Vowel context, rate and loudness effects on linguopalatal contact patterns in Hindi retroflex /t/

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A 96-channel electropalatograph was used to monitor linguopalatal contact patterns during normal, fast and loud productions of retroflex /t/ in the nonsense words /bi:tib/, /bu:tib/ and /ba:tib/ spoken in a carrier sentence by a native speaker of Hindi. A complete constriction was observed in all three vowel contexts and in all three speech conditions, suggesting that a tongue–palate constriction is a critical articulatory parameter for /t/. The contact pattern during maximal constriction in each token was examined for the anterior–posterior (A–P) location of the contact, its length in the A–P dimension, and its extent (as measured by number of contacted electrodes). The location of the constriction was more posterior in the context of /a/ than /u/ than /i/, indicating a strong coarticulatory effect of vowel context on /t/. This coarticulatory shift in the A–P location of /t/ constriction suggests that the degree of retroflexion decreased systematically from /a/ to /u/ to /i/ context. The A–P location of the /t/ constriction was also more posterior in the fast than normal or loud speech. However, other aspects of the contact pattern suggest that this shift reflects locational undershoot. The hypothesis that the extent of linguopalatal contact and the A–P length of /t/ constriction might increase in loud and fast speech compared with that in normal speech was only partially supported for loud speech, and remained largely unsupported for fast speech.

1. Introduction

Retroflex sounds have been traditionally described as being produced with the tongue tip retroflexed (curled back) to contact the highest part of the palatal vault. However, palatographic and/or X-ray studies on languages such as Ewe (a West African language), Gujarati, Hindi–Urdu (Hindustani), Marathi, Sindhi (North Indian Indo–Aryan languages), Tamil and Telugu (South Indian Dravidian languages) have shown that the position of the tongue–palate contact in stops described as...
retroflex varies enormously from the alveolar to the palatal regions of the tectum of the oral cavity across languages and speakers (Qadri, 1930; Śwarný & Zvelebil, 1955; Firth, 1957; Ladefoged, 1964; Ramasubramanian & Thosar, 1971; Balasubraman- nian, 1972; Nihalani, 1974; Dave, 1977; Ladefoged & Bhaskararao, 1983). Whether the anterior–posterior (A–P) location of the constriction, the length of constriction, or the degree of retroflexion for the retroflex stops differ also as a function of vowel context does not clearly emerge from the cited studies. Therefore, one purpose of this study was to examine the effect of vowel context on the place and length of constriction and on the degree of retroflexion in the retroflex stops of Hindi, which are said to be produced by placing the tongue tip or its underside against the alveolar or postalveolar parts of the alveolar ridge (Dixit, 1963; Catford, 1977). Other purposes were to examine the effects of paralinguistic contexts, by comparing fast speech and loud speech to normal productions of the test utterances.

In recent years, many studies have examined the effects of speaking rate on the articulatory target positions, the extent of articulatory displacements, and the rate of articulatory movements in the formation of vowels and non-retroflex consonants. These studies have revealed that the vowel and consonant targets are often achieved by the primary articulators (e.g., the tongue body for vowels, the apex for apical consonants, the lips for bilabial consonants, etc.) during normal speaking rate. However, during fast speaking rate the vowel targets are usually undershot (Lindblom, 1964; Gay, 1968; MacNeilage & DeClerk, 1969; Gay, 1974; Gay & Ushijima, 1974; Gay, Ushijima, Hirose & Cooper, 1974; Kuehn & Moll, 1976; Ostry & Munhall, 1985; Flege, 1988), although such is not the case in regard to the consonant targets. In fact no undershoot of the primary articulators for the consonant targets as a consequence of change in the rate of speaking has been reported; it appears that the primary articulators used to form consonants achieve about the same configuration at normal and fast speaking rates (Gay & Hirose, 1973; Gay & Ushijima, 1974; Gay et al., 1974; Kuehn & Moll, 1976; Tuller, Harris & Kelso, 1981). Kent & Moll (1972) do report undershoot of three tongue-point positions at a fast speaking rate for English /d/ and /z/, but this was in fact for the points (cups) located on the tongue body rather than on or near the tongue tip. They observed little difference in the position of the tongue tip for /d/ and /z/ spoken at normal and fast rates.

