1274

Journal of Phonetics (2002) **30**, 357–371
doi:10.1006/jpho.2001.0161
Available online at http://www.idealibrary.com on IDEAL®

MRI evidence for commonality in the post-oral articulations of English vowels and liquids

Bryan Gick*

Department of Linguistics, University of British Columbia, Vancouver, BC V6T 1Z1, Canada and Haskins Laboratories, New Haven, CT, U.S.A.

A. Min Kang

Haskins Laboratories, New Haven, CT, U.S.A. and Department of Linguistics, Yale University, New Haven, CT, U.S.A.

D. H. Whalen

Haskins Laboratories, New Haven, CT, U.S.A.

Received 9th November 2001, and accepted 14th December 2001

One advantage of using articulatory gestures in models of speech production is that a single gesture can function as a component in a number of different traditional segments (e.g., the tongue tip constrictions for /t/, /d/, /n/ and /l/). Few such claims, however, have been made with reference to more dorsal tongue gestures such as those in American /r/ and /l/. The present paper tests a proposed connection between the pharyngeal components of English liquids and vowels. Midsagittal MRIs of the vocal tracts of three speakers of American English were collected during the production of all vowels in each subject's inventory, plus /r/ and /l/. Midsagittal distances between the tongue and opposing surfaces were measured at intervals along the length of the vocal tract, and the vocal tract was divided into regions: lower pharyngeal, upper pharyngeal, uvular and oral. Vowel shapes were subtracted point by point from /r/ and /l/, allowing a single RMS difference to be calculated within each region of the vocal tract. Results support the prediction that, at least in some dialects, a single postoral gesture is shared between /l/ and /ɔ/, and between /r/ and schwa.

1. Introduction

A major advantage of gesture-based models of speech production is that a single, if complex, unit of speech motor activity can function as a common element of a

*Address correspondence to: B. Gick, Department of Linguistics, University of British Columbia, Vancouver, BC V6T 1Z1, Canada. E-mail: gick@interchange.ubc.ca

0095–4470/02/$ - see front matter

number of phonological segments. Thus, for example, some models consider the tongue tip components of /t/, /d/, /n/ and /l/ to be a single gesture (e.g., Browman & Goldstein, 1992), resulting in a much more efficient cognitive model than one based on segment-sized primitives. These shared gestures can also be used to categorize segments into groups corresponding to phonologically natural classes, allowing for gesture-based accounts of phonological processes. An understanding of these physical events is of central importance to other frameworks as well, as most phonological feature systems used today are based on articulatory constrictions. However, the great majority of studies relevant to this issue of gestural componency have focused on anterior gestures (e.g., tongue tip raising/fronting, tongue anterior raising/fronting) and/or nonlingual gestures (lip constriction, velum lowering); few if any claims have been made regarding gestural componency in the postoral tongue gestures, such as the pharyngeal constriction of American /r/ and the upper pharyngeal/uvular constriction in /l/. This omission is presumably partly the result of the limited means available for measuring the more dorsal regions of the vocal tract.

The remainder of Section 1 presents background and phonological evidence supporting a proposed link between the postoral gestures of different segments—specifically, between the liquids /r, l/ and the vowels /ə, ɔ/, respectively—in at least some English dialects. The present paper contends that this link indicates a sharing of postoral gestures across these segments. To date, the similarity between the vocalic gestures of the liquids /r, l/ and the vowels /ə, ɔ/, respectively, has remained theoretical. No quantitative evidence has been brought forth in support of these connections.

Section 2 of this paper describes an MRI investigation conducted to test this hypothesis, comparing pharyngeal configurations during productions of /r/, /l/ and vowels as produced by speakers of three dialects of American English; Section 3 discusses the results and implications of this MRI study.

1.1. *Linking liquids with vowels: V-gestures*

Sproat & Fujimura (1993), in a study of American English /l/ allophones, proposed what may be seen as a first step in establishing a connection between certain component gestures associated with English liquids and other gestures associated with vowels. Specifically, on the basis of temporal and spatial characteristics, they determined that the two component gestures of /l/ (tongue tip and tongue dorsum) are categorically distinct, with the tongue tip component categorized as a "consonantal" gesture, and the tongue dorsum component as a "vocalic" gesture. Gick (In press *a*) replicated these findings for /l/, under the terms "C-gesture" and "V-gesture". Recall that the tongue tip gesture of /l/ has previously been identified with the tongue tip gestures of other consonant segments such as /t/, /d/, /n/, etc. Findings of Sproat and Fujimura imply that the tongue dorsum constriction of /l/ is most likely to identify not with typically consonantal gestures like these, but rather with gestures found somewhere in the vowel system.

Paralleling findings of Sproat and Fujimura for /l/, Gick (1999) provides evidence that these same categories are likely to apply to the component gestures of /r/ as well. The next question to be asked is whether the vocalic components of these liquid segments are unique gestures, or whether they correspond with other vocalic gestures already used in the system.

Phonological evidence has provided some additional resolution to this issue by suggesting that there are in fact specific vowels that correspond closely with English liquids, both historically and synchronically. These arguments are drawn mainly from processes that involve the articulatory reduction or "vocalization" of postvocalic /r/ or /l/ in many dialects. Specifically, previous studies have generated the hypothesis that there may be connections between the dorsal component of /l/ and the low, back vowel /ɔ/ (Gick, 1999) and between the tongue root retraction of /r/ and a purported pharyngeal constriction in schwa (McMahon, Foulkes & Tollfree, 1994). Sections 1.2 and 1.3 will outline this hypothesis.

