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Chapter 4

Variability of North American English /r/ production in response to palatal perturbation

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Abstract

It is well established that the lowered third formant constituting the primary acoustic percept of American English /r/ can be achieved with different tongue shapes in production, which may be broadly grouped into 'bunched' and 'retroflex' production strategies. There is also evidence showing that some speakers select one or the other of these production strategies depending on the coproduction context, thus suggesting that the two are motorically equivalent. The research question pursued in this work is whether such motor equivalence in /r/ production is a generally accessible property of fluency in American English. While the vocal tract morphology of a given speaker may lead her to prefer one tongue shape uniformly, introduction of a perturbation interfering with normal articulation habits may potentially induce that speaker to explore the use of an alternative shape. To investigate this possibility, subjects in this study were fitted with a custom palatal prosthesis incorporating a protrusion along the alveolar ridge, and observed during /r/ production with and without the prosthesis using electromagnetometry. Results show that a majority of subjects responded to the artificial palate by alternating between tongue shapes. Regardless of tongue shape, no subjects showed significant differences across condition in formant patterns for /r/. All subjects showed a pattern of motor equivalence between tongue constriction location and corresponding lip protrusion, as displaced by the palate or as an aftereffect of wearing it. These results are consistent with the primacy of acoustic goals in the production of /r/.

4.1 Introduction

Human speakers have a remarkable aptitude for producing intelligible speech when confronted with constraints on normal articulation. Ventriloquists, for instance, speak effectively without moving their lips; surgical patients who have undergone resection of the tongue, lips, or other articulators find means of compensating for loss of function to recover adequate speech facility.

How speakers do this, how quickly and under what conditions, has been a matter of much scientific fascination.

One persistent question is whether such compensation is immediate, or whether speakers require a period of trial and error to reorganize their articulation effectively. In a pioneering bite-block study, Lindblom et al. (1979) established that speakers succeeded in producing near-normal vowel formants despite the constraint on mandible position, and were able to do so from the first glottal cycle. Studies in which the effects of unexpected perturbation of jaw position during bilabials were evaluated with respect to lip compensation (including Folkins and Abbs 1975; Gomi et al., 2002; Kelso et al., 1984) have shown that the time course of such compensation is both rapid (e.g. 15–35 ms in OOI reported by Kelso et al.) and complete (the lips achieve closure). However, studies investigating adaptation to prostheses affecting oral tract morphology have shown that such adaptation takes place gradually (though at subject-specific rates), and that learned modifications to normal production can persist as after-effects following removal (Baum and McFarland 1997; Jones and Munhall 2003; Hamlet and Stone 1978; Savariaux et al., 1995). Compensation has also been shown for cases where equivalent acoustic effects are produced by mechanically uncoupled articulators. For instance, insertion of a bite block limiting lip rounding did not prevent speakers from producing the rounded vowel /y/ in a study by Riordan (1977). Instead, and without practice, speakers immediately lowered their larynx to extend the length of the vocal tract, producing the formants characteristic of /y/ using this alternative strategy.

Another issue of interest is the degree to which such mechanisms of compensation resemble the coproduction effects of normal speech. A number of investigators have reported variation in the way articulator movements combine to produce acoustic output for particular segments: Perkell and colleagues (Perkell et al., 1993) have reported small but consistent 'trading relations' between lip rounding and tongue-body raising for /u/, and between lip rounding, backing of constriction along the palate, and palatal constriction degree for /r/ (Guenther et al., 1999). For /u/, lip rounding and tongue-body raising have the effect of lowering F2; in the Perkell et al. study, a greater degree of tongue-body raising was more likely to be accompanied by less lip rounding, and vice versa. For /r/, a more posterior constriction along the palate, lip rounding, and narrower constriction via tongue raising all serve to lower F3; again, the Guenther et al. study showed that more reliance on one of these articulatory maneuvers was accompanied by less of another, and vice versa. Clearly, alternative methods for achieving the same acoustic result occur during ordinary speech, even in the absence of gross perturbations such as bite blocks.

However, the motor equivalence demonstrated by trading relations among articulators for /u/ and /r/ is different in kind from the qualitatively different articulatory variants associated with production of North American English (AE) [ɹ]. Speakers of this family of dialects may use one of several tongue configuration types to produce acoustically similar patterns for F1, F2, and F3 (Delattre and Freeman 1968; Mielke et al., in press; Westbury et al., 1998). Broadly speaking, phonetic descriptions of AE /r/ group the observed variants into 'retroflex' (with the tongue tip raised and the dorsum lowered) and 'bunched' (with the tongue tip lowered and the dorsum raised) varieties. Although these tongue configurations are similar in that they divide the vocal tract into three cavities, with constrictions at the lips, palate, and pharynx, they use different articulators for the primary constriction (tongue tip vs. tongue dorsum). From an articulatory perspective they are thus qualitatively different in the same way that, say, tip-up /s/ (made with a raised tongue tip and blade) is different from /ʃ/ (made with a bunched tongue blade and dorsum). Unlike the sibilant contrast, however, in /r/ production the first three formants resulting from these different tongue configurations are indistinguishable (Delattre and Freeman 1968; Westbury et al., 1998; Zhou et al., 2008). AE /r/ is thus an unusual case of articulatory heterogenous homophony (Fig. 4.1).