EMG data from the superior longitudinal (SL) muscle reported in Gay & Ushijima (1974) are of particular interest in connection with the question of how (or if) speaking rate will affect the articulation of apical consonants. This is because the SL has been implicated as the muscle which is primarily responsible for raising and retroflexing the tongue tip. One or both of these tongue gestures are associated with the production of certain lingual consonants. Gay & Ushijima observed that an increase in speaking rate was accompanied by a corresponding increase in the level of SL activity for English /t/ production. EMG data from the orbicularis oris (OO) muscle reported by Gay & Hirose (1973), Gay & Ushijima (1974), and Gay et al. (1974) revealed similar trends with respect to the production of certain labial consonants across changes in speaking rate. They observed a higher level of OO activity accompanied by a faster speed of lip movement for labial consonants during fast than normal speech. Gay and his colleagues, therefore, concluded that there was an overall increase in the articulatory effort and in the velocity of articulatory movement with an increase in speaking rate for consonant sounds. This may be responsible for the apparent lack of undershoot in fast-rate consonants. The closure
of the consonants, which were found to be similar across fast and normal speech rates by Gay and his colleagues, point to the same conclusion. However, this is contradicted by Kent & Moll (1972), Abbs (1973), Tuller et al. (1981), and the present study, where closure durations of the consonants were found to be shorter during fast than normal speech.

If there is an overall increase in articulatory effort at a fast speaking rate, there should also be an increase in the area of linguopalatal contact or in the length of constriction in the sagittal plane for the consonants involved. However, there are a number of experimental findings which suggest that changes in speaking rate will have little or no effect on the extent of linguopalatal contact for the stop consonants. Gay and his colleagues found that the articulatory target configurations for the consonants involved remained essentially unchanged across speaking rates, as did Tuller et al. (1981). These latter researchers observed that the EMG levels in the O0 muscle and the consequent maximum displacements of the lips for the labial consonants remained unchanged with changes in the rate of speaking. Since there was virtually no difference in the peak activity of O0 as a function of speaking rate, one might assume that the rate of lip movement did not increase from normal to fast speech. Such a finding has been reported by Kent & Moll (1972) for the apical consonants. Kuehn & Moll (1976) observed that consonant targets were always achieved despite differences in speaking rate (although different speakers used different combinations of articulatory velocity and displacement to achieve those targets). Thus, we decided to test whether changes in speaking rate would affect the extent of the linguopalatal contact and its A–P length in Hindi retroflex stops.

Loud speech is produced with greater vocal effort than normal or soft speech. The only study that has examined the effects of loudness on articulatory parameters is that of Schulman (1989), who observed greater displacement and velocity of jaw and lip movements for loud than normal vowels. In terms of jaw displacement and lip rounding/spreading, vowel targets were overshot, although height-related distinctions between vowels were maintained. Vowels were longer in loud than normal speech, whereas the duration of intervocalic bilabial stop was shorter.

Production of loud speech is presumably similar to the production of stressed portions of normal speech. Thus, Kent & Netsell (1971) have shown that the tongue body, lips and jaw had relatively greater displacement toward vowel targets as a function of increased stress. In contrast, Tuller et al. (1981) did not observe significant differences in maximum articulatory displacement of the tongue body for /i/, nor in maximum articulatory displacement of the lips for /p/ as a function of stress. However, they did find evidence of greater articulatory effort in stressed than unstressed syllables (as shown by higher peaks and longer durations of EMG activity in the genioglossus (GG) and O0 muscles). Also the durations of the vowels as well as closure durations of the consonants were longer in stressed position than unstressed position. These results are consistent with those reported by Schulman (1989) and the present study for the durations of the stressed vowels in both normal and loud speech, but they are at variance with those reported for the closure duration of the intervocalic stop in loud speech. In Schulman's (1989) study the durations of stressed vowels in loud as well as normal speech were longer than those of unstressed vowels. Our results on the duration of the surrounding vowels and the closure duration of the intervocalic retroflex stop are similar to those reported by Schulman. That is, the vowels were longer in loud than in normal speech in both
stressed and unstressed positions, and the stressed vowels were longer than the
unstressed vowels in both normal and loud speech. Further, the closure duration of
the intervocalic /l/ was shorter in loud speech than in normal speech (96 vs.
104 ms).

On the basis of the findings reported in Kent & Netsell (1971) and Schulman
(1989), it might be hypothesized that in consonants (as in vowels) there may be
relatively greater articulatory displacement toward targets in loud than normal
speech. If so, then one would expect to observe a greater extent of linguopalatal
contact and perhaps a greater constriction length in loud than normal speech. This
hypothesis is consistent with EMG data on stressed portions of speech reported by
Tuller et al. (1981), but not with their data on maximum displacement of the lower
lip for /p/. To test these hypotheses, we investigated the effects of loudness on the
extent of linguopalatal contact and the length of constriction in Hindi retroflex
stops.

2. Method

The subject for the present study was the first author, a 56-year-old native speaker
of the western dialect of standard Hindi, who had lived in the United States for
about 24 years at the time of data collection for this study, but who communicated
regularly in Hindi with family and Hindi-speaking friends.

