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Using Regions and Indices in EPG Data Reduction

Research Note

Dani Byrd*
Edward Flemming**
Department of Linguistics
University of California, Los Angeles

Carl Andrew Mueller
TRW
Redondo Beach, CA

Cheng Cheng Tan
Department of Linguistics
University of California, Los Angeles

This note describes how dynamic electropalatography (EPG) can be used for the acquisition and analysis of articulatory data. Various data reduction procedures developed to analyze the electropalatographic data are reported. Specifically, these procedures concern two interesting areas in EPG data analysis—first, the novel use of speaker-specific articulatory regions and second, the development of arithmetic indices to quantify time-varying articulatory behavior and reflect reduction and coarticulation.

KEY WORDS: electropalatography, data reduction, EPG, indices, coarticulation

Currently, many aspects of speech research are best entered armed with articulatory data. However, the difficulty of obtaining accurate, quantified information on the movement of the articulators is well known to speech researchers. Instrumental information on the movement of the tongue has been particularly difficult to collect but is of great importance because the tongue is involved in all vowels and almost all consonants in language. For many sounds the tongue functions as the active (moving) articulator with the hard palate as the passive (nonmoving) articulator. The hard palate is generally ignored in studies of speech production because it does not move; however, it is important in understanding tongue dynamics (Stone, Faber, & Cordaro, 1991). "The palate provides the tongue with a solid base of contact for sensory feedback, for light support during rapid or complex movements, and . . . with resistance to help it assume various shapes" (Stone et al., pp. 354, 357). The approximation of the tongue to the palate is the immediate cause of many of the acoustic characteristics associated with a large number of consonants.

There are a number of ways to collect tongue movement data, although each has its limitations. Ultrasound provides two-dimensional images of the tongue surface through time at a rate of about 30 Hz (Stone et al., 1991) but is unable to penetrate bone and air (Foldvik, Husby, Kværness, Nordli, & Rinck, 1991). Three-dimensional reconstruction of the tongue based on ultrasonic images has been accomplished for sustained articulations (Watkin, 1991; Watkin & Rubin, 1989). Cinegraphic X-ray techniques and X-ray computerized tomography of articulatory movements have the harmful side effects of radiation. Magnetic resonance imaging (MRI) shows all the articulators and provides two-dimensional images; however, it generates a great deal of noise, making suitable acoustic data difficult to acquire. Conventional MRI requires long acquisition times and phonetically trained subjects who can freeze their articulation of a particular sound (Foldvik et al., 1991), making it impractical for collection of large amounts of data and for dynamic analysis. Reduced acquisition time is often associated with reduced spatial or contrast resolution or greater

*Currently affiliated with Haskins Laboratories, New Haven, CT.
**Currently affiliated with the Department of Linguistics and Philosophy, Massachusetts Institute of Technology, Cambridge.

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sensitivity to artifact (Cox, Roberts, & Moseley, 1994). High speed MRI such as echo planar imaging (EPI) requires in practice around 100 msec per slice in view of the repetition time between slices, allowing a series of images to be acquired within seconds. Movement may be visible in near real-time, but true dynamic movement tracking (in a multi-slice mode) remains a future goal (Cox et al., 1994). X-ray microbeam and electromagnetic articulograph/magnetometer technology provide high quality information about articulator movements in the midsagittal plane. However, these instruments provide no information about tongue behavior outside the midsagittal plane, degree of palatal contact, or tissue compression characteristics of tongue against palate. Lastly, MRI, microbeam, and magnetometer systems require specialized technical, and sometimes biomedical, expertise. The permissible exposure of the subjects may be limited, and access to the instrumentation can be costly and restricted.

Electropalatography

Dynamic electropalatography (EPG)—also known as dynamic palatography or palatometry—is a system for recording information about the tongue's contact with the hard palate over time. It is relatively inexpensive and technologically accessible. EPG is safe, collects movement data outside the midsagittal plane, provides spatial information on the shape of constriction contact, and allows the collection of reasonable acoustic data. Multiple sessions with a subject are possible and replicable (given fitted pseudopalates).