At present there are no known dialectal or anatomical factors that predict which configuration a speaker prefers (Delattre and Freeman 1968; Westbury et al., 1998). The different tongue configurations of North American English have been proposed as an example of 'covert allophony' (Mielke et al., in press) – that is, since any of the various configurations are equivalent for linguistic purposes, the choice of which configuration to use is in linguistic free variation. Since the articulatory configuration used by a speaker cannot be deduced by the listener from acoustic information, the choice is insensitive to sociolinguistic variables (like dialect) that might cause production to coalesce behind a particular production strategy. In other words, the choice of which configuration to use is peculiarly individual to the speaker. Moreover, although some speakers appear to produce /r/ with consistent tongue shape, certain other speakers seem to switch between configurations according to phonetic context (Delattre and Freeman 1968; Guenther et al., 1999; Secord et al., 2007). Figure 4.2 provides an example of a subject whose typical tongue configuration for /r/ is retroflex, but who switches to a more bunched configuration for /r/ when

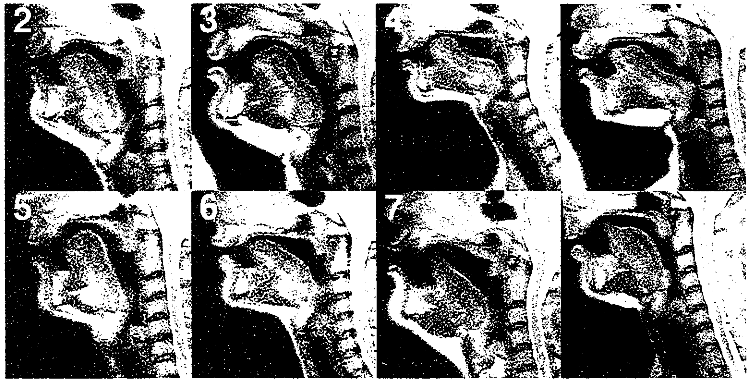

Fig. 4.1. Native speakers of North American English producing sustained /r/ as in 'pour'. Data from Tiede et al. (2004). The numbers correspond to the tongue shapes distinguished by Delattre and Freeman (1968); the additional two images without numbers show shapes not encountered by them.

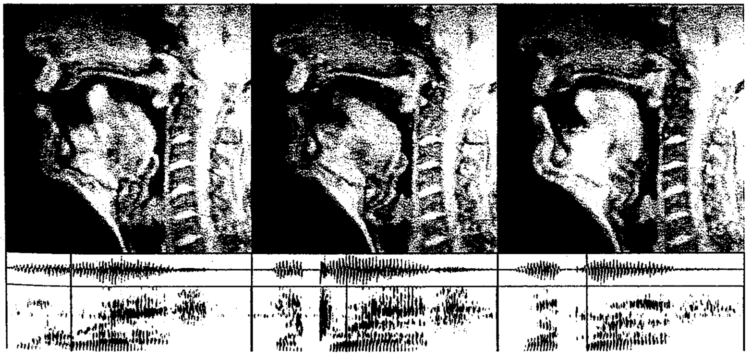

Fig. 4.2 Cine-MRI of the sequences (left to right) 'warav', 'wadrav', and 'wagrav', showing frames corresponding to /r/ midpoints. Collected by K. Honda and M. Tiede at ATR in Kyoto, Japan, using a synchronized sampling method (Masaki et al., 1999).

the preceding segment is velar. A study of 32 American English speakers by Mielke et al. (in press) found that speakers fall into three groups according to how they use alternative tongue configurations for /r/. Some speakers maintain two or more production strategies, and alternate between them freely in certain contexts. A second group also maintains two or more strategies, but adapts their selection to specific production contexts. Finally, a third group uses a single configuration consistently for all contexts in normal speech. Similar behaviour has been noted for real words by Delattre and Freeman (1968) and Kent (personal communication regarding data discussed in Shriberg and Kent 1995), and for nonsense words by Guenther et al. (1999). It appears to be the case that speakers work out individual solutions both to the problems of producing /r/ given personal vocal tract morphology, and of accommodating /r/ production to coarticulatory and prosodic demands.