1.2. *Evidence linking /r/ with schwa*

1.2.1. Historical evidence: intrusive r

It is well known that postvocalic /r/ undergoes a process of reduction, or "vocalization" in many dialects of English (e.g., Jones, 1989). The early development of this process was recorded by the English phonetician Daniel Jones (1928, xvii), who wrote that many speakers of early 20th-century British English not only reduced final /r/, but also inserted [r] following schwa-final words: "...at the end of every...word terminating with «ə». These pronounce *the idea of it* «ðiaidíəiəvit»". This phenomenon, known as "intrusive r", is now quite common across a number of dialects of English. Further, when /r/ vocalization follows a nonlow vowel, particularly in earlier/more conservative forms of RP, the final /r/ can be realized as a schwa (though note that most dialects no longer include schwa in some of these words): "...English /r/ before a consonant or [in final position] is reduced... . In Southern British speech this *r*...is replaced by [ə] in words like *fear, fair, fire, floor, boor,* or in *fierce, fairs, fires, floors, boors*" (Heffner, 1950; pp. 149–150). Many scholars have recognized these connections between /r/ and schwa, and have used schwa as a key component in otherwise theoretically disparate phonological accounts of intrusive r (e.g., Halle & Mohanan, 1985; McMahon *et al.*, 1994; Giegerich, 1997; Gick, 1999).

1.2.2. Articulatory evidence: final reduction

The only explanation proposed to date to account for this connection between /r/ and schwa is based on the idea that these segments have shared component gestures (McMahon *et al.*, 1994; Gick, 1999). This proposal draws on the well-known observation that English /r/ generally comprises multiple articulatory gestures, including tongue anterior raising and tongue root retraction (Delattre & Freeman, 1968; Hagiwara, 1995), and probably some lip adduction as well in many dialects. In addition to this, it is also known that C-gestures undergo a reduction in magnitude in postvocalic allophones. This "final reduction" phenomenon has been reported for the tongue and lip gestures of stop consonants (Turk, 1994; Browman & Goldstein, 1995), nasals (Browman & Goldstein, 1995), /l/ (Giles & Moll, 1975; Ash, 1982; Hardcastle & Barry, 1989, p. 15; Sproat & Fujimura, 1993; Gick, In press *a*), and glides (Gick, In press *a*).

The hypothesis proposed by McMahon *et al.* suggests that, if the tongue anterior raising gesture of /r/ is removed (i.e., reduced to zero or near-zero), the remaining tongue configuration will closely resemble that of schwa. For this to be true, first, it must be shown that the tongue anterior raising gesture of English /r/ is a C-gesture, i.e., that it is subject to final reduction. Gick (1999) tested this possibility for American English and found that the tongue anterior gesture of /r/ does in fact undergo significant reduction in postvocalic allophones. Second, it must be shown that, contrary to the common wisdom, schwa involves a pharyngeal constriction gesture that might be compared with that of /r/.

1.2.3. Articulatory evidence: pharyngeal constriction in English schwa

Until recently, the presence of a pharyngeal constriction predicted for schwa (McMahon *et al.*, 1994; Gick, 1999) had not been observed empirically, making it particularly suspect, as many linguists have considered schwa as lacking either an articulatory target or phonological features (e.g., Giegerich, 1992, p. 68; Halle & Mohanan, 1985, p. 82). Recent findings, however, have identified an active tongue root retraction (pharyngeal constriction) gesture in American English schwa. In a study using video data taken from an early pilot X-ray motion picture, Gick, Kang & Whalen (2000) found that casual observation of pharynx width showed a more retracted tongue root for schwa than for any other sound observed except [a]. Further, in an utterance like [áɾə], the tongue root was observed to drift forward during the intervocalic flap from a strongly retracted position for the [a], then to retract sharply again for the final schwa, as shown in Fig. 1.

In a more thorough follow-up study comparing schwa to the general rest position adopted during speech (the position to which the articulators drift during brief pauses between audible speech, presumably while the subject is still in a speech mode; cf. Barry, 1992, p. 66), Gick (In press *b*) found that the pharynx was indeed significantly more constricted during schwa than during speech rest position for all four subjects depicted in the X-ray video. In contrast, the pharynx width during the intervocalic flap was not significantly different from the rest position (Gick *et al.*, 2000). These findings supporting an active pharyngeal constriction in schwa lend support to the proposal that /r/ and schwa may in fact share a pharyngeal gesture.

1.3. *Evidence linking /l/ with /ɔ/*

Although less well known, /l/ undergoes a similar process of reduction and epenthesis to that of /r/. L-vocalization, "intrusive l" and related phenomena have been observed in parts of Southern Pennsylvania and in other areas of the Northeast United States (Gick, 1999). However, while reduction of the tongue anterior raising gesture for /r/ historically resulted in a final schwa (e.g., the homophonous *tuna* and *tuner* [tjunə]), the parallel reduction of the oral (tongue tip fronting) gesture for /l/ resulted in a final /ɔ/ (e.g., both *saw* and *Saul* [sɔː]). Gick (1999) proposes that, as with /r/ and schwa, this correspondence between /l/ and /ɔ/ indicates that the postoral (tongue dorsum backing) gesture of /l/ is shared with the tongue dorsum gesture of /ɔ/.