The electropalatograph uses an artificial palate of thin acrylic embedded with electrodes (usually over 60; Hardcastle, Gibbons, & Nicolaidis, 1991). Contact of the tongue to the pseudopalate is measured at each electrode. The pseudopalate may be manufactured individually for each subject from a dental cast or be uniform for all speakers with similar palate sizes. The palate is scanned, and linguapalatal contact data are acquired at a sampling rate of 60 to 200 Hz. The data are typically recorded by computer and are qualitatively examined visually in the form of diagrams showing the arrangement of electrodes on the palate indicating contact or no contact at each electrode. In most systems, the data is converted into a graphic representation of tongue-palate contact at each electrode.

Like any instrument, EPG has limitations. Many of these difficulties are commensurate with those encountered in using other types of movement-tracking systems. First, the cost and difficulty of making well-fitted pseudopalates may make prohibitively expensive experiments with enough subjects to be representative of a larger population (Ladefoged, 1957). Second, pseudopalates interfere with sensory feedback, which might cause nontypical articulatory patterns. However, researchers have concluded that it is unlikely that the "relatively simple tactile sensory resources of the palate would play a significant role in sensory discriminations in the mouth [McDonald & Aungst, 1967]" (Hardcastle, 1972). Fletcher (1992) states that lingual feedback is sufficient to compensate completely for the loss of tactile information from a thin pseudopalate. Third, the presence of an appliance in the mouth might interfere with normal articulation. Research has shown no significant difference in patterns of tongue-palate contact between direct palatography and EPG (Hardcastle, 1972; see also Flege, 1976; Fletcher, McCutcheon, Wolf, Sooudi, & Smith, 1975; Hardcastle, 1984; but see Hamlet & Stone, 1978). Kozhevnikov and Chistovich (1965) found no difference in intelligibility with versus without the palate. Flege (1986 cited in Flege, 1988) found that a snugly fitting pseudopalate produced no perceptible interference with speech after only 5 minutes of adaptation on the part of the speaker. Fourth, the electrode coverage is limited mostly to the hard palate area, making it likely that contact on the pseudopalate underrepresents the full area of velar contact, specifically contact occurring on the soft palate. However, this problem is not serious for front velars. Hardcastle and Roach (1979) observed complete velar closures on their pseudopalate in the phrase "catkin." In Byrd (1994a), using the EPG system described below, an examination of 50 repetitions of an utterance containing velars, "Say ba<u>g g</u>ab again," including five speakers, shows every token to have a seal across the back of the palate for the velar consonant. Some tokens have up to five electrodes contacted along the midsagittal line. An adjacent low front vowel, [æ], was chosen to create a somewhat front velar constriction that would be most observable on the pseudopalate and, at the same time, to minimize linguapalatal contact during the vowel. Lastly, EPG cannot record the very beginning and end of an articulator movement before the sides of the rising tongue touch the palate. Comparably, magnetometer and X-ray microbeam movement tracking misses the beginning of a movement if it occurs outside the midsagittal plane. Because EPG instrumentation only measures contact, inferences about the complete gestural trajectory, tongue shape, articulator velocity, or time of innervation are hazardous or impossible. It is important to emphasize that EPG data only shows the beginning and end of contact whereas the gesture itself is likely to be longer; the precise timing of motor commands cannot be measured.

We use the Kay Elemetrics Palatometer model 6300. For each speaker, a stone cast made from a dental impression is used by Kay Elemetrics to manufacture a custom-fitted artificial palate that extends around the teeth. These palates have 96 electrodes and are scanned at a 100 Hz sampling rate. The Palatometer interfaces with the Kay Computer Speech Lab (CSL), an acoustic analysis system, thereby allowing the simultaneous examination of time-synchronized spectrograms, waveforms, and palatograms. The speech audio signal is acquired simultaneously with the linguapalatal information at a sampling rate of 12,500 Hz (we use a head-mounted directional microphone for this). Both the EPG and audio signals are recorded directly into a single computer file.

Before each experimental recording, the speaker wore his or her artificial palate for an hour of normal activity to accommodate and diminish any salivation response. For recording, subjects were seated near the EPG device, facing away from the computer monitor. Speakers were cued for each sentence individually by the experimenter, and there was a pause after each one for file management.