The procedures followed in constructing the pseudopalate, in positioning the
sensors on it, and in recording the electropalatometric data have been described
elsewhere (Fletcher, McCutcheon & Wolf, 1975; McCutcheon, Smith, Kimble &
Fletcher, 1983; Flege, Fletcher & Homiedan, 1988). Briefly, a thin (0.3 mm)
pseudopalate is custom-made from a sheet of acrylic that has been vacuum-molded
onto a stone model of the hard palate, alveolar ridge and maxillary teeth of the
subject. The sensors, which are embedded in the oral surface of the pseudopalate,
are small (less than 0.5 mm in diameter) gold-plated beads that have been
heat-formed on the end of 32-gauge wire. A 27.8 kHz common signal, current
limited to 100 μA, is applied to the subject's wrist by means of a surface electrode.
The tongue contact with the sensors completes the circuit.

The pseudopalate used in this study contained 96 sensors, or which 93 were
located in the dental, prealveolar (anterior part of the alveolar ridge), and
postalveolar (posterior part of the alveolar ridge) areas. The remaining three sensors
were located in the prepalatal (anterior part of the hard palate) area. The sensors on
the pseudopalate were arranged from front to back in 11 rows spaced 2 mm apart.
The median sensors in rows 7 and 8 were left out owing to the limit of 96 sensors
(see Fig. 1).

The position of the sensors on the pseudopalate was determined from the
linguopalatal contact areas observed in the direct palatograms (see Ladefoged, 1957;
Abercrombie, 1965, p. 125), which were made from the subject during a normal
production of the words used in the present study. To obtain such palatograms a
mixture of powdered charcoal and chocolate was sprayed directly on the oral surface
of the maxillary teeth and the roof of the mouth (including the alveolar ridge, the
hard palate and the soft palate). Then the subject articulated the word containing
the sound to be examined. During articulation the sprayed black powder was wiped
off from those areas of the upper surface of the oral cavity where the tongue made
the contact. These areas were then photographed to obtain a direct palatogram of the articulated word.

The contacted areas on the upper surface of the oral cavity were photographed using a Polaroid camera system for still palatograms. This system consists of a CU-5 Polaroid Land camera and a stainless steel reflector. The reflector is inserted into the subject's mouth immediately after the articulation of the intended word to make the photograph of the reflected contact areas. The light needed to make such photographs is provided by the built-in flash of the camera. (Palatograms photographed with the Polaroid camera system are said to be in one to one correspondence with the upper surface of the oral cavity.) Unfortunately, the part or parts of the tongue that touched the upper surface of the oral cavity during the articulation of the target words were not photographed. Hence, no linguograms are available on these words. However, it should be mentioned that some black powder was found to be present on the underside of the tongue tip and a very thin adjacent stripe on the underside of the tongue blade during /t/ in all three vowel contexts. The front-to-back location of the sensor rows in relation to the maxillary teeth is shown in Fig. 1. Row 1 was located on the oral surface of the central maxillary incisors about 5 mm above their edges, row 2 over the lateral incisor line (which forms the boundary between the dental and the prealveolar zones), rows 3–5 in the prealveolar zone, row 6 over the canine line (which separates the prealveolar zone, from the postalveolar zone), rows 7–9 in the postalveolar zone, row 10 over the 1st pre-molar line (separating the postalveolar zone from the prepalatal zone), and row 11 in the prepalatal zone. The upper articulatory zones illustrated in the figure are more or less based on the dentition plan suggested by Firth (1957, p. 151).

The subject was seated in a dental chair in a sound-treated room during data

![Diagram of dental zones](image-url)

**Figure 1.** Front-to-back location of 11 rows of 96 sensors on the oral surface of the pseudopalate in relation to the maxillary teeth of the subject. The reference lines and articulatory zones are more or less based on the dentition plan suggested by Firth (1957, p. 151).
acquisition. He practiced the test sentences wearing the pseudopalate for about 15 min to minimize its effect on his speech production. Then data collection began. The 96 sensors were individually calibrated so that even a very light touch could be registered.

The speech samples consisted of bisyllabic nonsense words /bɪtɪb/, /bʊtɪb/ and /bɑtɪb/ in which retroflex /t/ occurred in a symmetrical vocalic context. The second vowel of these words was stressed. The words were embedded in the frame sentence /didi__lidʒɪe/ “Elder sister__(please) take”.

The subject repeated each test sentence 15 times in quasi-random order, first with normal rate and level of loudness, then with normal level of loudness at a faster rate, and finally loudly at normal rate. It should, however, be mentioned that a number of tokens were redone because of speech errors. The intensity of the sentences was monitored during the recording session using a Brüel & Kjaer sound level meter (type 2203) placed at a distance of 30 cm from the lips of the subject. The loud sentences were approximately 8–10 dB more intense than sentences produced with a normal level of loudness. The duration of the sentences produced with faster rate was approximately two-thirds of that of the sentences produced at a normal rate. (Pooled mean durations were 1060 vs. 1527 ms) This was also true with respect to the duration of the target words (397 vs. 556 ms), and of the /t/ closure (72 vs. 104 ms).