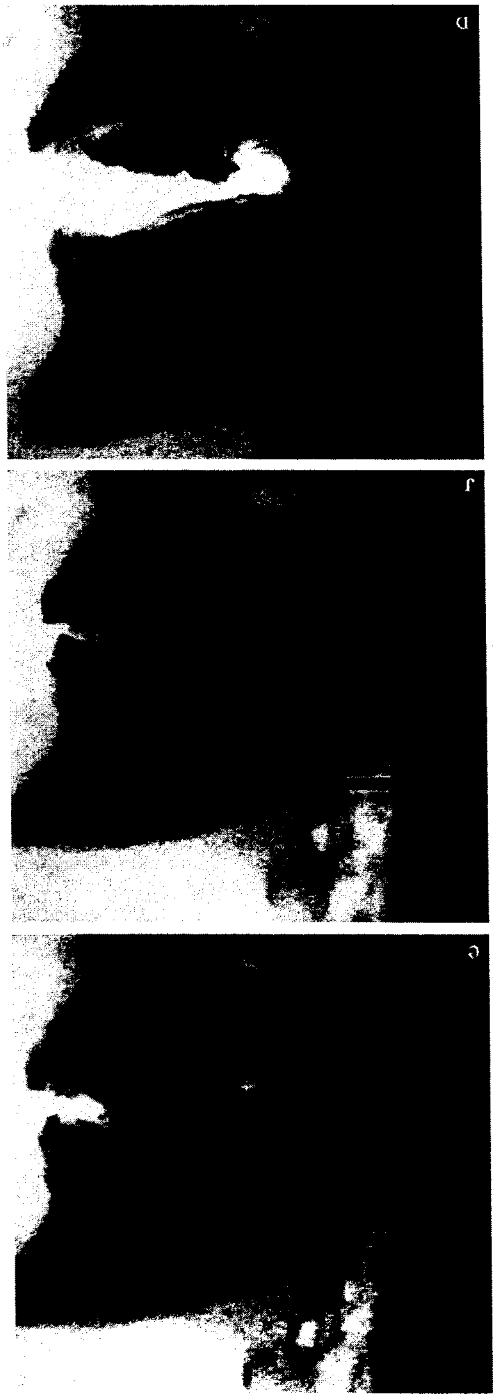

Figure 1. X-rays of [árə] produced by female talker (adapted from Gick *et al.*, 2000). Horizontal bars indicate approximate midsagittal pharynx width at a uniform vertical displacement from maxillary bone points. These images were extracted from a video copy of an early pilot X-ray film made at Haskins Labs (Cooper & Abramson, 1960).

1.4. *Dialect-specific predictions*

The main hypothesis of this paper—that the English liquids share gestures with certain vowels—is based upon historical and synchronic processes that have been observed only in certain dialects. Thus, the predicted sharing of gestures may be presumed to vary from one dialect of English to another (in fact, the English liquids are known to exhibit a great deal of variation both within dialects and within speakers (e.g., Delattre & Freeman, 1968; Ong & Stone, 1998; Westbury, Hashi & Lindstrom, 1998; Guenther, Espy-Wilson, Boyce, Matthies, Zandipour & Perkell, 1999). This, however, presents something of a "Catch-22" for experiment design: The dialects discussed in Sections 1.2 and 1.3 have all undergone complete vocalization of /r/ or /l/, to the point where the liquid has effectively merged with final schwa or /ɔ/, respectively. Thus, finding similarity in the pharyngeal configurations of schwa and /r/, or of /ɔ/ and /l/, in such dialects would be fully expected and uninteresting. The ideal subjects to test in this case would be, for example, speakers of turn-of-the-century Massachusetts English for /r/, or those of mid-20th-century Southern Pennsylvania for /l/, where we now know such reductions and mergers took place. However, we can still make some predictions about which subjects are likely to show these patterns. Namely, we propose that subjects who are natives of larger regions where the historical /r/-schwa or /l/-/ɔ/ merger took place, but whose dialects do not themselves contain the merger, will be the likeliest to show the correspondence between the postoral gestures of the liquids and vowels in question. While we recognize that this correspondence may theoretically be found in any dialect, we believe that such connections may be reinforced through exposure to the vocalized and/or merged forms.

2. Methods

An experiment was conducted to compare the static shapes of the midsagittal vocal tract configuration of the pharyngeal and uvular regions for /l/ and /r/ with the shapes for each of the vowels in the system. This MRI study tests the hypothesis that, of all of the vowels, the configuration for schwa will correspond most closely with that of /r/, and that of /ɔ/ will correspond most closely with that of /l/.

MRI was used in this study to enable the imaging of the entire length of the vocal tract along the midline, providing midsagittal images analogous to (and more complete than) static data collected for the upper oral tract using other techniques (e.g., electromagnetic articulometry (EMA)). While it would certainly be more precise to use full volumetric data in this study, this would introduce additional costs in the form of longer acquisition times, requiring speakers to sustain these normally unsustained sounds over even longer durations. Therefore, a minimum number of slices was collected wherever possible.