Data Reduction

Much EPG research has concentrated on the extent of assimilations or the effect of vowels on a single consonant's place of articulation. Marchal (1988) uses a qualitative approach to describe temporal characteristics of two-stop sequences in French, with four classes of articulatory and acoustic behavior as evidenced in closure and acoustic release patterns. Barry (1985) uses a similar qualitative classification of two-stop sequences, with three classes—"non-assimilated," "assimilated plus residual articulation," and "totally assimilated." Nolan (1992) employs a similar categorization in examining coronal reduction using the terms "full-alveolar," "residual-alveolar," and "zero-alveolar." Much work has discussed spatial patterns of contact at a particular moment, without exploiting the dynamic capability of EPG. However, work by Barry (1991, 1992), Butcher (1989), Hardcastle, Gibbon, and Nicolaidis (1991), Hardcastle and Roach (1979), Marchal (1988), and Nolan (1992) all emphasize the importance of temporal analysis of EPG data. Often data reduction efforts have taken the form of selecting a few specific frames of the data on which to concentrate further analysis (e.g., Hardcastle, 1984, Hardcastle et al., 1989). Here, data reduction procedures that do not necessitate the exclusion of data are the focus. This note on data reduction addresses the utility of user-defined pseudopalate regions and indices based on these regions in quantifying electropalatographic data.

The data analysis methods for EPG data are relatively straightforward, and the reader is encouraged to see Hardcastle et al. (1991) for an overview. Quantitative data are generally obtained in the form of numerical indices to describe the amount or frequency of contact. An index calculation might include contact across the whole palate or contact in a particular articulatory region or contact for a certain row or arc of electrodes. An index of linguapalatal contact might be given for a specific point in time or contact might be represented across time. This latter has been called a "totals" display (Hardcastle et al., 1989). Most temporal displays show the total number or percent of electrodes contacted at each frame over time. These curves have been called "trajectories" or "contact profiles." Measurements can be obtained from these displays. This method has been used by Barry (1991), Butcher (1989), and others.

For our work, software was written to calculate contact profiles in user-defined regions of the palate. A *percent* display was used that shows the percent of contacted electrodes, rounded to the nearest integer, in defined regions of the palate across time. These contact profiles serve as the foundation for the quantitative analyses. The novel use of speaker-specific articulatory regions, the criteria used in establishing these regions, and some indices based on these contact profiles are described further.

If every electrode contact at every sample were considered independently, the massive amount of data would be unwieldy and probably uninterpretable. Informative data analysis demands that this information be reduced in some form. There are two aspects to this data reduction. In the spatial domain, relevant parameters of the contact patterns at a given moment are considered. In the temporal domain, the changes in contact pattern over time are primary.

Region Definition

Electrodes in a particular subsection of the palate may be grouped together for purposes of data analysis and/or acquisition. One approach to reducing the degrees of freedom in the data contained in a single frame is to collect the individual electrodes into articulatory regions on the pseudopalate. A frame can then be described in terms of one number for each region: the number of electrodes contacted in a region, expressed in absolute terms, or as a percentage of the total number of electrodes in that region. These regions typically correspond to traditional places of articulation.

All previous EPG work of which we are aware has used *predetermined* regions on the pseudopalate that are the same for all speakers in an experiment or even hardwired into the pseudopalate itself. Given that there is considerable inter-speaker variability in palate size and shape, a region that is fixed across speakers in terms of the included electrodes may bear no consistent relationship to physiological landmarks or the area of articulation for a particular sound (although systems with *custom*-fitted pseudopalates, e.g., the Reading system, do try to address this issue by placing electrodes according to anatomical landmarks for individuals, e.g., Hardcastle, Jones, Knight, Trudgeon, & Calder, 1989.)

In our view, regions used for data reduction should be determined according to the goals of a specific experiment and should be sensitive to individual differences in physiology and articulation. Thus, we determine articulatory regions empirically for each experimental subject based on the articulatory patterns each demonstrates. This approach allows for inter-speaker differences in the details of electrode placement with respect to anatomical configurations or in speaker-specific articulatory patterns.