Given that /r/ is an articulatorily complex sound, requiring three constrictions along the vocal tract in addition to precise positioning of the lateral edges of the tongue, it is unsurprisingly one of the last to be mastered in language acquisition (Smit 1993). Presumably, some portion of the developmental trajectory for /r/ production involves exploration by children of the various possible vocal tract configurations that produce appropriate acoustics, followed by solidification of strategies for dealing with coarticulatory demands (Hoffman et al., 1980). It is suggestive that speech pathologists make use of palatal perturbation as a means of facilitating /r/ production in school-age children with persistent /r/ production difficulties. For example, a study reported by Clark et al.(1993) found that those treated with a prosthesis incorporating mid-palatal thickening made significant improvements relative to a control group in all aspects of /r/ production. It seems likely that the children who improved in this study were encouraged by the perturbation to explore alternative methods for producing /r/, perhaps by switching from one production variant to another. Having learned to use a particular method successfully under perturbed conditions, they were then able to exploit the new skill in normal speech production.

Depending on the speaker, the developmental period may thus conclude with a single, preferred tongue configuration for /r/ and suppression of alternative production strategies, or a mix of active strategies that depend on production context. But even for those speakers adopting a single strategy, retention of a previously practiced alternative would be potentially advantageous in maintaining intelligible speech when facing unanticipated or unusual articulatory constraints. Some evidence for such a 'fallback' strategy is provided by an X-ray study conducted by Putnam and Ringel (1976), in which pre- and post-production articulations were contrasted for subjects undergoing a trigeminal nerve block intended to eliminate somatosensory feedback from oral structures (including the anterior two-thirds of the tongue): they report that although neither subject used retroflex tongue shapes consistently in the control condition, in the nerve-block condition both subjects increased tongue bunching and retracted the location of their primary tongue constrictions, with acoustic changes described as minor and 'primarily nonphonemic' in nature (p. 247). Their results suggest that when confronted with loss of afferent feedback necessary for appropriate control of the tongue tip, these subjects were able to make use of a secondary production strategy relying less on tongue body/tip differentiation.

To summarize: fluent speakers of North American English produce /r/ with one or more qualitatively different tongue configurations; tune these configurations as needed via trading relations among articulators; and adapt readily to perturbation, sometimes by switching between configurations. In this work, we explore the ability of adult speakers to adjust their production of /r/ in reaction to a form of palatal perturbation likely to interfere with well-established articulatory habits. We anticipate the following range of responses: First, speakers may not compensate at all but instead continue to use their habitual patterns of articulation, though this would likely produce distinct differences in the acoustic output. Second, speakers may compensate through small 'trading relations' made to their preferred tongue configuration for /r/. For instance, they may move a retroflex tongue shape backwards along the palate, or use a more extreme form of lip rounding, thus maintaining a formant structure equivalent to their pre-perturbation production. A third possibility is that speakers may maintain equivalent acoustic patterns under perturbation by switching between alternative tongue configurations for /r/; in other words, behaviour similar to that shown for one speaker in Guenther et al. (1999), and for a number of speakers in Mielke et al. (in press), in which qualitatively different tongue configurations selected for articulatory efficiency in coproduction resulted in equivalent acoustic output. We hypothesize that all subjects may use trading relations, but those subjects who do switch configurations in their normal speech will also make use of these alternative postures when their normal articulatory habits are disrupted.

4.2 **Methods**

4.2.1 **Subjects**

Four adult native speakers of North American English participated in this study, two males and two females, with normal hearing and no apparent speech deficits. All spoke rhotic dialects with substantial third formant lowering in all /r/ contexts. Each subject participated in a speech production experiment in which their speech and articulatory movements were recorded.

4.2.2 **Materials**

Subjects were asked to produce the nonsense words 'ara' (/ara/), 'eeree' (/iri/), and 'ooroo' (/uru/) in isolation. For three of the subjects (F1, F2, M1) these were elicited in a randomized order within a larger study observing obstruents in VCV contexts (Shiller et al., 2006). The fourth subject (M2) was asked to produce randomly permuted stimuli drawn from these templates: VrV, VCrV, VrCV; where V was one of /a/, /i/, or /u/, and C was one of /b/, /d/, or /g/.

4.2.3 **Production conditions**

Each of these utterances was repeated ten times within four separate blocks (in the final block only five repetitions were elicited), with each block corresponding to a distinct perturbation/adaptation condition. In two blocks, subjects wore a custom-fitted palatal prosthesis with retaining ball clasps that followed the design of Baum and McFarland (1997): a buildup of dental acrylic was used to centre a perturbation over the alveolar ridge, measuring 6 mm at maximum, tapering to 1 mm in parallel with the premolar teeth (see Fig. 4.3). Three subjects wore prostheses constructed for an earlier study (Aasland et al., 2006); that worn by M2 was fabricated to the same specifications.

The experiments proceeded as follows:

Block 1: pre-perturbation, pre-adaptation (BASE)

Block 2: perturbed, pre-adaptation (PERT)

Block 3: perturbed, adapted (ADAPT)

Block 4: prosthesis removed, adapted (POST)

An intervening 20-min adaptation period during which subjects read aloud with prosthesis in place was interpolated between Blocks 2 and 3.

