Normal adult speakers' tongue palate contact patterns for alveolar oral and nasal stops

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Abstract

This study compared tongue palate contact patterns for oral stops (/t/, /d/) with those for the nasal stop /n/ in order to provide normative data for diagnosing and treating individuals with speech disorders. Electropalatographic (EPG) data were recorded from fifteen English speaking adults for word initial /t/, /d/ and /n/ in a high and a low vowel context. EPG frames were classified according to three criteria: (1) anterior constriction; (2) bilateral constriction; and (3) zero posterior central contact. Total amount of contact and variability were also measured. The results showed that almost all (99%) stops met criteria 1 and 3, with fewer articulations (88% of /t/; 83% of /d/ and 55% of /n/) meeting criterion 2. Although all stops had similar spatial patterns, /t/ and /d/ had more contact and were more likely to have bilateral constriction than /n/. There were no differences in variability between /t/, /d/ and /n/, however. The clinical implications of the results for the management of individuals with speech disorders are discussed.

Key words: stops, electropalatography (EPG), articulation disorder.

Introduction

Alveolar stops /t/, /d/ and /n/ are acquired at an early age in typically developing children and are not among the most frequently misarticulated sounds in children with speech disorders (Smit, Hand, Freilinger, Bernthal and Bird, 1990; Smit, 1993). Nonetheless, some children with speech disorders, most notably those with cleft palate, do produce the oral stops /t/ and /d/ as errors. These errors often involve abnormally retracted placement such as palatal, velar, pharyngeal or glottal articulations (Morley, 1970; McWilliams, Morris and Shelton, 1990; Trost, 1981). Some children with retracted placement for /t/, /d/ are at the same time able to articulate /n/ with correct alveolar placement. A study using electropalatography (EPG) by Houston (2002) found that almost two thirds of a group of children with cleft palate produced /n/ at a significantly more forward placement compared to /t/. Other EPG studies have found similar patterns of retracted placement for oral stops but normal alveolar placement for the nasal stop in school aged children with functional articulation disorders (Gibbon, Dent and Hardcastle, 1993; Gibbon, Stewart, Hardcastle and Crampin, 1999).

For children who have abnormally retracted placement for /t/ and /d/, the ability to produce /n/ at an alveolar placement is positive; it shows that alveolar placement is achievable. Furthermore, evidence of alveolar placement suggests that the abnormally retracted placement could be due to abnormal learning. The reason why some children learn incorrect placement is not known. For other children, especially those who have a previous or ongoing vocal tract anomaly (e.g. oronasal fistula or velopharyngeal dysfunction), the reason could be that they have learned to produce retracted placement as an active compensatory strategy adopted to achieve the necessary oral pressure for plosive sounds. Whatever the reason, it has been suggested that speech therapy is effective for errors due to abnormal learning (Hutters and Bronsted, 1987). In addition, normal placement for /n/ could be a useful facilitating context to establish correct placement for errors affecting /t/ and /d/, and perhaps other alveolars such as /s/ and /z/, in a therapy programme.

Traditionally, /t/, /d/ and /n/ are described as having alveolar placement indicating that they all have the same place of articulation. Placement for /n/ may be identified by perceptual analysis as like /t/ and /d/, but there may be subtle differences in its articulation that can only be detected with an instrumental technique such as EPG, which measures details of the tongue’s contact against the palate. A number of previous EPG studies of normal adult speakers’ productions of alveolar stops have shown that /t/, /d/ and /n/ do in fact have similar “horseshoe” shaped configurations (Dagenais, Lorendo and McCutcheon, 1994; Goozée, Murdoch and Theodoros, 1999; Hardcastle and Gibbon, 1997; McLeod and Roberts, 2005; McLeod, 2006; McAuliffe, Ward and Murdoch, 2001; Stone and Lundberg, 1994). EPG studies show that normal speakers (adults and children) produce this horseshoe configuration by a combination of lateral bracing and an upward movement of the tongue tip/blade to the alveolar ridge (Dagenais and Critz-Crosby, 1991; Fletcher, 1989). An important additional feature is that speakers need to “tense the lateral borders of the tongue to produce a spoon-shaped configuration” (Fletcher, 1992, p. 99).