The following exemplifies one method of determining pseudopalate regions that correspond to the place of articulation of specific segments. In an experiment (reported in full in Byrd, 1994a, 1994b) considering coarticulation of alveolar and velar consonants in clusters spanning a word boundary, [s#g], [g#s], [d#g], and [g#d], the designation of front (alveolar) and back (velar) regions was based on a set of control utterances. Ten repetitions of [d#d], [s#s], and [g#g] sequences were used to establish front and back regions of the pseudopalate for 5 speakers. They were read in the carrier phrase "Say baC Cab again." Crucially, no electrodes that were contacted at a speaker's minimum contact for the preceding [æ] were included in the consonantal region. This ensured that the moment of initial contact measured in the sequence was in fact the concomitant of the formation of the consonant constriction. All electrodes contacted after the vowel minimum through the frame(s) of maximum contact during the consonant were assigned to the front region for the consonants [s] and [d] and to the back region for [g]. Electrodes that this metric assigned to both regions were also excluded. These cases were few and always adjacent to the excluded "vocalic" electrodes. All other (i.e., uncontacted) electrodes were also included in one of the two regions. It was important to make the regions as large as possible to avoid saturation whereby the contact level remains at 100% over a period of time. If an electrode was never contacted during the control sequences, it was included in the region to which it was physically closest as determined by measurements made with a flexible ruler on the acrylic palates themselves. As a result, this procedure is conservative in identifying the frame of initial contact for a consonant, but there is a high degree of confidence that the contact measured is actually attributable to the upcoming consonant in that region. The resulting regions for one speaker can be seen in Figure 1 on his pseudopalate. The front of the mouth is oriented to the top of the pictures. The electrodes are shown by small circles. Electrodes that were excluded from both regions are shown with an X over them. The heavy dark horizontal line marks the division of the remaining electrodes into front and back region groups. Significantly, the dividing line between front and back regions will differ for each speaker. This is particularly so in the central portion where the height and angle of the palatal vault varies. (Regions for other speakers can be found in Byrd, in press.)

The regions established for any particular experiment will depend on its empirical goals. The flexibility of user-defined pseudopalate regions is an important benefit of this data-reduction approach. There is no overt limitation that these regions correspond to a place of articulation or even include only adjacent electrodes on the palate. This allows the experimenter, for example, the freedom to define the sides of the palate as belonging to a particular region that may be called "the lateral region" even though these electrodes are nonadjacent. Empirical and theoretical goals of the research and the experimental design should determine region definition.

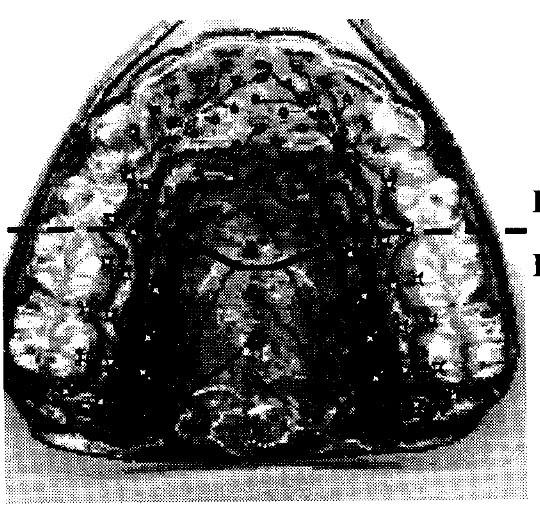

FIGURE 1. The pseudopalate for Speaker M with user-defined front and back regions.

Indices

Many data reduction procedures used in EPG research ignore temporal characteristics of the data by considering only a single moment in the utterance or temporally "smear" the data by evaluating a contact characteristic determined from multiple frames of data. Butcher (1989) notes: "Two major advantages of the [EPG] technique are that the information it provides is (a) dynamic and (b) quantitative. Either or both of these advantages sometimes get lost, however, in the process of data reduction . . ." (p. 42). Our work concentrates on the extraction of temporal parameters from the linguapalatal contact data. Certain spatial and spatio-temporal parameters descriptive of the shape of the contact profile are also considered. These parameters are called indices.

Indices quantify characteristics of time-varying contact patterns that are of experimental interest. We consider here indices relevant in two general experimental situations. First, measuring the relative coordination of two (or more) phonetic events, and, second, comparing the articulatory characteristics of two (or more) gestures, either of different types (e.g., alveolar vs. velar stops) or of the same type in different environments (e.g., alveolar stops in syllable-initial and syllable-final positions).

Given the division of the palate into regions, as described above, a consonant is characterized by the contact profile for its region. A sequence of consonants is thus represented by temporally aligned contact profiles for the consonants in the sequence.