2.1. *Subjects*

As discussed in Section 1.4 above, the ideal subjects for testing this hypothesis are not available. However, we have predicted that subjects who are natives of a general area where the historical /r/-schwa or /l/-/ɔ/ mergers occurred will be more likely to show the predicted correspondence between the postoral gestures of the liquids and vowels. Broadly speaking, the primary areas of the United States where historical r-intrusion and l-intrusion are known to have originated are New England and Southern Pennsylvania, respectively. Three native speakers of American English, one male and two females, participated in the present study. The male subject, EM, is a native of Maine; the first female subject, CB, is a native of Illinois; and the second female subject, HM, is a native of Philadelphia. Subjects EM and HM produced both /a/ and /ɔ/. All subjects are phonetically trained. All subjects produce postvocalic /r/ and /l/; however, we may think of subject EM as the New England /r/ subject (likeliest to share a common gesture with schwa), subject HM as the Southern Pennsylvania /l/ subject (likeliest to share a gesture with /ɔ/), and subject CB as the "General American" control (for whom neither /r/ nor /l/ is substantially vocalized).

2.2. *Stimuli*

Images of subject CB and EM were collected for previous studies, in 1992 and 1999, respectively. Data collection methods used for these subjects are described in Whalen, Kang, Magen, Fulbright & Gore (1999). For HM and EM, each sustained vowel/liquid was produced to match that of a keyword presented orally by the experimenters, e.g., for /r/ and /l/, subjects were asked to hold allophones as in *herd* and *hull*. Because CB's data were recorded in an earlier study, the stimuli used in collecting her data are not known. The liquids /r/ and /l/ were collected for all subjects, as well as 11 vowels for subjects EM and HM: /i, ɪ, e, ɛ, æ, a, ʌ, ɔ, o, ʊ, u/; and 10 for CB: /i, ɪ, e, ɛ, æ, a, ʌ, o, ʊ, u/. Only noninitial allophones of /r/ and /l/ were collected because of the requirement that focus sounds be sustained. The vowel /ʌ/ (as in, e.g., the words *gut*, *but* in most American dialects of English) was collected in place of unstressed schwa, as acquisition time for a single token was in excess of 10 s for all subjects, requiring sustained vowels (presumably in the future, better temporal resolution in MRI technology will allow measurement of a truly unstressed schwa using better dynamic imaging). However, schwa is not the only vowel presenting difficulties for MRI studies. For /l/, all of the short vowels, and possibly /r/, it is particularly relevant to recall that all of the subjects in this study were phonetically trained. Because the constraints of the data collection method used in this study require that normally unsustained sounds be sustained, the use of trained subjects was crucial (see, e.g., Alwan, Narayanan & Haker (1997) and Narayanan, Alwan & Haker (1997) for treatment of similar issues with MRI studies of American /r/ and /l/).

2.3. *Apparatus*

Midsagittal *T*1-weighted MR images were obtained on a GE 1.5 T Signa magnet (see Whalen *et al.* (1999) for details on the localizing prescan). For subject EM, three 5-mm slices (midsagittal plus two parasagittal) were collected using a fast spin-echo technique with the following parameters: skip = 0, TR = 400 ms, TE = 14 ms, ETL = 4, Esp = 14 ms, 128 × 128, 1nex, FOV = 28 cm. For subject HM, full volumetrics were collected (4-mm slice thickness) using a 2D fast SPGR technique, with skip = 0, TE = 2.2, TR = 134 ms, 30° flip angle, matrix 256 × 160, BW = 15.63, 1nex, FOV = 28 cm. For subject CB, three 5-mm slices (midsagittal plus two parasagittal) were collected using skip = 0, TE = 14, TR = 400 ms, ETL = 4, Esp = 14 ms, flip angle unknown, matrix 128 × 128, BW = 32, 1nex, FOV = 28 cm.

2.4. *Procedure*

In all three data collection sessions, subjects were verbally prompted with a target vowel in a keyword context using an intercom system. Scanning was started when subjects began phonation. The number of repetitions available for each vowel/liquid for EM (5/4) and CB (1) were limited by the constraints of the original studies for which their data were collected. Likewise, because of magnet time constraints, only one repetition of each vowel/liquid was collected for HM as well. Fig. 2 shows all 11 vowels and both liquids collected for subject EM.

2.5. *Analysis*

Vocal tract widths were measured from MR images on a Power Macintosh using public domain software NIH Image v1.61. Using macros first developed by Mark Tiede (ATR Labs), an array of lines was superimposed on the images at 3-mm intervals along the vocal tract length, approximately perpendicular to the tract. Forty-eight intervals were used for EM, 41 for CB, and 31 for HM, varying according to tract length. The uvula was removed from each image before measurement and replaced with a line following the palatal contour, for the following reasons: (1) the tongue–uvula distance is not representative of the overall cross-sectional area of the vocal tract at that point, (2) the uvula intruded into the image to different extents for different utterances, and (3) it has been shown previously (Magen & Kang, 1997) that inclusion of the uvula in articulatory synthesis does not significantly affect acoustic output. Fig. 3 shows an example of the overlaid array of lines.

Distances between the tongue and opposing surfaces were automatically extracted along each of these lines (see Whalen *et al.* (1999) for further details on this technique). The tract was then divided into pharyngeal, uvular and oral regions, with pharyngeal divided into upper and lower halves. Because the pharynx was consistently about twice the length of the uvular region, it was possible to specify three regions of equal length, running from the top of the uvula to just above the larynx. Equal lengths (equal numbers of intervals) were thus ascribed to each of the uvular, upper pharyngeal, and lower pharyngeal regions, with the uvular region being defined approximately as the area where inclusion *vs.* exclusion of the uvula in the airspace affected the midsagittal width of the tract, and the lower end of the lower pharyngeal region located just above the larynx. Airspace for each vowel/liquid was measured (the five repetitions of each were averaged together for subject EM), and each vowel was then subtracted point by point from /r/ and /l/, allowing a single RMS difference to be calculated for each vowel within each region of the vocal tract (see Ong & Stone (1998; p. 4, 5) for discussion of a similar method using mean squared error of vocal tract cross-sections to compare tract shapes for English liquids).

