pre-aspiration in Icelandic; b) correlation of duration of breathy and noisy components with combined duration of preceding vowel and pre-aspiration; c) correlation of duration of breathy and noisy components with combined duration of preceding vowel and pre-aspiration.

Figure 4: a) A diagram of the relationship between the oral and glottal articulations in pre-aspirated stops (cf. Petursson 1976), b) variation in the interval between the onsets of the oral articulations, without varying the glottal articulation, leading to varying amounts of overlap of the interval of wide glottal abduction which produces the noisy component of pre-aspiration by the stop closure.


A
CLOSURE (solid): y = 5.7766 + 0.406x r = 0.80
VOWEL (open): y = - 16.9391 + 0.6515x r = 0.92
PREASPIRATION (ms)
CLOSURE (solid), VOWEL (open) (ms)
0
50
100
150
0
50
100
150
200
250
300


CLOSURE (solid): y = - 5.1092 + 0.3821x r = 0.61
VOWEL (open): y = 15.6067 + 0.2376x r = 0.73
B
0
50
100
150
200
250
300
CLOSURE (solid), VOWEL (open) (ms)
150
100
50
0
POSTASPIRATION (ms)

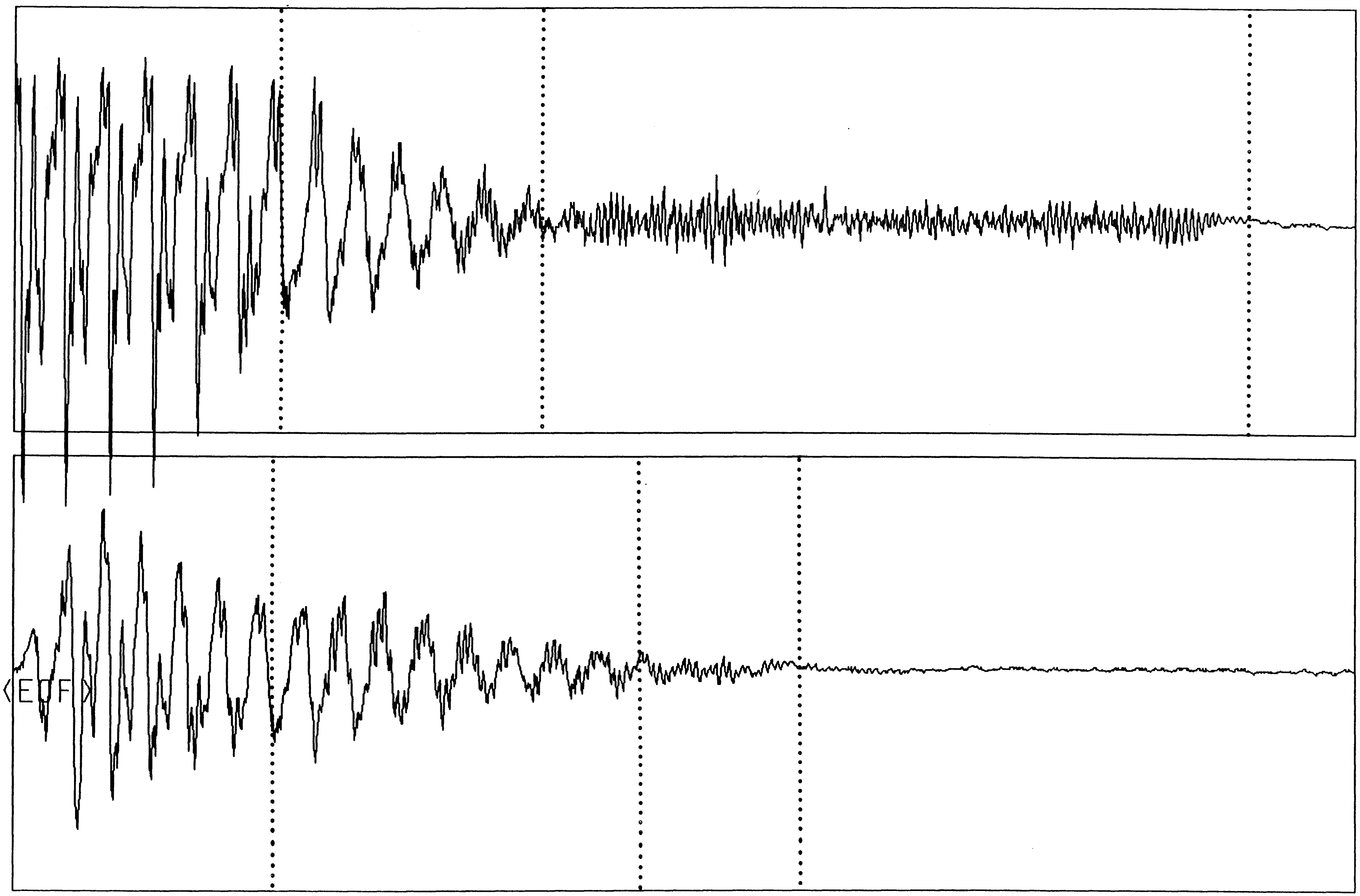

CLOSURE (solid) y = - 12.9565 + 0.531x r = 0.83
VOWEL (open): y = 3.4519 + 0.2534x r = 0.38
C
BREATHINESS (ms)
CLOSURE (solid), VOWEL (open) (ms)
0
50
100
150
200
250


CLOSURE (solid): y = - 8.6663 + 0.4273x r = 0.79
VOWEL (open): y = - 10.5888 + 0.4871x r = 0.67
D
100
50
0
0
50
100
150
200
250
POSTASPIRATION (ms)
CLOSURE (solid), VOWEL (open) (ms)

C3SECTOR 1, STARTING FRAME 150, 55 FRAMES, CONTEXT 50

A1DM3:[3,16]EX621

2.