Contact data from the 96 electropalatographic sensors were stored on disk at a 100 Hz sampling rate along with acoustic data from a 32-channel filter bank (Voice Identification Model 500). The 10 ms sampling interval which had the largest number of sensors contacted was selected from each /t/ segment for analysis. The number of sensors contacted provided a quantitative measure of the area of linguopalatal contact in the articulatory zones where the sensors were located.

The A–P location and the length of /t/ constriction in the A–P dimension were determined by visual examination of linguopalatal contact patterns similar to those in Fig. 2. In the fully contacted rows, the one farthest from the central maxillary teeth was considered to be the most posterior row contacted. Any row anterior to this row was considered to have been contacted if five or more adjacent, centrally located, sensors were contacted. In the anterior rows, the one closest to the central maxillary teeth was considered to be the most anterior row to have been contacted. If the two sensors found in row 1 were contacted, then it was considered the most anterior row contacted. (Recall that row 1 was located on the oral surface of the central maxillary teeth.) The A–P location and length of /t/ constriction were derived from the location of the most anterior and the most posterior rows contacted. The number of rows that formed the /t/ constriction was determined by subtraction the number of the most anterior row contacted from the number of the most posterior row contacted and then adding 1 (row) to the remainder. (The length of /t/ constriction in millimeters can be calculated by multiplying the number of rows contacted by 2.0 mm, the inter-row distance.)

3. Results

The mean number of sensors contacted at the time of maximum linguopalatal constriction for Hindi /t/ is presented in Table I. The differences in the number of contacted sensors in the three speech conditions (normal, fast and loud) and vowel
contexts (/i/, /u/ and /a/) were generally small, except in a few cases. For example, large differences in the number of contacted sensors were found in the context of /i/ between fast and loud, and between normal and loud conditions (four and five sensors, respectively). Also under loud conditions, large differences were found between /a/ and /i/, and between /u/ and /i/ vowel contexts (seven and eight sensors, respectively). The area of linguopalatal contact also shows an interaction between the different vocalic contexts and the different speech conditions. It appears that in the context of the back vowels /u/ and /a/, loud speech showed slightly greater linguopalatal contact than did normal or fast speech, whereas in the context of the front vowel /i/ loud speech exhibited much less linguopalatal contact than fast or normal speech.

The number of contacted sensors in each of the 135 /t/ tokens (three vowel contexts × three speech conditions × 15 repetitions) were submitted to a two-way repeated measures ANOVA to test the significance of the differences described above. The ANOVA yielded a significant Condition × Vowel interaction \([F(4, 56) = 89.4; \ p < 0.01]\), because the effect of speaking loudly varied as a function of vowel context. The simple main effect of Condition was significant in all three vowel contexts \((p > 0.05)\). Newman–Keuls post-hoc tests revealed that significantly fewer sensors were contacted in loud than in either normal or fast speech in the context of /i/, whereas in the context of /a/ significantly more sensors were contacted in loud than in either normal or fast speech, and in the context of /u/ significantly more sensors were contacted in loud than in fast speech, but the difference between loud and normal speech was non-significant. There was no significant difference between normal and fast speech for any vowel contexts. Nor was there any significant difference between any two vowel contexts at these two rates.

Linguopalatal contact patterns obtained during the production of retroflex /t/ are shown in Fig. 2 as a function of speaking condition and vowel context. Sensors contacted in 80% or more of the tokens are shown by solid squares, those contacted in less than 80% of instances or not at all are shown by dots. As expected, all /t/ tokens were produced with a complete central-lateral closure, but the A–P location of the constriction shifted dramatically as a function of vowel context. Averaged across conditions, the center of constriction was 3.8 mm more anterior in the context of /i/ than /u/, and 2.0 mm more anterior in the context of /u/ than /a/. In the /i/ context the center of constriction was located about 2.0 mm behind Row 1 which was on the oral surface of the central incisor teeth. The A–P length of linguopalatal contact (generally three rows) suggests that both the tip and the blade of the tongue were involved in forming the constriction for /t/.

It cannot be determined from electropalatograms whether the underside or the upper side of the tongue tip and blade formed the constriction for /t/. However, when the direct palatograms were made to determine the position of the sensors on the pseudopalate (see Method), some black powder (wiped off from the dentialveolar or alveolar areas) was noticed on the underside of the tongue tip and on a very thin adjacent stripe on the underside of the tongue blade, indicating that the tongue was actually retroflexed during those prior normal productions of /t/. It seems likely, therefore, that the normal tokens produced during the experiment and summarized in the left most column of Fig. 2 also involved a retroflexed tongue. Since the loud speech tokens were also produced at a normal rate, it is expected that
TABLE I. The mean number of sensors contacted (out of a possible 96) during the production of Hindi retroflex /t/ in three speech conditions and three vowel contexts. Each mean is based on 15 observations. Standard deviations are shown in parentheses.