In addition to the above nonstatistical comparisons, because subject EM produced multiple repetitions of each vowel/liquid (5 and 4, respectively), it was possible to

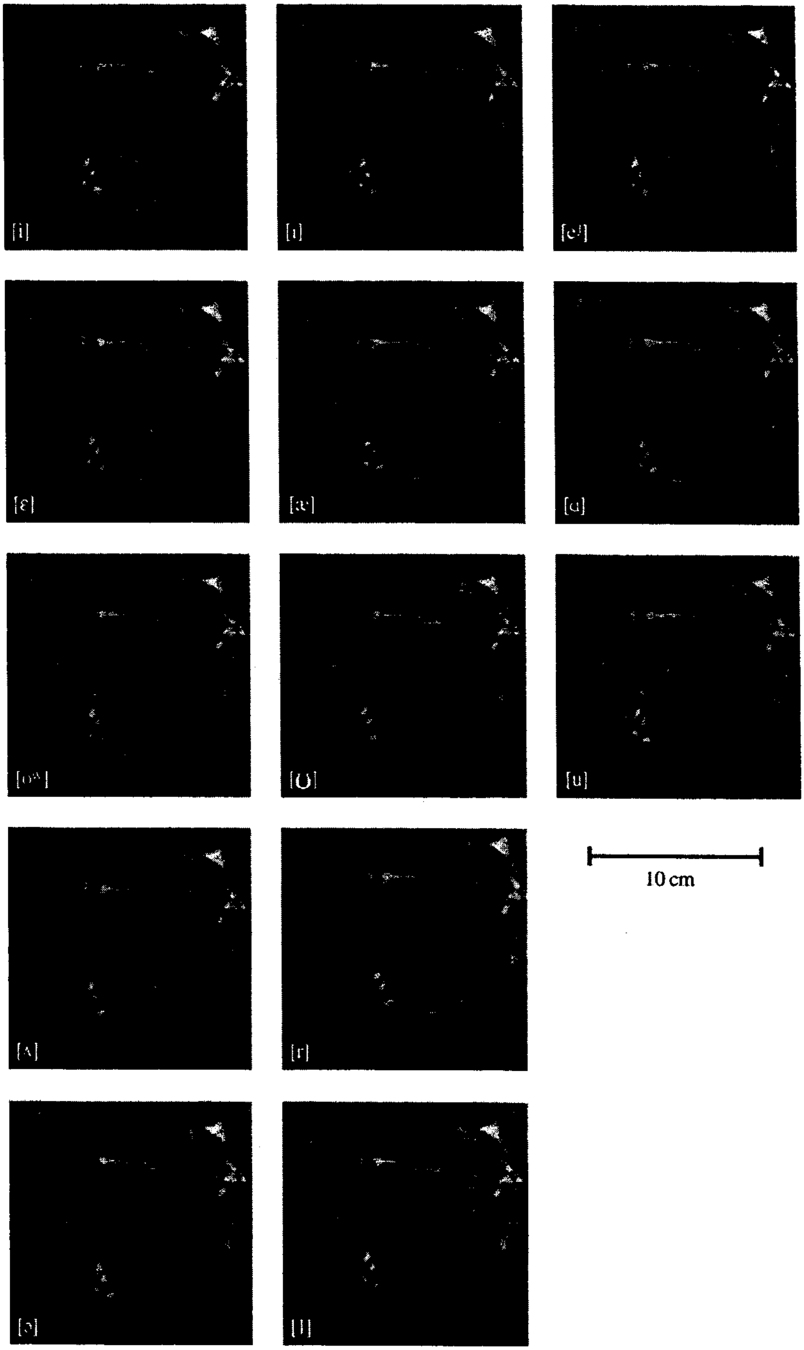

Figure 2. Eleven vowels plus /r/ and /l/, as produced by subject EM.

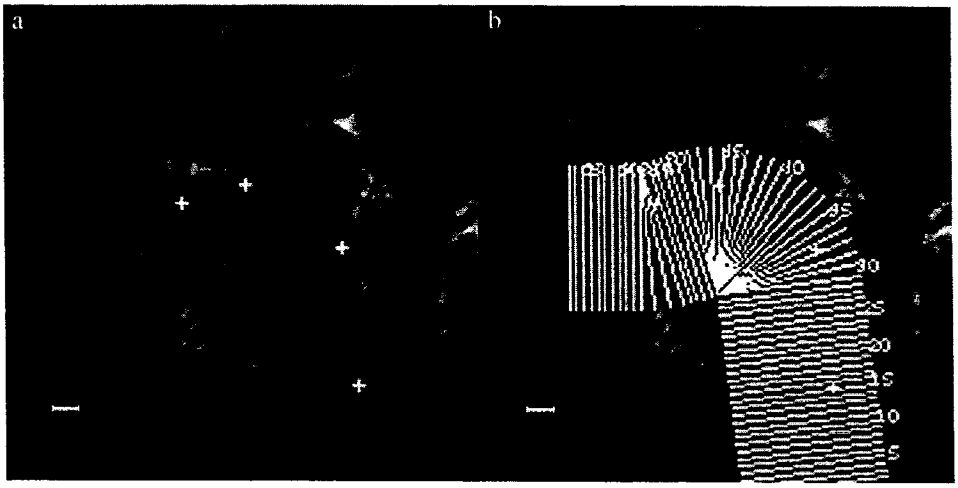

Figure 3. Example array of measurement lines overlaid on a midsagittal image of subject EM (from Whalen *et al.*, 1999).

compare statistically (ANOVA) the similarity of the tract widths line-by-line for the liquids *vs.* vowels for this subject.