Stone, Faber, Raphael and Shawker (1992) suggest that control of the lateral margins of the tongue is essential for normal speech production because lateral anchorage gives stability to the whole of the tongue. Studies of children with cleft palate and functional articulation disorder have found that some do not show evidence of being able to brace the tongue in the normal way (Gibbon, 1999; Howard, 2004). Children’s ability to produce alveolar stops is important because it is thought to underpin the subsequent development of other gestures. For instance, Fletcher (1992) maintains that the ability to produce anterior stops is a prerequisite for the development of other gestures such as sibilant sounds, stating that “the anterior stop gesture is postulated to serve as a fountainhead for the remaining lingual consonant gestures” (p. 99). Thus, as Fletcher (1992) implies, a speech disorder affecting alveolar stops is predicted to have a detrimental and widespread effect on speech development and intelligibility.

Although productions of the alveolar stops have characteristic articulatory features, such as the horseshoe shape seen on EPG traces as described above, a number of studies have highlighted that alveolar stop productions are also highly variable. Shockey (1991) found that alveolar stops were most likely to be fully formed in syllable initial position, especially word initial, and in stressed syllables. Normal speakers usually produce fully formed alveolar articulations in these contexts, but less fully realised (i.e., reduced) spatial patterns otherwise and there is considerable inter speaker variation.

Various factors affect EPG patterns for /t/, /d/ and /n/ giving rise to the “instability” of alveolars (Kohler and Hardcastle, 1974). First, intervocalic and word final alveolars are likely to be either absent or assimilated totally or partially to placement of the preceding or following sound and this is particularly clearly seen on the EPG traces when the preceding or following sound is a velar articulation. Second, less than fully realised versions of alveolar stops are often produced in connected speech compared to their production in single word citation forms. Shockey (1991) suggests that the reduced spatial patterns may be due to a lower long-term jaw and tongue setting in conversational speech, which leads to less side contact and incomplete closures. A third factor is vowel context. Waters, Nicolaidis, Hardcastle and Gibbon (1995) found that /t/ and /d/ in a high vowel context had more contact than the same targets produced in low vowel contexts. Similar patterns of tongue palate contact have been found in other languages, such as Catalan, (Recasens, 1984) and Italian (Farnetani and Recasens, 1993).

Although previous EPG studies have described EPG patterns for alveolar stops and highlighted factors that affect their spatial configurations, studies have not specifically compared patterns for oral and nasal stops. This comparison is particularly important for therapists wishing to use EPG to diagnose and treat abnormal alveolar stops produced by individuals with speech disorders, particularly if they wish to use /n/ as a facilitating context. Any differences are likely to be relatively subtle; therefore this study used controlled speech material in the form of minimal pairs in order to find out whether normal adult speakers’ EPG patterns for /t/, /d/ differed from /n/.

Method

Participants

The participants were 15 normal English adult speakers, five males (M1-M5) and ten females (F1-F10) ranging in age from 24 to 61 years and a mean of 44 years. The participants were either faculty members at Queen Margaret University College in Edinburgh or they were speech and language therapists who worked in the UK and had artificial plates because they used EPG in their clinical work. They had no history of speech, language or hearing difficulties and were native speakers of English. An institutional ethics board approved the study and consent was obtained from participants. The consent procedure did not inform participants about the purpose of the study, so they were unaware of how their EPG data would be analyzed in the experiment.

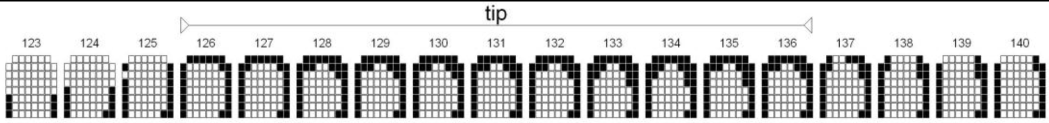
EPG Instrumentation

The WinEPG^{TM} system was used in this experiment (Wrench, Gibbon, McNeill and Wood, 2002) with the EPG sampled at 100 Hz simultaneously with the acoustic signal at 22,050 Hz. In order to record the dynamic tongue palate contact patterns, each participant had an artificial plate individually constructed to fit against the hard palate. The plate contained 62 electrodes, placed in eight horizontal rows according to well-defined anatomical landmarks, with the electrodes arranged such that Row 1 had 6 electrodes, with Rows 2-8 each containing eight electrodes (Hardcastle and Gibbon, 1997).