4.2.4 **Recordings**

An electromagnetic midsagittal articulometer (EMMA) system was used to transduce the movement of sensors attached to each subject's speech articulators (see Fig. 4.4). Three subjects were recorded using an AG200 system (Carstens Medizinelektronik); M2 was recorded using the

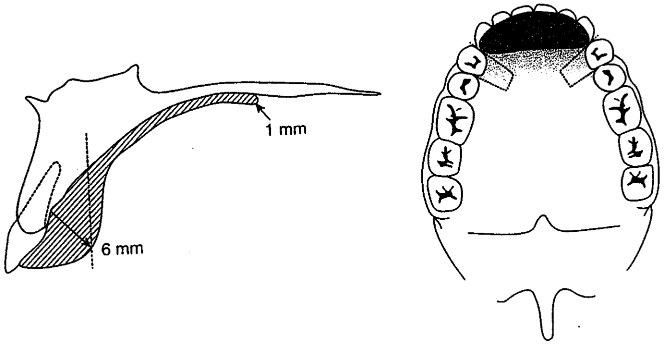

Fig. 4.3 Midsagittal and inferior views of palatal prosthesis (reproduced with permission from Baum and McFarland 1997; copyright 1997 Acoustical Society of America).

system of Perkell et al. (1992). Subject M2 had an especially large tongue, and so four sensors were placed in his case to maintain the approximate 12-mm separation between sensors used for the other subjects. Movement data were recorded at 200 Hz, and concurrently recorded audio at 16 kHz.

4.2.5 Data analysis

Raw EMMA voltage signals were first converted to positions over time on the midsagittal plane, and the reference sensors (N, I) were used to translate and rotate each position signal to a consistent maxillary frame of reference. For each token, a temporal measurement offset was determined by the point of minimum tongue velocity corresponding to /r/, with that velocity computed (as central-differenced Euclidean speed) across all tongue sensors (see Fig. 4.5).

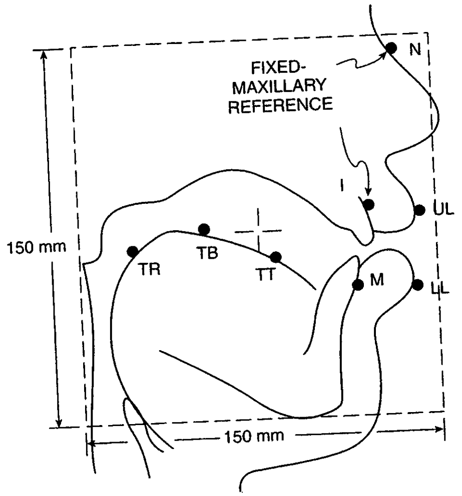

Fig. 4.4 EMMA sensor arrangement (adapted, with permission, from Perkell et al., 1992; copyright 1992 Acoustical Society of America).

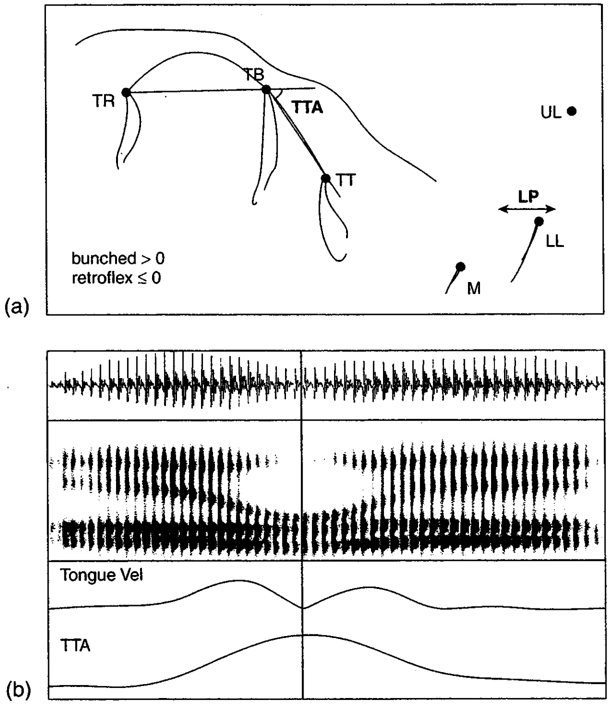

Fig. 4.5 A. Example token of unperturbed bunched shape /ara/ produced by subject M1 showing tongue tip angle measure (TTA) as defined on EMMA sensor measurements. Lip protrusion (LP) is characterized using horizontal position of lower lip. The tongue sensors are connected with a cubic spline, and the upper line shows a palatal trace. B. Corresponding temporal plot showing minimum tongue velocity measurement offset corresponding to /r/.