3. Results

Fig. 4 shows plots of superimposed average tract shapes of selected vowels for subject EM; Fig. 5 shows superimposed tract shapes for subjects CB and HM.

For subject EM (see Table I), as predicted, /r/ showed a greater correspondence with /ʌ/ than any other vowel in the system throughout the entire pharynx and into the uvular region; in addition, despite the lack of dialect-based expectation, /l/ was most similar to /ɔ/ in the upper pharynx and surrounding regions as well. For subject CB (see Table II), /r/ showed a greater correspondence with /ʌ/ in the upper pharynx only. For subject HM (see Table III), again as predicted, /l/ showed the greatest correspondence with /ɔ/ throughout the pharynx; HM showed no correspondence between /r/ and /ʌ/.

Finally, the line-by-line ANOVA results for subject EM are shown in Table IV. An asterisk placed in a cell indicates that the tract width of that vowel at that cross-section is not significantly different ($p > 0.05$) from the width of /r/ (Table IV(a)) or from that of /l/ (Table IV(b)). Confirming the RMS results in Table I, the ANOVA results show significant similarity between /r/ and /ʌ/ throughout both the lower and upper pharynx. While results for /l/ are less marked, /l/ and /ɔ/ show the greatest similarity in cross-sections 8–12 at the upper–lower pharynx boundary, with substantial overlap from /ʌ/ in the lower pharynx and /a/ in the upper pharynx.

4. Discussion

The results of this study show strong correspondences between static vocal tract shapes for all of the predicted liquids and vowels (/l/ and /ɔ/ for subject HM, and

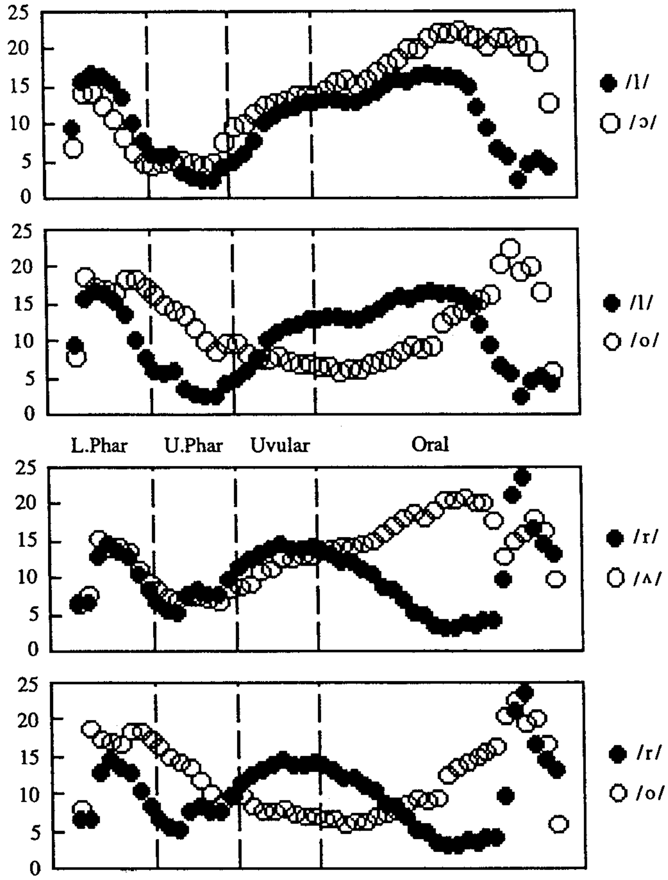

Figure 4. Superimposed average tract shapes of selected vowels for subject EM; from top to bottom: /l/ *vs.* /ɔ/, /l/ *vs.* /o/, /r/ *vs.* /ʌ/, /r/ *vs.* /o/ (y-axis indicates midsagittal distance). Note the similarity of /l/ and /r/ to /ɔ/ and /ʌ/ (top and third plots), respectively, in the pharyngeal and uvular regions. Comparisons with /o/ (second and bottom plots) are included to illustrate contrast.

/r/ and /ʌ/ for subject EM) throughout the pharyngeal or pharyngeal/uvular regions. In addition, subject EM showed a strong correspondence between /l/ and /ɔ/, while subject CB showed a correspondence between /r/ and /ʌ/, limited to the upper pharynx. Overall, these findings support the hypothesis that these liquids and vowels share phonological post-oral articulatory gestures.