<table>
<thead>
<tr>
<th>Vowel context</th>
<th>Speech condition</th>
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<tbody>
<tr>
<td></td>
<td>Normal</td>
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<tr>
<td>/i/</td>
<td>52</td>
</tr>
<tr>
<td></td>
<td>(3)</td>
</tr>
<tr>
<td>/u/</td>
<td>53</td>
</tr>
<tr>
<td></td>
<td>(2)</td>
</tr>
<tr>
<td>/a/</td>
<td>51</td>
</tr>
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<td></td>
<td>(2)</td>
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</table>

Figure 2. Contact patterns summarized by vowel context and condition. Pseudopalatal sensors contacted in 80% or more of the /t/ tokens are shown by solid squares. Sensors contacted less often or not at all are shown by dots.

The tongue was retroflexed during the loud productions of /t/ shown in the right-hand column of Fig. 2, as well. This may also be true for the fast productions in the context of /u/ and /a/. However, in the context of /i/, where the tongue blade and apex are physiologically greatly constrained, it may or may not be true.

The most anterior row of sensors contacted during /t/ production is shown in the top panel of Fig. 3. A Condition × Vowel ANOVA yielded a significant main effect of Condition \([F(2, 28) = 13.7]\) and of Vowel \([F(2, 28) = 854.6] (p < 0.01)\). The Condition × Vowel interaction was non-significant. Post-hoc tests showed that the
most anterior row contacted was located significantly farther back in the mouth in the context of /a/ than /u/ than /i/ (4.1 vs. 3.2 vs. 1.2), it was also located significantly farther back in the mouth in the fast speech condition compared with the normal or loud speech conditions (3.0 vs. 2.7 and 2.6) ($p < 0.01$). The difference between loud and normal speech was non-significant.

The most posterior row of sensors contacted in /t/ is shown in the bottom panel of Fig. 3. As expected, much the same pattern of results was obtained as in the analysis of the most anterior row of sensors contacted, providing additional evidence that the place of constriction for /t/ was more anterior in the context of /i/ than in the /u/ or /a/ contexts, and that the effect of vowel context was much greater than that of speech condition. Again, the ANOVA yielded a significant main effect of Condition $[F(2, 28) = 70.0]$ and Vowel $[F(2, 28) = 588.8]$ ($p < 0.01$), but the Condition x Vowel interaction was non-significant. Post-hoc tests showed that the most posterior row contacted was located significantly farther back in the mouth in the context of /a/ than /u/ than /i/ (6.5 vs. 5.5 vs. 3.6), and in the fast speech condition compared

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**Figure 3.** Mean values by vowel context and condition of (a) the most anterior row and (b) the most posterior row of sensors contacted. Error bars indicate standard deviations.
with the loud or normal speech conditions (5.4 vs. 5.3 vs. 4.8). The differences between fast and normal, and between loud and normal were significant (p < 0.01), whereas that between fast and loud was non-significant.

Figure 4 shows the mean A–P length of the /t/ constriction, which was derived from the data shown in Fig. 3. Unlike the two measures of constriction location, constriction length was affected about equally by both the speaking condition and the vowel context. Moreover, the ANOVA yielded a significant Condition × Vowel interaction \( F(4, 56) = 3.85, p < 0.01 \). The simple main effect of Condition was significant in the context of /a/ and /u/, but not /i/. Post-hoc tests showed that the constriction length in the /a/ context was significantly greater in the loud and fast speech conditions than in the normal speech condition \( p < 0.05 \). It was also significantly greater in loud than in fast speech \( p < 0.05 \). In the /u/ context, constriction length was significantly greater in loud than in normal speech \( p < 0.05 \), but the differences between loud and fast, and between fast and normal speech were non-significant.

The effect of Vowel context on constriction length was significant in loud speech, but not in fast or normal speech. Post-hoc tests indicated that for the loud speech, constriction length was significantly greater in the /a/ context than in the /i/ context, but the differences between /a/ and /u/, and between /u/ and /i/ contexts were non-significant.

4. Discussion

The tongue body is likely to begin assuming the position needed for the upcoming vowel during the formation of a prevocalic lingual consonant, which may affect the position of the tongue for the consonant itself. This palatographic study showed that the A–P location of the place of articulatory constriction for the Hindi retroflex stop /t/ shifted as a function of vowel context. Both the anterior and posterior boundaries of the constriction moved progressively forward from /a/ to /u/ to /i/
context, which seems to reflect the shift in the place of maximal constriction as a consequence of the effect of those vowels. In the context of /a/, the constriction for /t/ was formed partly in the prealveolar and partly (with only slight encroachment) in the postalveolar zones; in the context of /u/, it was formed in the prealveolar zone; and in the context of /i/, it was formed partly in the dental and partly in the prealveolar zones. The location of the constriction partly overlapped among the three vowel contexts, but the centers of constriction areas were quite distinct. The shift in the place of /t/ constriction is apparently a coarticulatory effect of the vowel context. The effect of vowel context on certain lingual consonants, particularly velars, has been noted in previous studies (Ladefoged, 1957; Nihalani, 1974; Butcher & Wieher, 1976; Dave, 1977). Besides Dixit (1990) and the present study, Dave's is the only other study that reported some coarticulatory effect of vowel context on retroflex /t/ (that of Gujarati, which is similar to the Hindi /t/).