Tongue configuration at that offset was characterized by the tongue tip angle (TTA), subtended by lines between sensors TR:TB and TB:TT (for subject M2, the midpoint between the two central sensors was used as 'TB'). By convention, negative TTA values were characterized as 'retroflex'; positive values as 'bunched.' Negative angles indicate that the TT sensor is raised towards the alveolar ridge relative to tongue body position (as captured by the TB and TR sensors). Conversely, if the angle formed by the line segments is positive, then the TT sensor is lowered relative to TB and TR, indicating a bunched tongue shape. Figure 4.6 shows examples of both tongue 'polarities' from a subject switching between configurations.

An additional measure of lip protrusion (LP) was obtained using the horizontal position of the lower lip sensor at the measurement offset, relative to the coordinate sensor I (upper incisor). Larger values for LP indicate greater lip protrusion. Formant values were evaluated using order-20 LPC evaluated on a 25-ms Hamming-filtered window centred on the measurement offset.

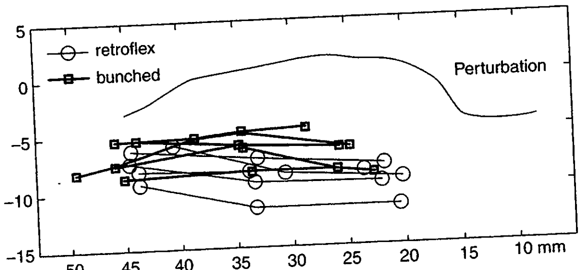

Fig. 4.6 Line segments connecting tongue sensors measured at velocity minimum associated with /r/ for individual tokens of subject F1 producing /uru/ (ADAPT block: perturbation in place and post-adaptation). The upper line shows a palatal trace.

The resulting measures obtained for each token were thus TTA (measured in degrees), LP (measured in mm), and F3 (measured in Hz).

4.3 **Results**

4.3.1 **Articulation**

As a first step in understanding subject response to perturbation, consider Fig. 4.7, which shows the distribution of TTA measures by vowel context, subject, and condition. The mean value is shown with 95% confidence intervals. In those instances where a subject produced both bunched and retroflex examples for the same stimulus (e.g., M1 PERT), distributions for each have been computed separately.

It is immediately apparent that /r/ production is idiosyncratic. As noted above, cross-speaker differences in tongue configurations for /r/ are well documented. It has also been reported that while a speaker's preferred tongue shape is typically consistent for a given phonetic context, many speakers alternate between different configurations depending on context. Data obtained from these subjects in the pre-perturbation BASE condition support both observations. Speaker F1, for instance, uses a retroflex tongue configuration for the /ara/ vowel context (median TTA = −6.8°), a strongly bunched configuration for /iri/ (29.2), and a less strongly bunched configuration in the /uru/ context (9.8). Speaker F2 uses a bunched configuration for all of the vowel conditions, although the degree of bunching is much more strongly marked for the /iri/ context (63.5 vs. 38.1, 47.5 for the other vowels). Speaker M1 also prefers a bunched configuration for all vowel contexts, but he reserves the greatest amount of bunching for /ara/ (49.1 vs. 42.9, 35.6). Speaker M2 however is highly consistent, using approximately the same degree of bunching for all vowel contexts (median values between 33° and 35° for all vowels).

Whatever their preferred pattern, all of the subjects are consistent in their use of either retroflex or bunched tongue configuration across the ten repetitions of the BASE condition. The only exception to that generalization comes from subjects F1 and M1, who each produce nine bunched and one retroflex productions in the /uru/ context. It is notable that for each the single retroflex production came within the first few trials after placement of the sensors, when subjects were presumably still adapting to their presence (itself a form of perturbation).

Responses to perturbation (PERT condition) were also idiosyncratic. Two subjects (F2, M1) show a mix of productions including retroflexion despite their initial preference for bunched configurations. Subjects F1 and M2 react to the loss of oral tract volume by moving the tongue tip away from the alveolar perturbation, which has the effect of enhancing their preferred production strategy by either increasing retroflexion (F1) or degree of bunching (M2). In all cases the general trend was towards increased variability. A non-parametric Friedman's test for column effects (BASE vs. PERT conditions) adjusting for possible row (vowel, subject) effects confirms a significant response ($p < 0.05$) to the perturbation measured on TTA (see Table 4.1).