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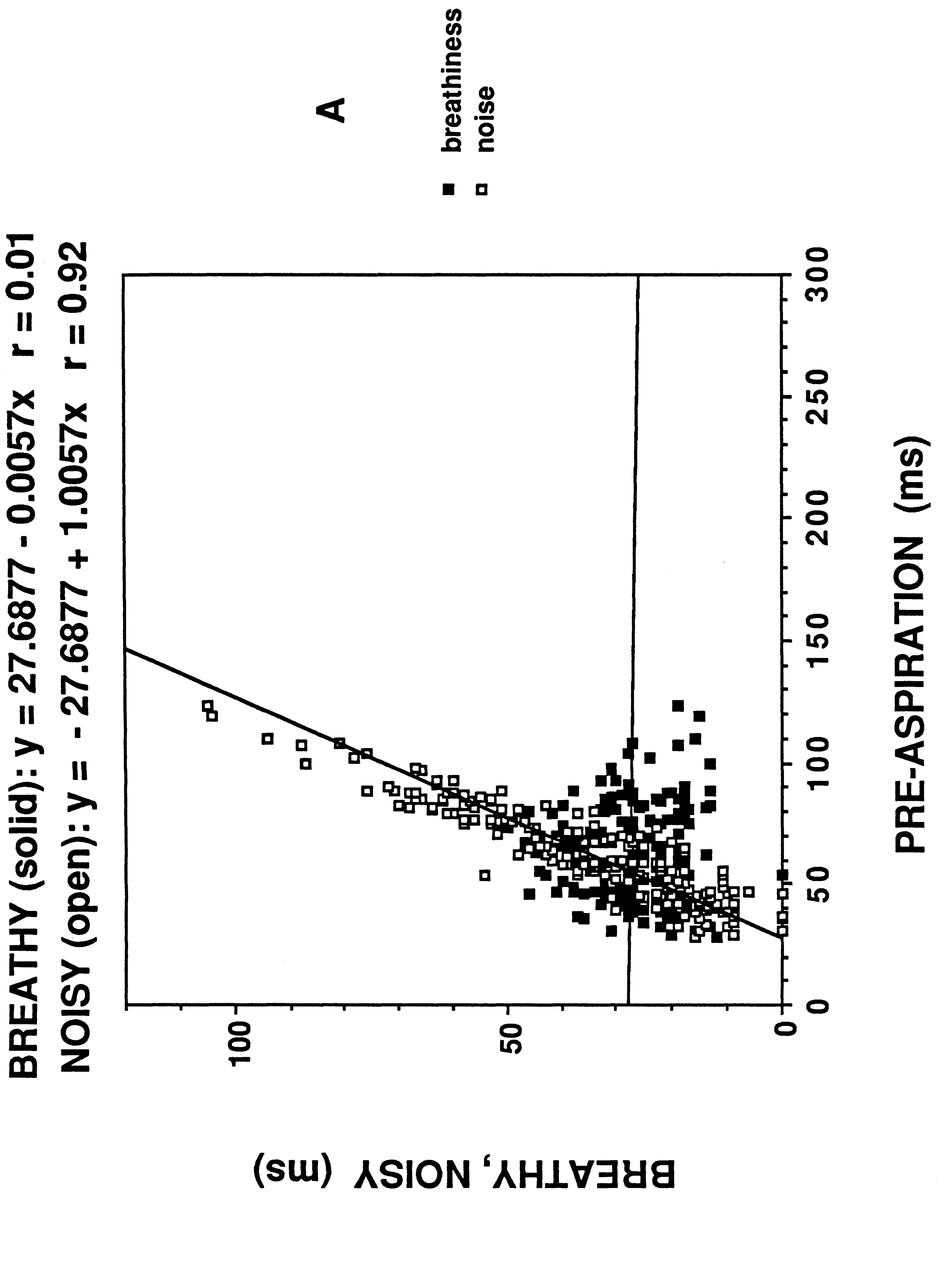
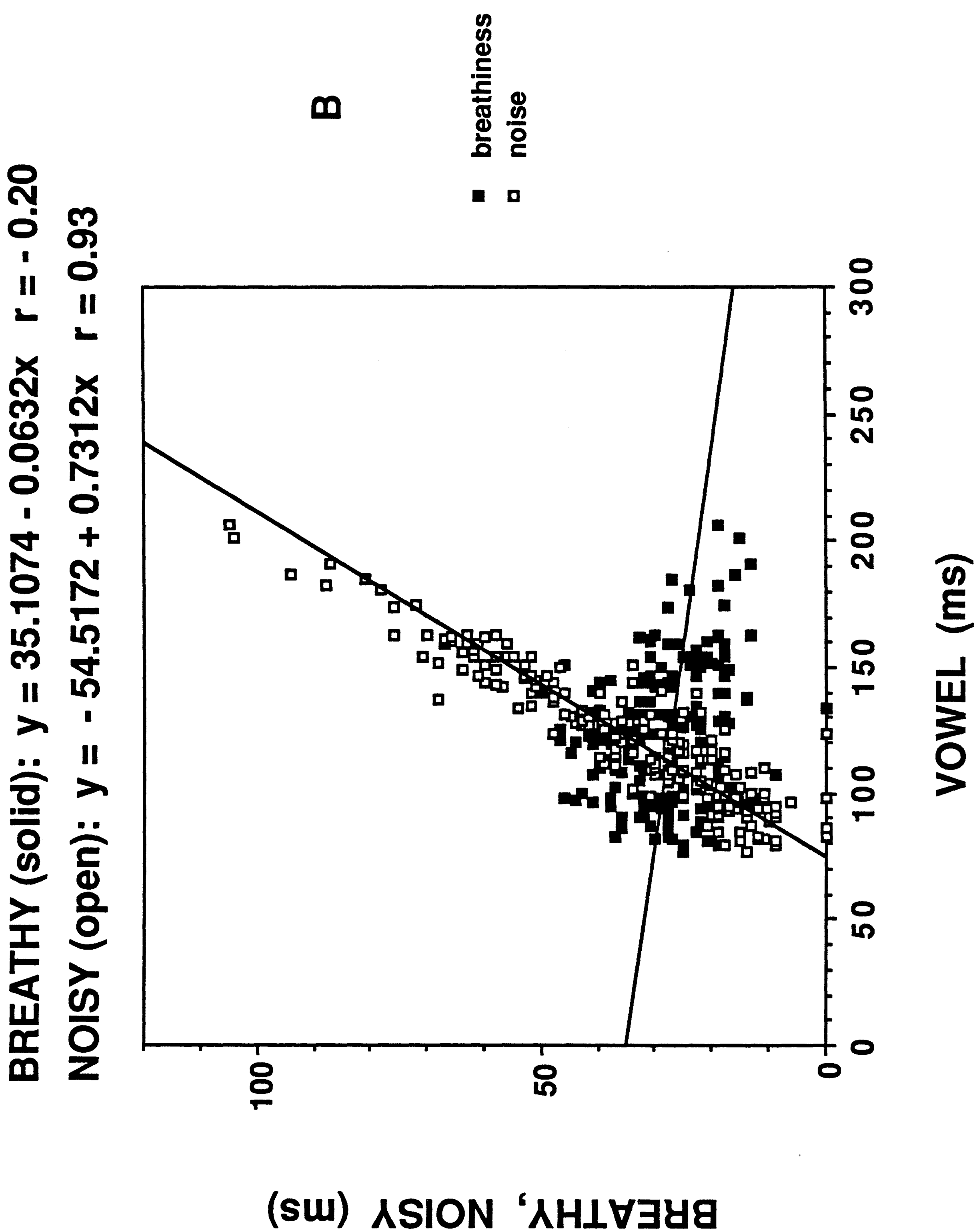
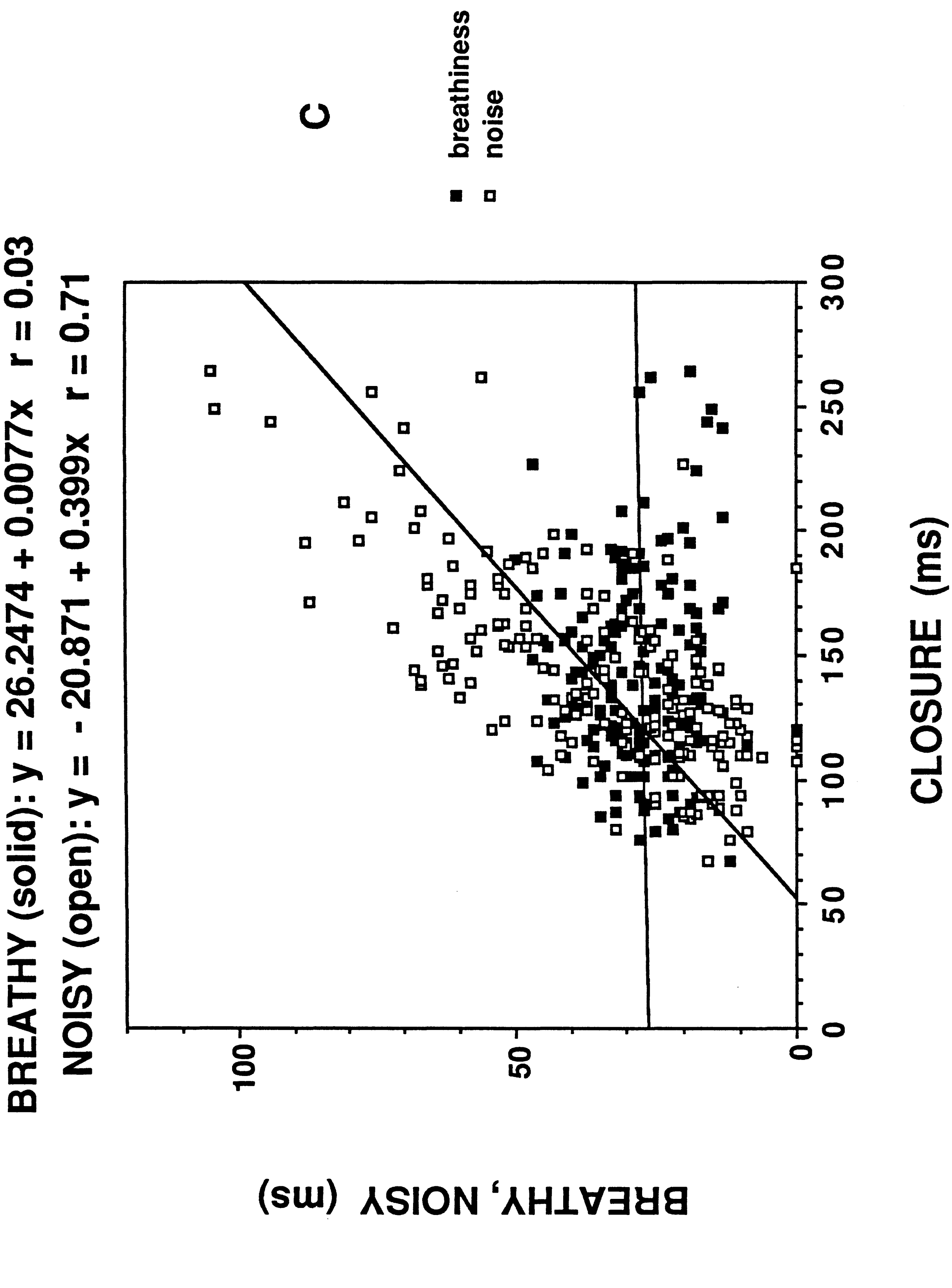