Although it is clear from previous studies that degree of retroflexion varies from language to language and from speaker to speaker (see Introduction), only one previous study (Śvarný & Zvelebil, 1955) has shown differences in the degree of retroflexion as a function of vowel context. X-rays in Śvarný & Zvelebil's study show a relatively greater degree of retroflexion in the context of a low back vowel than of a high back vowel. The palatographic data presented here agree with their X-ray data, for it was shown that the A-P location of the /t/ constriction shifted progressively backward from the /i/ to the /u/ to the /a/ context, suggesting that the degree of retroflexion increased progressively as the location of the /t/ constriction moved from front to back in the mouth. (Although the correlation between contact location and degree of retroflexion may not be necessary, this is what is usually observed. This appears to be generally true even in the same vowel context for different languages and speakers depending on whether the constriction is made more forward or more backward in the mouth (see X-rays in Ladefoged & Bhaskararao, 1983).) Physiologically, the tongue tip and blade seem to be less constrained in the context of /u/ than /i/, and least constrained in the context of /a/. Thus the tongue tip and blade can curl back relatively more in the context of /u/ than /i/, and can curl back the most in the context of /a/.

No previous palatographic study has examined the effect of speaking rate or loudness level on the A-P location of linguopalatal constriction. Our results showed that the coarticulatory effects of vowel context on the location of /t/ constriction in fast and loud speech were similar to those observed in normal speech: the location of constriction moved progressively backward from the /i/ to the /u/ to the /a/ context. With respect to the effect of speech condition overall, the results revealed that the constriction for /t/ was formed somewhat farther back in the mouth in fast speech than in normal or loud speech. Since this backward shift of the constriction occurred in all three vowel contexts irrespective of whether the vowel was a front or a back vowel, it is not analogous to the constriction shift that resulted from the coarticulatory effect of these vowels and we do not interpret it as indicating an increase in tongue retroflexion. Rather, this backward shift of the /t/ constriction in fast speech may be considered an instance of “locational undershoot”. By “locational undershoot”, we mean that the place of tongue-palate contact receded in fast speech probably because the general shape of the tongue was more like its bunched shape in the surrounding vowels. Therefore, the tongue tip or blade did not reach the same articulatory place in fast speech as it did in normal or loud speech.
We definitely do not mean an incomplete or loose linguopalatal contact by "undershoot" here, since a complete central-lateral constriction for /t/ was always formed in fast speech just as in normal or loud speech. Thus this A–P locational undershoot of the /t/ constriction is fundamentally unlike the undershoot of vowel targets in fast speech. However, its underlying source might be similar.

Undershoot in vowels is often explained in terms of physiological differences between the articulators or muscles involved in vowels as opposed to consonants. For example, Perkell (1969, p. 61) speculates as follows:

Many parts of the vocal tract play a role in the production of both vowels and consonants, but in general the same organs seem to behave differently under the influence of the two different classes. Consonant articulations by the tongue and lips are generally observed to be faster and more geometrically complex, and they require more precision in timing than vowel articulations. To some extent there also seems to be an anatomical division. For example, the tongue tip is more active in consonant articulations, whereas the body of the tongue is active in articulating both consonants and vowels. The general differences in velocity, complexity, precision of movement, and in anatomy suggest that different types of muscles are generally responsible for consonant and vowel production. It is probable that articulation of vowels is accomplished principally by the larger, slower extrinsic tongue musculature which controls tongue position. On the other hand, consonant articulation requires the addition of the precise, more complex, and faster function of the smaller, intrinsic tongue musculature.

Similar observations to Perkell's were made earlier by Öhman (1966, p. 166), whose X-ray tracings also suggest that the general tongue body shape of a following vowel is anticipated during a stop articulation. These observations suggest that movement of the tongue for vowel production is a sluggish gesture. Thus, sluggishness of the tongue gesture and the availability of less time in fast speech seems to be the cause of the commonly observed undershoot of vowel targets. In contrast, the production of consonants, particularly stops, involves movements of the tongue which are definitely not sluggish, so that the necessary constriction is always formed. Thus the commonly observed undershoot of vowel targets and the locational undershoot of the /t/ target observed in this study are essentially quite different.