Indices relevant to the comparison of consonant articulations quantify characteristics of individual contact profiles. An important characteristic is the maximum linguapalatal contact achieved during a consonant. The degree of linguapalatal contact, indicated by our index MAX, is indicative of a consonant's degree of lingual displacement. On the assumption that reduced consonants will have less contact, this measure provides an index of reduction. Many researchers have used a maximum contact measure to quantify EPG data.

Reduction is likely to have a temporal component that is not reflected by MAX—that is, a shortened duration. The index REGION DURATION is the time between initial and final regional contact for a consonant. Barry (1991) also uses the indices of maximum and "gestural" duration. He also uses an index that we do not pursue, namely, the duration of "closure," which he identifies as duration of regional contact saturation, or 100%, of his pseudopalate regions.

The index AREA takes into account duration and contact by summing the contact at each frame in the region duration, that is, the area under the contact profile. AREA is a more sensitive measure of reduction since it depends on both duration and amount of contact. AREA is also relevant to coordination. The index NON-OVERLAPPED AREA is the area for only that portion of the contact profile during which the other region in the sequence had no contact. The measure NON-OVERLAPPED AREA additionally attempts to reflect articulatory *hiding* where two (or more) gestures co-occur, potentially obscuring the perception of one or the other, thereby yielding a seeming reduction or deletion (Browman & Goldstein, 1989).

If a full gesture involves maintenance of peak contact for some duration, a reduced gesture might still achieve the same peak contact, but for a shorter duration. The index MAX is not sensitive to this difference. AREA might reflect it, but a more direct measure is the mean contact divided by the maximum contact—a measure we call FLATNESS. This index will be closer to 1 if contact remains near maximum for more of the duration of the consonant, that is, if the contact profile is relatively flat. Gestures that maintain a constriction will be flatter than those that form a closure that is quickly released.

A final index of profile shape is SKEW. The skewness, or third moment, of the contact profile is a measure of the degree of asymmetry between the onset and offset portion of the contact profile. A positive skew indicates that the closure formation occurs more quickly than its release (at least, as indicated for the portion of the gesture during which linguapalatal contact occurs).

Indices relevant to measuring the relative coordination of two (or more) phonetic events are of interest. These generally involve latencies between points in the contact profiles of consonants in a sequence. We calculate two measures of overlap as indices of consonant cluster coarticulation. The first, SEQUENCE OVERLAP, is the percent of the total sequence duration, from initial contact for C1 to final contact for C2, during which contact occurred in both regions. The second overlap measure represents the proportion of the first consonant overlapped by the second. This measure, C1 OVERLAP, is the time of regional contact for C1 for which contact for C2 occurred, expressed as a percent of total C1 regional contact duration.

We consider two indices as measures of absolute latency: the time between the initial contact in each region, ΔONSETS, and the time between maximum contacts, ΔMAXS. When maximum contact extends for more than one frame, the temporal center is used as the basis for calculation. Barry (1991) pursues a slightly different measure of absolute latency, the interval between "closure" onsets. This is similar to our time between maximum contacts but calculated slightly differently. As measures of relative latency, we calculate the percent of the time through the first consonant at which initial and maximum contacts for the second consonant occur—C2 ONSET RELATIVE TO C1 and C2 MAXIMUM RELATIVE TO C1. These measures take into account differences in the duration of the first consonant.

Figure 2 shows a sample contact profile for an [s#g] sequence (where # indicates a word boundary) using defined front and back regions. Time is on the x-axis and the percent of a region contacted on the y-axis. Notice that front region contact increases first, reflecting the articulation of [s]. Contact in the back region for [g] initiates at .08 seconds. That is, at any time point, contact made in the front region is considered to reflect the [s] and to be independent of contact in the back region (since electrodes contacted by both articulations in the control utterances were excluded). Similarly, any contact in the back region is considered to reflect the articulation of [g]. Hence, in Figure 2, there is a period between .08 and .21 seconds during which contact