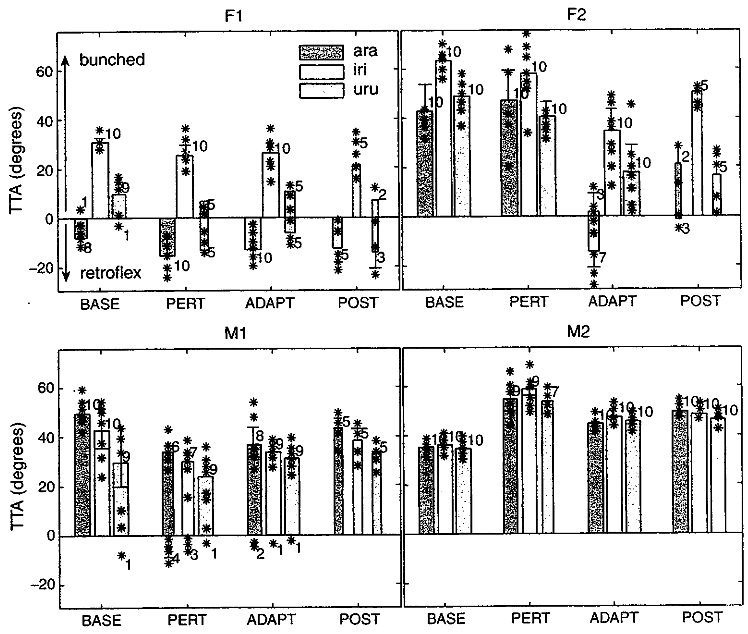

Fig. 4.7 Distribution of TTA results, by vowel context, subject, and condition, showing 95% C.I.s. Separate confidence intervals were computed for 'retroflex' (TTA< = 0) distributions where appropriate. Individual values plotted as asterisks. The width of each bar is proportional to the number of repetitions for that condition.

Table 4.1 Friedman's test for column effects (BASE vs. PERT conditions) adjusting for possible row (vowel, subject) effects on TTA. The null hypothesis is that the palatal perturbation has no effect on TTA, rejected here with p < 0.05

Source	SS	df	MS	Chi-square	p > Chi-sq
Columns	147.3	1	147.3	4.209	0.040
Interaction	3303.9	11	300.4	–	–
Error	4526.8	216	20.1	–	–
Total	7978.0	239	–	–	–

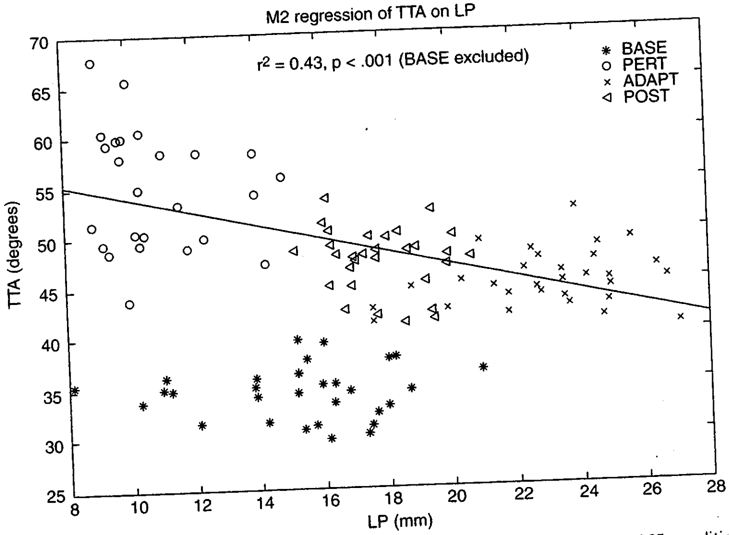

Fig. 4.8 Regression of TTA on LP for subject M2. Excluding the initial uncorrelated BASE condition, TTA and LP show a significant trading relation following the introduction of the perturbation.

Clear patterns of adaptation (ADAPT condition) were suggested only in the responses of M2. After increasing his overall degree of bunchiness and variability in the PERT condition, both declined after adaptation, though not to the initial baseline values, and remained higher in the final POST perturbation condition. LP for this subject, initially uncorrelated with TTA, showed a significant ($r^2 = 0.43$, $p < .001$) trading relation with degree of bunching following introduction of the perturbation (see Fig. 4.8). F2 showed reduced TTA overall in the ADAPT condition, including retroflex productions for the first time.

4.3.2 Acoustics

As noted above, previous studies have failed to find any consistent differences in formant patterns across the different tongue configurations for /r/. Of interest here is the extent to which subjects control their acoustic productions for /r/ in response to a perturbation that disrupts their habitual articulatory production, particularly when they show a mix of qualitatively different tongue configurations in response. Figure 4.9 shows F3 for /r/ scatterplotted against the TTA of the tongue configuration that produced it, superimposed on a histogram of TTA values.

The first point to be noted is the lack of correlation between F3 values and tongue configuration types. Certainly different speakers produce F3 values in different parts of the formant space, and Hagiwara (1995) has shown that productions of F3 may vary by 500 Hz or more. However, these different minimum F3 values are equally likely to occur for retroflex or bunched tongue configuration patterns: acoustically, the two are indistinguishable. This was confirmed by a repeated measures ANOVA, which showed no significance on the possible effects of Tongue Polarity (TTA grouped into retroflex/bunched levels) on measured F3 values (see Table 4.2).