5. Conclusion

The findings in this paper support the phonologically based prediction that the post-oral gestures of English liquids may be identified with those of certain vowels. Midsagittal MRI data supported the predicted similarity between the pharyngeal configurations of /l/ and /ɔ/, and of /r/ and /ə/ in certain regional dialects of

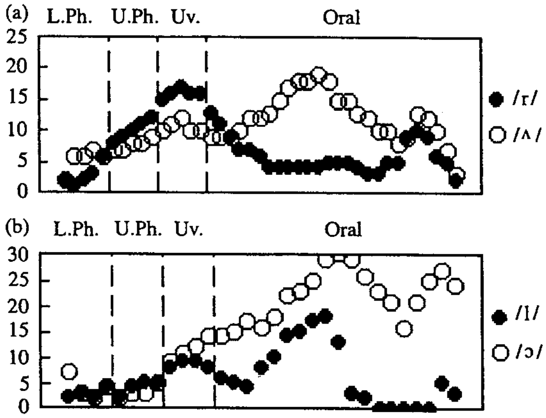

Figure 5. Superimposed tract shapes for (a) subject CB /r/ *vs.* /ʌ/, and (b) subject HM /l/ *vs.* /ɔ/.

TABLE I. Subject EM. RMS distances (in mm) between (a) /l/ and its most similar vowel, and (b) /r/ and its most similar vowel, within each vocal tract region

	By region	Pharynx	UPhar/Uv	Phar/Uv
(a) /l/				
L. Phar	ʌ (2.33)	ɔ		
U. Phar	ɔ (1.83)	(2.56)	ɔ	ʌ (2.44)
Uvular	ʌ (1.71)		(2.22)	
Oral	æ (2.45)			
(b) /r/				
L. Phar	ʌ (0.99)	ʌ		
U. Phar	ʌ (1.39)	(1.10)	ʌ/ɔ	ʌ (1.47)
Uvular	ɛ (0.94)		(1.71)	
Oral	ɪ (3.49)			

Note: Regions showing the predicted correspondence (with /ɔ/ or /ʌ/) are shown in gray.

TABLE II. Subject CB. RMS distances (in mm) /r/ and its most similar vowel, within each vocal tract region (no comparisons are listed for /l/, as CB did not produce the vowel /ɔ/)

	By region	Pharynx	UPhar/Uv	Phar/Uv
/r/				
L. Phar	æ (0.06)	ʊ		
U. Phar	ʌ (2.17)	(1.70)	ɛ	æ (2.07)
Uvular	æ (2.2)		(2.55)	
Oral	ɪ (2.14)			

Note: Regions showing the predicted correspondence (with /ʌ/) are shown in gray.

TABLE III. Subject HM. RMS distances (in mm) between (a) /l/ and its most similar vowel, and (b) /r/ and its most similar vowel, within each vocal tract region

	By region	Pharynx	UPhar/Uv	Phar/Uv
(a) /l/				
L. Phar	ɔ (1.25)	ɔ		
U. Phar	ɔ (0.75)	(1.00)	ʌ	ɔ (1.67)
Uvular	ʌ/o (1.50)		(1.75)	
Oral	ɪ (5.37)			
(b) /r/				
L. Phar	ε (2.75)	ʊ		
U. Phar	ʊ (2.25)	(2.62)	ʊ	ʊ (2.33)
Uvular	ε /ʊ (1.75)		(2.00)	
Oral	ɪ (3.89)			

Note: Regions showing the predicted correspondence (with /ɔ/ or /ʌ/) are shown in gray.

TABLE IV. Subject EM. Significant non-dissimilarity (ANOVA) to (a) /r/ and (b) /l/

	LPhar									UPhar								Uvula						
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
(a)																								
ʌ	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*				*	*	*	*	*
a	*	*	*						*	*	*									*	*	*	*	*
æ	*	*	*	*	*	*	*	*	*			*							*	*	*	*	*	*
ε	*	*	*	*	*	*	*											*	*	*	*		*	*
e	*	*	*	*	*													*	*					
ɪ	*	*	*	*	*	*												*	*	*	*		*	*
i		*																	*					
ɔ	*		*						*	*	*				*				*	*	*	*	*	*
o	*															*								
ʊ			*	*									*	*	*	*								
u																	*							
(b)																								
ʌ			*		*	*	*	*	*	*	*									*	*	*	*	*
a									*	*	*	*								*	*	*	*	*
æ							*	*	*													*	*	*
ε			*		*	*															*	*	*	*
e	*			*	*	*														*	*			
ɪ	*			*	*	*														*	*	*	*	
i	*			*	*															*	*			
ɔ		*	*					*	*	*	*	*								*	*	*	*	*
o	*		*	*	*														*	*	*			
ʊ	*	*	*	*	*													*	*	*	*	*	*	*
u	*		*																*	*				

Note: Asterisks indicate lack of significant difference ($p > 0.05$) between widths for vowels *vs.* liquids at each cross-section through the postoral regions of the vocal tract. Focus vowels (ʌ and ɔ, respectively) are indicated with gray.

American English. While these findings are by their nature nonconclusive (it is not possible to measure a phonological unit *per se*), they corroborate an already strong phonological argument—and more importantly, they are equivalent to the evidence supporting other generally accepted shared gestures across segments. These findings provide a basis for incorporating a more efficient model of tongue root specification into articulatory models of speech production, and for a unified treatment of the tongue root component of liquids and vowels in theories of phonology. Future studies using full volumetric and/or dynamic data of pharyngeal constrictions will be needed to elucidate more clearly these connections between the gestures of the liquids and vowels of English.

The authors wish to thank guest editor Phil Hoole and two anonymous reviewers for valuable comments on this paper, as well as audiences at the 138th Meeting of the Acoustical Society of America, Columbus, OH, 1999 and at the 5th Seminar on Speech Production, Seeon, Germany, 2000. This work was supported by NIH grant DC-02717 to Haskins Laboratories.