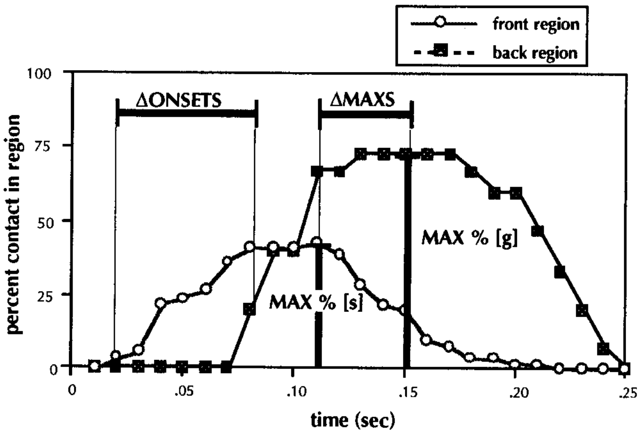

FIGURE 2. Sample contact profile for [s#g] in which indices—MAXIMUM, onset latency (ΔONSETS), and maximum contact latency (ΔMAXS)—are shown schematically.

for both [s] and [g] occurs. The indices MAXIMUM contact, ΔONSETS, and ΔMAXS are shown schematically in Figure 2. The measures of latency reflect the temporal coordination of the tongue tip and tongue body movements in coronal#velar sequence. The onset latency is the time between the first frame of contact in the front region and the first frame of contact in the back region. Analogously, maximum contact latency is the time between the maximum contact in the front region and the (temporal midpoint) of maximum contact in the back region.

The indices proposed here will be discussed in the con-

TABLE 1. Mean indices for Speaker M [s#g] and [g#s].

Indices	[s#g] mean (s.d.), n = 7	[g#s] mean (s.d.), n = 7
REGION DURATION (s)		
FRONT [s]	.174 (.017)	.176 (.015)
BACK [g]	.153 (.017)	.130 (.025)
MAXIMUM (%)		
FRONT [s]	39.9 (11.2)	50.7 (9.9)
BACK [g]	77.1 (6.6)	64.7 (8.4)
SEQUENCE OVERLAP (%)	62.6 (4.2)	32.7 (8.1)
C1 OVERLAP (%)	72.4 (4.3)	57.7 (9.1)
ΔONSETS (s)	.049 (.012)	.054 (.011)
ΔMAXS (s)	.041 (.017)	.048 (.021)
C2 ONSET RELATIVE TO C1 (%)	27.6 (4.3)	42.3 (9.1)
C2 MAXIMUM RELATIVE TO C1 (%)	68.7 (4.9)	84.9 (17.4)
AREA (Σ%)		
FRONT [s]	392 (100)	503 (86)
BACK [g]	841 (105)	577 (90)
NON-OVERLAPPED AREA (Σ%)		
FRONT [s]	80 (25)	202 (58)
BACK [g]	69 (59)	250 (61)
SKEW		
FRONT [s]	+.226 (.110)	+.331 (.100)
BACK [g]	+.012 (.073)	+.138 (.130)
FLATNESS		
FRONT [s]	.540 (.045)	.540 (.051)
BACK [g]	.671 (.032)	.648 (.083)

text of data from one speaker's productions of [s#g] and [g#s] sequences (these data from an experiment reported in Byrd, 1994a, 1994b). Contact profiles derived from seven repetitions of each are shown in Figures 3A [s#g] and 3B [g#s]. The indices described above were calculated for these productions and used to compare them. The mean values of the indices for each sequence are given in Table 1. Although the purpose here is not to present a statistical analysis, these indices could easily form the basis of such an analysis.

Many of the characteristics that appear qualitatively to be noteworthy in Figure 3A and 3B are reflected quantitatively by the indices. In examining the contact profiles, one immediately notes the differences in degree of coarticulation and some differences in profile shape. In fact we find that both [s] and [g] show lower MAX and AREA in syllable-final position (C1) than in syllable-initial position (C2). Presumably this reflects coda reduction. REGION DURATION is relevant also, and we see that it is shorter for the stop, [g], in coda than in onset. REGION DURATION does not differentiate onset and coda [s], however. In the examples considered, the index FLATNESS does not clearly distinguish onset consonants from coda consonants, but it does differentiate [g] from [s], [g] being flatter than [s]. It can also be observed in Figure 3 that [s] is less symmetrical than [g], having a longer offset than onset. This is quantified by SKEW, which is small for [g], but larger (and positive) for [s]. Finally, we can clearly see in Figure 3 that the [s#g] sequence is consistently more coarticulated than the [g#s] sequence. The indices reflecting the coordination of these events indicate greater overlap and shorter latencies for [s#g]. Also, C2 onset and maximum occur relatively later in C1 for [g#s]. Due to the greater overlap in [s#g], the measure of NON-OVERLAPPED AREA is much smaller for both consonants in [s#g] than in [g#s].