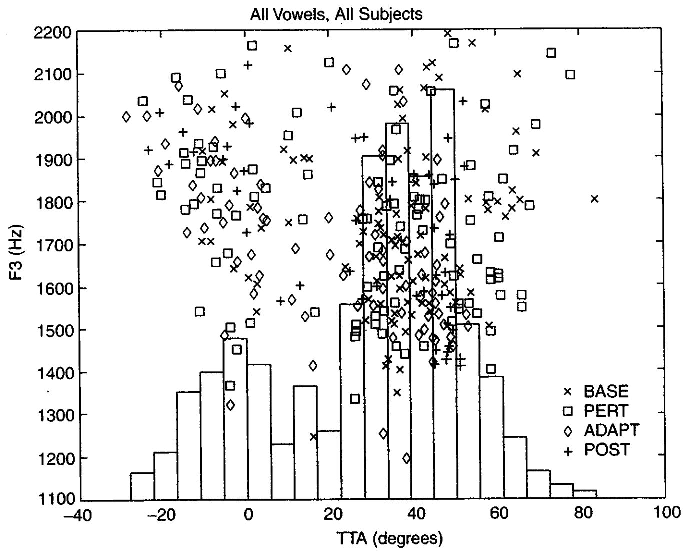

Fig. 4.9 Scatterplot of TTA with corresponding F3, superimposed on a histogram of TTA values, showing no effect of tongue configuration on acoustics. Note the bimodal distribution of TTA.

Table 4.2 Repeated measures one-way ANOVA testing for an effect of independent variable Tongue Polarity [retroflex,bunched] classification on observed F3 measures. The percentage of variability in F3 associated with Polarity (eta squared) is 8.54; the null hypothesis (that tongue configuration has no effect on F3) is sustained

Source	SS	df	MS	F	P
Subjects	3703392.0	3	1234464.0	0.922	0.5262
Polarity	374875.2	1	374875.2	0.280	0.633
Error	4017062.0	3	1339020.7	–	–
Total	8095329.2	203		–	–

These results confirm for within-subject data the results of previous work on between-subject data, namely, that the perceptually salient third formant values for /r/ produced using retroflex and bunched tongue shapes are indistinguishable.

Secondly, Fig. 4.9 illustrates that there is a clear bimodal distribution in tongue tip angle. This indicates that subjects are not using the full continuum of possible tongue configurations between bunched and retroflexed postures. Rather, the results show that subjects select *either* a bunched or a retroflex configuration, with variations for tuning purposes within those categories presumably subject to the kinds of trading relations illustrated in Fig. 4.8.

4.4 Discussion

The results from this chapter point to several conclusions. First, it appears that subjects react to palatal perturbation differently in different vowel contexts. For subjects who switched between tongue configuration types, one subject (F1) showed the most extreme behaviour for /uru/, another subject (F2) showed the most extreme behaviour for /ara/, and a third subject (M1) switched between configuration types for all three vowel contexts. As noted above, previous observations (Delattre and Freeman 1968; Westbury et al., 1998; Mielke et al., in press) have shown that normal speakers of North American English produce /r/ using a variety of tongue configurations. The subjects in this study appear to be a typical sample; in the BASE condition, only subjects F2 and M2 show the same tongue configuration for all vowel contexts, while subject F1 shows retroflex only for /ara/ and M1 shows retroflex only for /uru/. Given this level of variability across subjects in the BASE condition, it is not surprising that subjects in this study would show idiosyncratic patterns of adaptation.

Second, different subjects have different patterns of adaptation to the presence of the prosthesis; some subjects (F1, M1, M2) show a change in articulatory behaviour immediately while others react later in the experiment, after adaptation (F2). Further, when they did react to the prosthesis, subjects showed considerable variability within context and condition. Given our data from the BASE condition, we suggest that, before perturbation, subject F1 belongs to the Mielke et al. (in press) group that uses tongue configuration in free variation, subjects F2 and M1 belong to the group that uses different configurations in different phonetic contexts, while subject M2 belongs to the group that uses a single configuration in all contexts. (Note that their BASE data show that subjects F2 and M1 have patterns of switching according to vowel context.)

Of the four subjects, only three (F1, F2, and M1) switched between retroflex and bunched configurations for at least one condition and one vowel context. It is notable that these are the same subjects who showed signs of using both configurations in the BASE condition. Only one subject, M2, was consistent in terms of tongue configuration under all conditions and vowel contexts; however, he did increase the amount of bunching under perturbation. It may not be a coincidence that of the three subjects who switched, two were female and one was an average-sized male. In contrast, subject M2 had the largest vocal tract of all the subjects (as well as the largest tongue). Because the prosthesis was made to the same dimensions for each subject, it presumably took up more of the available room, and represented a greater disruption, in the vocal tracts of the smaller subjects. It is possible that these subjects reacted by switching because the proportionately greater disruption forced them into using a secondary strategy. In contrast, subject M2 was able to maintain a consistent tongue configuration (while adjusting his TTA somewhat in the direction of greater bunching) because the prosthesis to him represented a smaller disruption.