On the other hand, while the facile tongue tip gesture of the /t/ closure is not sluggish, if we think of it as superimposed upon the sluggish tongue body gestures for the preceding and/or following vowels, the root cause of the undershoot may be the same. That is, in fast speech, the tongue body cannot move as far from its bunched shape for the vowels. (See Engstrand, 1988, Fig. 8 which clearly shows that "...the relaxation of vowel-related tongue position observed in slow-stressed production of symmetrical /ipi/, /apa/, and /upu/ is weak or absent at faster speaking rate...") Thus, while the tongue tip may be as retroflexed relative to the tongue body, if the tongue body is higher or backer is fast speech, the retroflexed tongue would contact the palate in a relatively more posterior location. In this way, the A–P locational undershoot of the constriction in fast speech (like the displacement undershoot of a vowel) might be due to an overall reduction in the time available for the tongue to move from one target position to another. The tongue configuration for the retroflex /t/ is quite complex, the tongue as a whole is moved somewhat forward (compare X-rays of /t/ and /t/ in Švarný & Zvelebil, 1955), and the tongue tip is moved upward and curled backward to form the occlusal
constriction by the underside of the tongue tip or of the tongue tip and blade. Since such a "retroflex" constriction appears to be a "critical" articulatory parameter for /t/ (see, however, Flege, Fletcher & Homiedan, 1988), the contact must be made and the tongue tip must be raised and curled back to a certain degree in making it. Thus, the only "redundant" articulatory dimension that remains free to vary is the A–P location of /t/ constriction.

In the context of /a/ and /u/, the backward shift in A–P location might be understood in terms of an accommodation to the dorsal configuration in the surrounding vowels. Although the raising and curling of the tongue tip away from the tongue body is preserved, there is less time to achieve the full fronting of the tongue body as a whole by the relaxation of vowel-related tongue position during the intervening /i/. In the context of /i/, on the other hand, it is more difficult to explain the more posterior location of the linguopalatal contact in fast speech. If we consider that the tongue body is relatively less high and less forward in /i/ (as expected in fast speech) and that the relaxation of vowel-related tongue position is weak or absent, we might speculate that the quick raising gesture of the tongue for the apical constriction is superimposed on a relatively bunched configuration of the tongue body, achieving a contact that is higher up the alveolar ridge, and hence more posterior in terms of the points on the electropalate. An examination of tongue body shapes for retroflex consonants and surrounding vowels is called for.

The shift in the A–P location of /t/ constriction as a function of vowel context was considerable: the constriction in the context of /i/ was approximately 4 mm and 6 mm more anterior than in the context of /u/ and /a/, respectively. On the other hand, the shift in the A–P location of /t/ constriction as a function of speech condition was quite small: the constriction was less than 1 mm more posterior in fast speech than in normal or loud speech. These results stand in contrast to the results of previous studies examining the effects of speaking rate and/or stress. The previous studies have not reported undershoot in the A–P location of constriction of apical and bilabial stops as a function of speech condition. Nor have they noted any coarticulatory shift in the A–P location of constriction of apical stops as a function of vowel context. It seems that the expected articulatory positions and configurations were always achieved whatever the speaking rate, stress, or vowel context.

On the basis of EMG data reported by Gay & Hirose (1973), Gay & Ushijima (1974), and Gay et al. (1974), it was hypothesized that there may be more extensive linguopalatal contact and substantially greater constriction length for /t/ in fast than normal speech as a result of increased force. However, we found that the number of sensors contacted in fast speech vs. normal speech differed very little. There was one more sensor contacted in fast speech than in normal speech in the context of /a/, whereas there was one fewer sensor in the contexts of /i/ and /u/. The A–P length of constriction was greater in fast speech than in normal speech, but the difference was quite small: only 0.4 mm in the context of high vowels and only 0.8 mm in the context of the low vowel. Thus, there was little clear-cut support in the data of this study for the proposed hypothesis; rather the data showed only small differences as a function of speaking rate in the area of linguopalatal contact and the length of /t/ constriction. This seems to be in agreement with the findings that articulatory target configurations and maximum displacements for certain apical and/or labial consonants remained virtually unaffected with changes in speaking rate (Gay & Hirose, 1973; Gay & Ushijima, 1974; Gay et al., 1974; Tuller et al., 1981).