References

Alwan, A. A., Narayanan, S. S. & Haker, K. (1997) Toward articulatory-acoustic models for liquid approximants based on MRI and EPG data. Part II. The rhotics, *Journal of the Acoustical Society of America*, **101(2)**, 1078–1089.

Ash, S. (1982) *The vocalization of /l/ in Philadelphia*. PhD dissertation, University of Pennsylvania.

Barry, W. (1992) Comments on Chapter 2 [Browman & Goldstein]. In *Papers in Laboratory Phonology II: Gesture, Segment, Prosody* (G. Docherty & R. Ladd, editors), pp. 65–67. Cambridge: Cambridge University Press.

Browman, C. P. & Goldstein, L. (1992) Articulatory phonology: an overview, *Phonetica*, **49**, 155–180.

Browman, C. P. & Goldstein, L. (1995) Gestural syllable position effects in American English. In *Producing Speech: Contemporary Issues. For Katherine Safford Harris* (F. Bell-Berti & L. J. Raphael, editors), pp. 19–34. Woodbury, NY: American Institute of Physics.

Cooper, F. S. & Abramson, A. S. (1960) *A pilot X-ray film of English articulations with stretched sound*. Haskins Laboratories and Columbia-Presbyterian Medical Center, New York.

Delattre, P. C. & Freeman, D. C. (1968) A dialect study of American *r*'s by X-ray motion picture, *Linguistics*, **44**, 29–68.

Gick, B. (1999) A gesture-based account of intrusive consonants in English, *Phonology*, **16**, 29–54.

Gick, B. (In press *a*) Articulatory correlates of ambisyllabicity in English glides and liquids. In *Papers in Laboratory Phonology VI: Constraints on Phonetic Interpretation* (J. Local, R. Ogden & R. Temple, editors). Cambridge: Cambridge University Press.

Gick, B. (In press *b*) An X-ray investigation of pharyngeal constriction in American English schwa, *Phonetica*.

Gick, B., Kang, A. M. & Whalen, D. H. (2000). MRI and X-ray evidence for commonality in the dorsal articulations of English vowels and liquids. In *Proceedings of the 5th seminar on "speech production: models and data and the crest workshop on models of speech production: motor planning and articulatory modeling"*, Kloster Seeon, Bavaria, Germany.

Giegerich, H. (1992) *English Phonology*. Cambridge: Cambridge University Press.

Giegerich, H. (1997) The phonology of '/ɔː/' and '/ɑː/' in RP English: Henry Sweet and after, *English Language and Linguistics*, **1**, 25–47.

Giles, S. B. & Moll, K. L. (1975) Cinefluorographic study of selected allophones of English /l/, *Phonetica*, **31**, 206–227.

Guenther, F. H., Espy-Wilson, C. Y., Boyce, S. E., Matthies, M. L., Zandipour, M. & Perkell, J. S. (1999) Articulatory tradeoffs reduce acoustic variability during American English /r/ production, *Journal of the Acoustical Society of America*, **105**(5), 2854–2865.

Hagiwara, R. (1995) Acoustic realizations of American /r/ as produced by women and men. *UCLA Working Papers in Phonetics*, **90**.

Halle, M. & Mohanan, K. P. (1985) Segmental phonology of modern English, *Linguistic Inquiry*, **16**(1), 57–116.

Hardcastle, W. & Barry, W. (1989) Articulatory and perceptual factors in /l/ vocalisations in English, *Journal of the International Phonetic Association*, **15**(2), 3–17.

Heffner, R.-M. S. (1950) *General Phonetics*. Madison: University of Wisconsin Press.
Jones, C. (1989) *A History of English phonology*. London: Longman.
Jones, D. (1928) *An English Pronouncing Dictionary* [revised from 1917]. London: J. M. Dent & Sons.
Magen, H. S. & Kang, A. M. (1997) Effects of the uvula and the epiglottis on measurements of vowel production: assessment by synthesis, *Journal of the Acoustical Society of America*, **102**, 3093(A).
McMahon, A., Foulkes, P. & Tollfree, L. (1994) Gestural representation and lexical phonology, *Phonology*, **11**, 277–316.
Narayanan, S. S., Alwan, A. A. & Haker, K. (1997). Toward articulatory-acoustic models for liquid approximants based on MRI and EPG data. Part I. The laterals, *Journal of the Acoustical Society of America*, **101**(2), 1064–1077.
Ong, D. & Stone, M. (1998) Three dimensional vocal tract shapes in /r/ and /l/: a study of MRI, ultrasound, electropalatography and acoustics, *Phonoscope*, **1**, 1–13.
Sproat, R. & Fujimura, O. (1993) Allophonic variation in English /l/ and its implications for phonetic implementation, *Journal of Phonetics*, **21**, 291–311.
Turk, A. (1994) Articulatory phonetic clues to syllable affiliation; gestural characteristics of bilabial stops. In P. Keating (ed.), *Papers in Laboratory Phonology 3: Phonological Structure and Phonetic Form*. Cambridge: Cambridge University Press, pp. 107–135.
Westbury, J. R., Hashi, M. & Lindstrom, M. J. (1998) Differences among speakers in lingual articulations of American English /ɹ/, *Speech Communication*, **26**, 203–226.
Whalen, D. H., Kang, A. M., Magen, H. S., Fulbright, R. K. & Gore, J. C. (1999) Predicting midsagittal pharynx shape from tongue position during vowel production, *Journal of Speech, Hearing and Language Research*, **42**, 592–603.