Speech Material

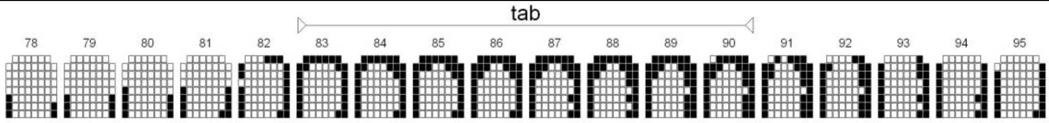
Simultaneous EPG and acoustic data were recorded as the participants read out loud a list of minimal pair sets. The minimal pairs were *a tip/a dip/a nip; a tab/a dab/a nab* and the participants were instructed to speak at a natural, conversational rate. Each word was preceded by a schwa in order to initiate each consonant from a neutral tongue position. Each participant repeated the minimal pair sets 10 times, hence 60 tokens per participant were analysed. The EPG and acoustic data were recorded and displayed on a computer screen using Articulate Assistant 1.11 software (Wrench et al., 2002) and the /t/, /d/, /n/ segments were identified on the EPG frames. The beginning of the segment was identified as the first EPG frame showing complete constriction, with the end of the segment identified as the last EPG frame showing complete constriction. Examples of EPG data with annotated /t/ and /n/ segments are shown in Figure 1. The EPG frame showing maximum constriction within the annotated target segment was selected and exported for statistical analysis using the ‘data export’ function of the software.

tip



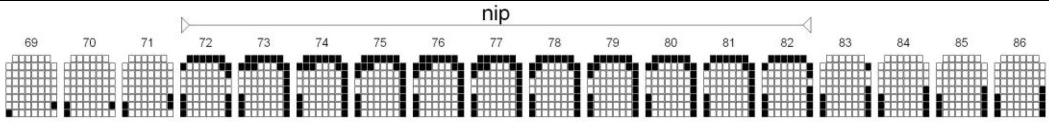
Maximum contact from frames 133 to 134

tab



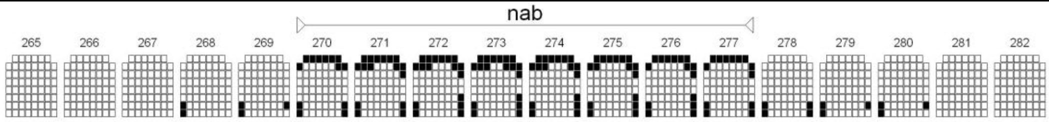
Maximum contact at frame 89

nip



Maximum contact from frames 75 to 77

nab



Maximum contact at frame 273

Figure 1. EPG printouts from one participant's (F9) productions of /t/ and /n/ in the minimal pairs *a tip/a nip* and *a tab/a nab*, with the stop segments marked above the EPG frames. Note that although F9 has anterior constriction for all alveolar stop targets and zero contact in the posterior region, bilateral constriction occurs for /t/ but not /n/ even though both targets occur in the same context.

Data Analysis

Three selection criteria were used to classify the EPG frame at maximum constriction within the annotated target segment:

1. Anterior constriction – 100% contact at either row 1 or row 2 or both;
2. Bilateral constriction – 100% contact at both the left-most column and the right-most column;
3. Contact in posterior central region – zero contact at the four electrodes at the centre from row 5 to row 8.

To illustrate the criteria from the EPG printouts in Figure 1, the data for *nip*, *nab, tip* and *tab* all meet criteria 1 and 3 (anterior constriction and zero contact in the posterior region), but only *tip* and *tab* meet criteria 2 (bilateral constriction).

Two measures were made at the selected EPG frame within each annotated target consonant. The first was the amount of contact (Percent Contact), which was measured by calculating the percentage of contacted electrodes across the whole palate. The second was a measure of token to token variability using the Variability Index. The Variability Index (Farnetani and Provaglio, 1991) is a measure based on the frequency with which each EPG electrode is contacted over repetitions. To calculate the index, the percent frequency of activation of each electrode across repetitions is measured. 100% and 0% of activation frequency represent invariance and are assigned an index value 0. The Variability Index was calculated by summing index values for all contacts and dividing the sum by the total number of electrodes on the palate, i.e. 62. Thus, an index value of 0 indicates absolute invariance with higher values indicating greater variability (maximum value is 50).