Previous research suggests that loud speech is produced with greater articulatory
effort than normal speech, much as the sounds in stressed syllables are produced with more articulatory effort than those in unstressed syllables (Kent & Netsell, 1971; Tuller et al., 1981; Schulman, 1989). In accordance with the above, Schulman (1989), and Kent & Netsell (1971) reported greater articulatory displacement for vowel targets in loud and stressed speech, respectively. (See, however, Tuller et al., 1981, who observed that there was virtually no difference in maximum displacement of the tongue for the vowel /i/, and of the lower lip for the stop /p/ as a function of stress.) Following the observations of Schulman (1989) and Kent & Netsell (1971) described above, we had hypothesized that there would be a greater area of linguopalatal contact and greater A–P length of constriction for /t/ in loud speech than in normal speech. The results of the present study revealed that the number of contacted sensors was indeed greater (by two to three sensors) in the context of /u/ and /a/. However, in the context of /i/ just the opposite was true; normal speech had five contacted sensors more than loud speech. With respect to the A–P length of the /t/ constriction, the data showed that in the context of /u/ and /a/ it was considerably (1.0–1.6 mm) greater in loud than normal speech, but in the context of /i/ the difference in constriction length between loud and normal speech was negligible (being greater by only 0.2 mm in normal speech). Thus, the hypothesis that there may be a greater area of linguopalatal contact and a greater A–P length of constriction was confirmed in the back vowel contexts but not in the front vowel context.

The differences in the overall area of linguopalatal contact for /t/ between loud and normal speech can be explained simply in terms of the greater force of the contact in loud speech; the sides of the tongue pressed laterally against the alveolar processes along the sides of the hard palate, and the areas of the retroflexed tip adjacent to the initial contact point are pressed centrally against the alveolar ridge. The source of this effect is thus the same as that which presumably causes overshoot of vowel targets in loud speech.

The differences in A–P length in the context of /a/ and /u/ can be explained similarly in terms of the greater force of tongue–palate contact in loud speech. The Vowel × Condition interaction in A–P length, on the other hand, is more complicated to explain. To understand this interaction, it is necessary to take into account differences between consonants and vowels. Recall that in this study (as in Schulman’s 1989 study), stop closure durations are not like vowel durations; they are shorter in loud speech rather than longer. Also, as discussed above, consonants tend to achieve a full closure whatever the speech condition, whereas vowel targets show positional undershoot in unstressed or fast speech and overshoot in loud speech. Given the shorter constriction duration and the more extreme tongue body position during the neighboring vowels in loud speech, it seems likely that the tongue body cannot move as far from its position for the neighboring vowel during the stop closure, which will adversely affect the degree of tongue retroflexion for /t/. Presumably, this effect will be minimal in the context of /a/, moderate in the context of /u/, and maximal in the context of /i/. That is, the tongue configurations for /a/ and /u/ leave the blade and tip of the tongue relatively more free to maneuver into a retroflex configuration even in loud speech.

Another key to explaining the Vowel × Condition interaction is the fact that the degree of retroflexion is less in the context of /i/ than in the context of back vowels. The universality of this pattern presumably is the cause of the diachronic tendencies
noted by Bhat (1974) for retroflex consonants to deretroflex in the context of front vowels and for nonretroflex consonants to become retroflexed in the environment of back vowels. The pattern is quite understandable when we consider that front vowels in general, and /i/ most of all, involve a bunched fronted tongue shape, with the tongue tip tucked under the lower front teeth. Thus, the tongue shape of /i/ is inherently less compatible with the retroflex gesture. We can think of this as an inherent configurational undershoot for retroflex stops in the environment of /i/. Also, as stated above, we can reasonably assume that the part of the tongue contacting the roof of the mouth is the undersides of the tongue tip and of the tongue blade edge in the context of /a/ and /u/, but the front and lateral edges of tongue tip and blade in the context of /i/. Thus, in the context of /a/ and /u/, the effect of the greater articulatory force during loud speech would be to press more of the underside of the tongue tip and blade against the palate, resulting in a longer A–P contact. In the context of /i/, on the other hand, there would be no comparable effect from pressing the rim of the tongue with greater articulatory force against the alveolar ridge.

5. Summary

The anterior and posterior boundaries of the /t/ constriction moved progressively forward from /a/ to /u/ to /i/ context, which reflects the shift in the place of /t/ articulation as a consequence of coarticulatory effects of vowel context. These coarticulatory effects of vowel context on the place of /t/ constriction were quite large and similar across normal, fast and loud speech conditions. This forward shift in the A–P location of /t/ constriction suggests that the degree of retroflexion during /t/ production decreased systematically from /a/ to /u/ to /i/ as a function of vowel context.

There was also a shift in the place of articulation of /t/ as a function of speech condition, but it was quite small by comparison to the vowel context effect. This small backward shift of the /t/ constriction in fast speech may be considered an A–P locational undershoot of linguopalatal contact.

Contrary to expectation, changes in speaking rate did not substantially affect the extent of the area of linguopalatal contact or A–P length of /t/ constriction. The area of linguopalatal contact and the A–P length of /t/ constriction, however, were somewhat greater in loud speech as compared to normal speech, but only in the back vowel contexts. Further, the central-lateral occlusal constriction was always formed in all three vowel contexts and under all three speech conditions indicating that an occlusal constriction is critical for the production of /t/.

Any conclusions drawn from these results should be considered tentative since they are based on the data from a single speaker of Hindi.

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