The amount of individual variation in subject behaviour found in this study across context and conditions, although considerable, is consistent with previous findings in studies using a palatal prosthesis (Baum and McFarland 2000). In general, subjects showed a greater degree of switching behaviour as a result of perturbation. Two of the three subjects who switched configurations showed more of that behaviour in the early perturbation conditions, PERT and ADAPT. In contrast, subject F2 changed her degree of tongue bunching in the two prosthesis conditions, PERT and ADAPT, but switched from bunched to retroflex only for /ara/ in the ADAPT condition. Additionally, for any one context/condition combination subjects used a retroflex configuration for some trials and a bunched configuration for other trials. In other words, when subjects switched between retroflex and bunched configurations, they did so inconsistently.

These results show that the presence of a prosthesis does affect subject articulatory behaviour. In fact, the generalization seems to be that subject behaviour becomes more variable – that is, more labile – under perturbation. Subjects appear to be experimenting with alternate methods of producing /r/, and this experimental behaviour appears to continue for some subjects into the ADAPT and POST conditions, though for these subjects it may be the case that insufficient time and practice were available for effective adaptation. At the same time, the alternative tongue configurations used by the subjects do not cover the articulatory space between retroflex and bunched configurations in a continuous fashion. Instead, there is a bimodal distribution of tongue tip angle (TTA), such that most tongue configurations occur with a tongue tip angle over 20° or under 5°. These results confirm the hypothesis that subjects have two distinct strategies for tongue configuration while producing /r/.

An additional point concerns the lack of an effect of tongue configuration on the produced F3 minimum. As noted above, investigators have consistently reported that the different tongue configurations used by speakers for North American /r/ show indistinguishable acoustic profiles, at least for the first three formants. Further, as Guenther et al. report, the formant values at F3 minima during /r/ are consistently maintained over different phonetic contexts by a complex combination of adjustments to lip position, constriction size, and constriction location. Our data show a similar picture; even in the PERT and ADAPT conditions, when subjects appear to be experimenting with alternative tongue configurations, there is no corresponding bimodal distribution of F3 minima to match the bimodal distribution of TTA. A notable aspect of the Guenther et al.'s (1999) paper was the finding that the F3 minimum value remained consistent between retroflex and bunched configurations. However, in the said paper, only one subject appeared to switch tongue configuration, and in only one phonetic context. Our data include a wider variety of subjects producing a wider variety of tongue configurations in a wider variety of phonetic contexts. Thus, our results provide strong support for the notion that speakers (1) have a repertoire of articulatory strategies for /r/ (including the use of qualitatively different tongue configurations) that produce equivalent acoustics in normal speech, and (2) call on these strategies in the face of articulatory perturbations.

What might be the nature of these articulatory strategies, and how would they develop? On the one hand, studies of trading relations show that speakers readily make small, mutually offsetting adjustments as needed when tuning a basic production plan to resolve competing demands on the articulators. However, given the articulatory complexity of /r/, it may be that the possible range of such adjustments for some speakers is insufficient to comfortably adapt to all contexts. Instead, such speakers prefer to make a wholesale change to the basic plan when that alternative can be more readily adapted to a particular production context. We suggest that speakers normally acquire such alternative production strategies during the exploratory period associated with childhood, and that a likely pathway is through learning to coproduce /r/ in clusters. As an

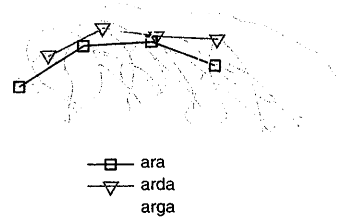

Fig. 4.10 Subject M2 productions of /ar(C)a/. The upper line shows a palatal trace. Note the tendency towards retroflexion in the 'arda' context.

example, Fig. 10.10 shows sensor positions at the F3 minimum associated with /r/ contrasting representative examples of /ara/, /arda/, and /arga/ productions from subject M2. Although this subject did not switch from his preferred bunched tongue configuration in the VCV productions of his experiment, he nonetheless shows clear signs of retroflexion in his production of /arda/.

Coarticulatory experiences of this sort may be the mechanism whereby subjects learn to produce and continue to maintain alternate tongue configurations for /r/, although (as noted above, and as we found in the BASE condition), speakers may or may not choose to incorporate both sets of allophones into their normal articulatory habits. We propose, however, that the option of using an alternative tongue configuration remains 'in storage' and available for use when changes in the articulatory environment disrupt normal speaking habits. In this view, when the presence of a perturbation leads speakers to explore a new set of articulatory habits, the ability to revisit alternative production strategies for /r/ makes the task of adaptation both easier and, on 'least effort' principles, more efficient.

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