Results

Criteria

Almost all (99%) of /t/, /d/ and /n/ EPG frames met criteria 1 of complete anterior constriction and the same percent met criteria 3 of zero contact in the central posterior region. These results highlight the similarities of EPG patterns produced by speakers for oral and nasal stops. Fewer (75%) EPG frames met criteria 2 of bilateral constriction, with 88% of /t/, 83% of /d/ and 55% of /n/ targets (see Table 1), when they were averaged across the two vowel contexts. For /t/ and /d/, most participants showed few differences in the frequency of bilateral constriction between /I/ and /a/ contexts. The difference was greater for /n/, however. There was considerable inter speaker variability in the extent to which their productions had bilateral constriction, with two participants (M1 and M3) observed to have 100% bilateral constriction for /t/, /d/ and /n/ and another participant (F10) who had 0% contact for these targets.

EPG measures

Two separate univariate ANOVAs were conducted on two dependent variables: Percent Contact and the Variability Index. There were three factors: Speakers (15 levels), Consonant-types (3 levels) and Vowel-contexts (2 levels). The analysis showed three main effects on Percent Contact: Speakers, Consonant types and Vowel contexts (Appendix 1). The effect of Consonant types is illustrated in Figure 2, in which the Percent Contact was higher for the oral stops than for the nasal stop, and this difference was statistically significant. The Figure shows that mean Percent Contact was 49.4% for /t/ and 49% for /d/, with /n/ showing the least contact at 44.2%. Post-hoc tests (Games-Howell) were conducted to see if the three types of stops were different from one another, with a criterion set at $p < 0.05$. Pairwise comparisons showed that both oral stops were statistically different from the nasal stop.

Table 1. Frequency (%) of bilateral constriction in 15 speakers' productions of /t/, /d/ and /n/ in two vowel contexts (/I/ and /a/).

	/t/		/d/		/n/		Mean
Speakers	/I/	/a/	/I/	/a/	/I/	/a/	
M1	100%	100%	100%	100%	100%	100%	100%
M2	100%	70%	100%	90%	70%	30%	77%
M3	100%	100%	100%	100%	100%	100%	100%
M4	78%	89%	50%	90%	0%	0%	51%
M5	50%	50%	0%	0%	0%	0%	17%
F1	100%	100%	100%	100%	30%	0%	72%
F2	100%	100%	100%	90%	90%	80%	93%
F3	100%	100%	100%	100%	90%	100%	98%
F4	100%	100%	100%	100%	50%	10%	77%
F5	90%	100%	100%	90%	100%	60%	90%
F6	100%	89%	100%	90%	80%	50%	85%
F7	100%	100%	100%	100%	90%	90%	97%
F8	100%	100%	100%	100%	90%	100%	98%
F9	100%	100%	90%	100%	10%	20%	70%
F10	0%	0%	0%	0%	0%	0%	0%
Mean	88%	87%	83%	83%	60%	49%	75%

No significant difference was observed between the oral stops, however. The finding that /n/ had less contact than /t/ or /d/ is consistent with /n/ having fewer instances of bilateral constriction (see Table 1). Figure 1 illustrates the finding that /n/ had less contact than /t/ and the finding that /n/ was less likely to have bilateral constriction than /t/ even when these targets were produced by the same speaker in the same phonetic contexts. The significant main effect of Vowel Contexts is due to lower Percent Contact in the /a/ context than in the // context, which relates to the finding of fewer instances of bilateral constriction for /n/ than /t/ or /d/ in the /a/ context as seen in the mean values in Table 1.

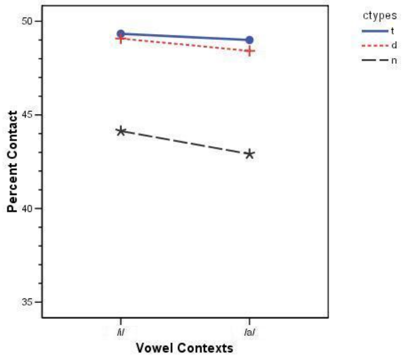


Figure 2. Mean Percent Contact for /t/, /d/ and /n/ in two vowel contexts (/I/ and /a/).

Table 2. Mean Percent Contact (standard deviation in brackets) for /t/, /d/ and /n/ illustrating inter speaker variability in amount of tongue palate contact.