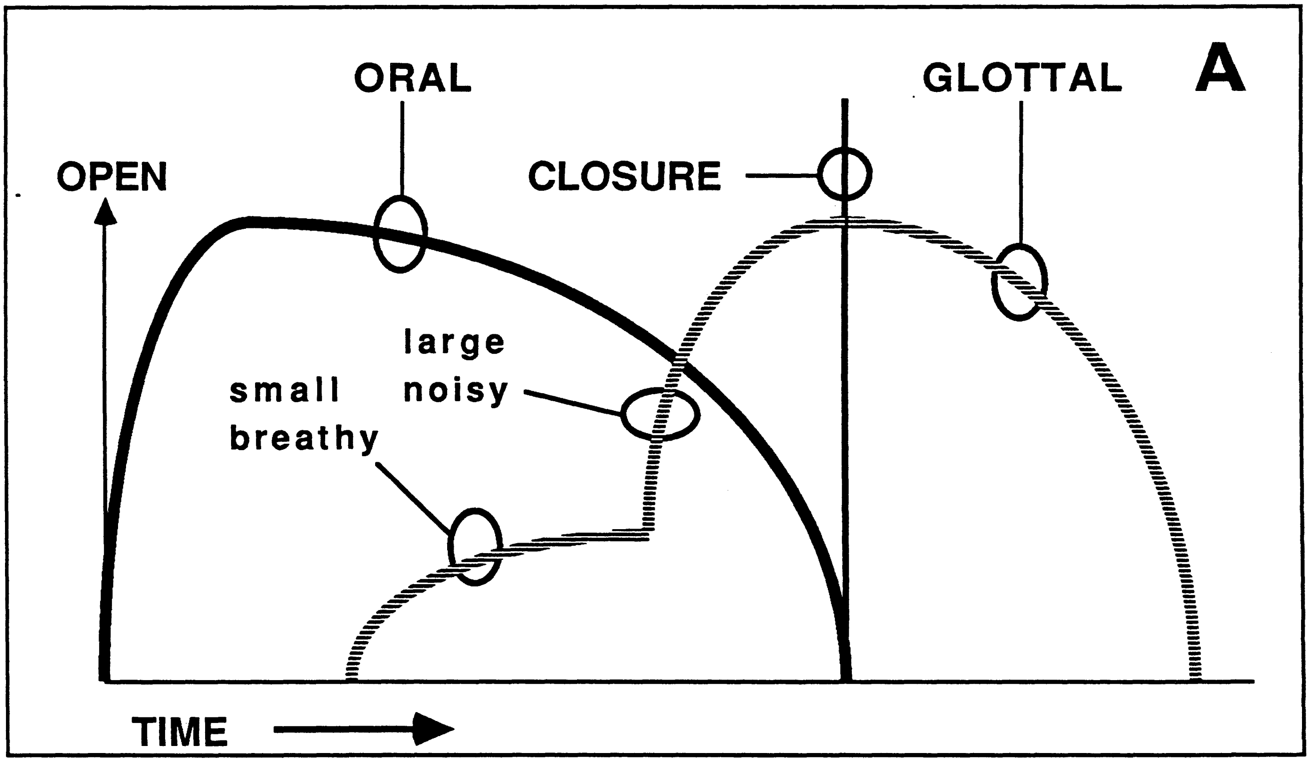
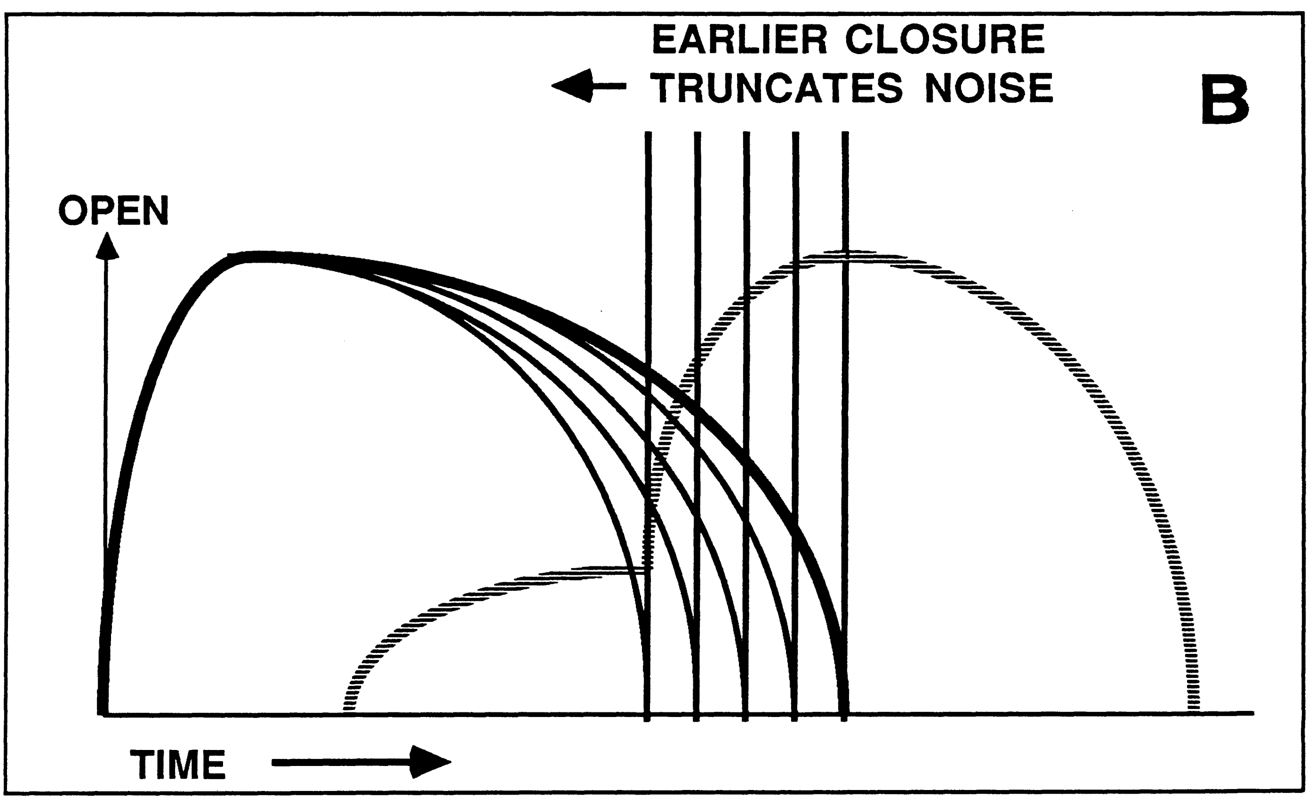

BREATHY (solid): y = 27.6877 - 0.0057x r = 0.01
NOISY (open): y = - 27.6877 + 1.0057x r = 0.92
A
breathiness
noise
0
50
100
150
200
250
300
PRE-ASPIRATION (ms)
0
50
100
BREATHY, NOISY (ms)


BREATHY (solid): y = 35.1074 - 0.0632x r = - 0.20
NOISY (open): y = - 54.5172 + 0.7312x r = 0.93
B
breathiness
noise
0
50
100
150
200
250
300
VOWEL (ms)
0
50
100
BREATHY, NOISY (ms)


BREATHY (solid): y = 26.2474 + 0.0077x r = 0.03
NOISY (open): y = - 20.871 + 0.399x r = 0.71
C
breathiness
noise
BREATHY, NOISY (ms)
CLOSURE (ms)
0
50
100
150
200
250
300


ORAL
GLOTTAL
A
OPEN
CLOSURE
large
small
noisy
breathy
TIME


EARLIER CLOSURE
TRUNCATES NOISE
B
OPEN
TIME