Conclusion

In conclusion, we would like to restate our support for electropalatography as an accessible method for the collec-

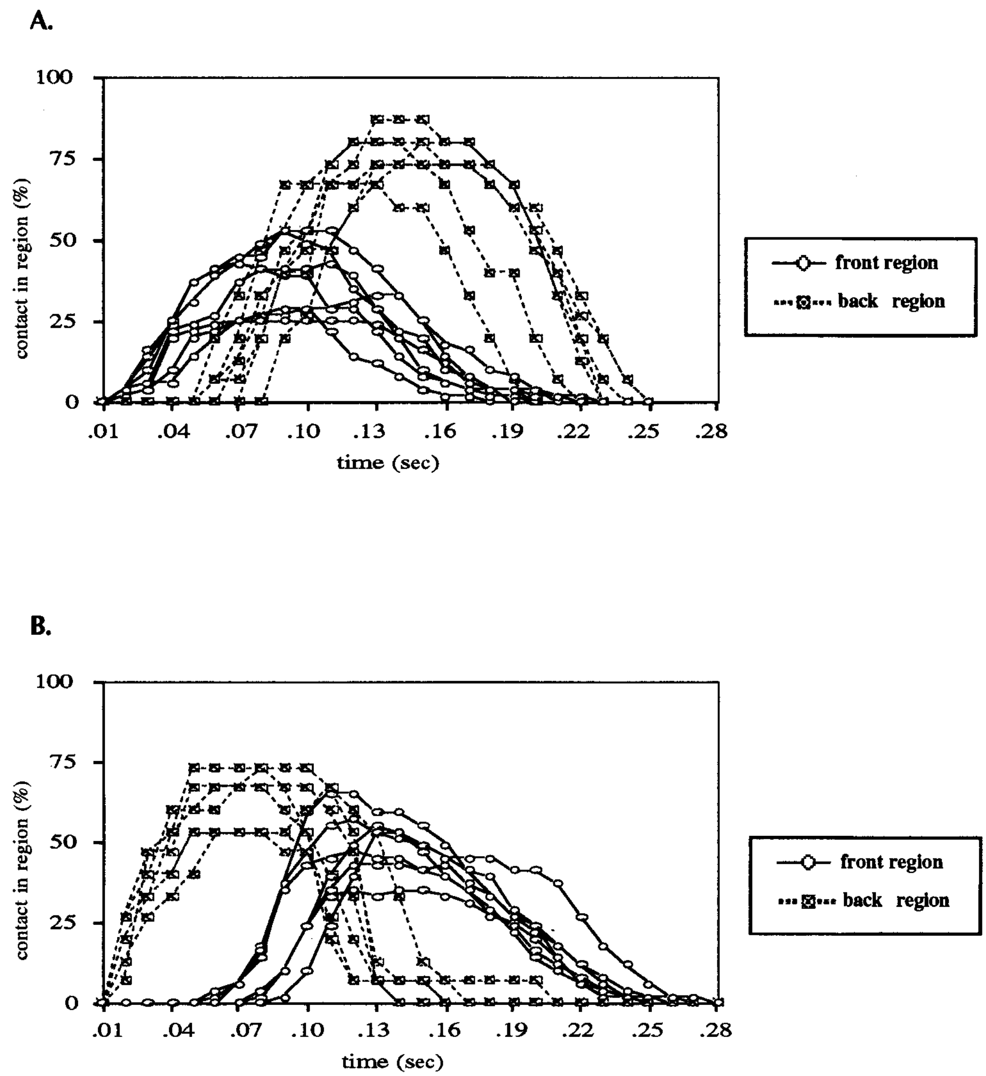

FIGURE 3. Contact profiles for [s#g] (panel A) and [g#s] (panel B) for Speaker M.

tion and analysis of articulatory data from a wide variety of subject populations. Specifically, we have described the use of speaker-specific, user-defined articulatory regions on the pseudopalate as the basis for the calculation of contact profiles. Indices based on these contact profiles were proposed to reflect both spatial and temporal aspects of articulation. The use of regions and indices is found to be valuable means of data reduction in the quantitative analysis of EPG data.

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Contact author: Dani Byrd, Haskins Laboratories, 270 Crown Street, New Haven, CT 06511-6695.