Speakers	/t/	/d/	/n/	Mean
M1	56 (6.7)	59 (6.5)	54 (4.2)	56
M2	66 (2.7)	59 (3.1)	52 (1.6)	59
M3	61 (3.3)	60 (3.5)	62 (3.3)	61
M4	46 (2.5)	46 (3.5)	39 (3.3)	44
M5	39 (3.0)	35 (2.2)	22 (5.1)	32
F1	45 (3.4)	44 (3.2)	38 (4.3)	42
F2	55 (4.0)	54 (4.6)	43 (4.2)	51
F3	58 (4.6)	56 (5.0)	52 (3.7)	55
F4	47 (3.9)	46 (4.1)	40 (4.6)	44
F5	52 (5.2)	49 (4.0)	51 (3.1)	51
F6	41 (3.2)	42 (4.6)	35 (3.0)	39
F7	47 (2.1)	44 (2.9)	44 (1.8)	45
F8	46 (4.5)	58 (7.9)	50 (5.7)	51
F9	42 (3.1)	43 (2.4)	38 (4.3)	41
F10	38 (3.5)	36 (2.0)	36 (2.2)	37
Mean	49	49	44	47

The significant main effect of Speakers on Percent Contact is illustrated in Table 2 and Figure 3. Table 2 shows mean Percent Contact for all participants, illustrating the inter speaker differences in amount of contact. The range of contact was wide: 38%-66% for /t/;

35%-60% for /d/; and 22%-62% for /n/. Figure 3 illustrates inter speaker differences in amount of contact, by showing EPG printouts from participants with the highest and lowest mean Percent Contact for /t/ and /n/ targets.

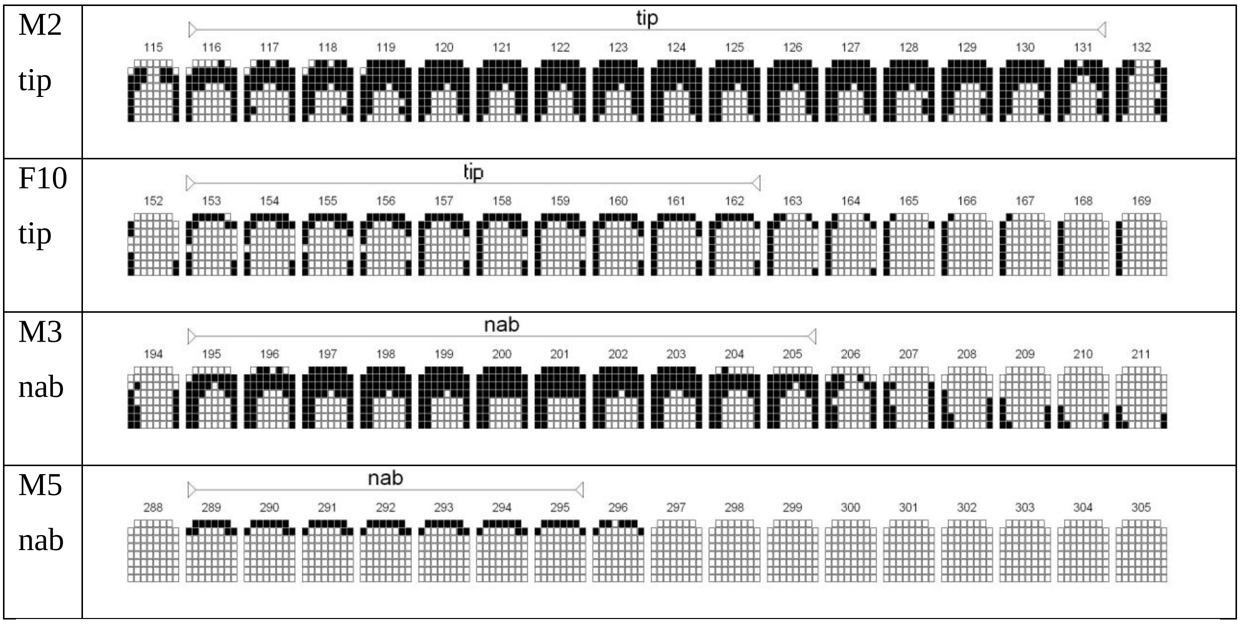


Figure 3. EPG printouts illustrating inter speaker differences in amount of contact. Compared to the other participants, M2 has a high amount of contact and F10 has a low amount of contact for /t/ in *a tip*. Similarly, M3 has a high amount and M5 has a low amount of contact for /n/ in *a nab*. The stop segments are marked above the EPG frames.

Figure 4 shows that mean Variability Index values for /t/ and /d/ were similar at around 2.73 in both // and /a/ contexts. The mean index value for /n/ was higher in /a/ context (2.85) than in // context (2.68), consistent with the finding of fewer instances of bilateral constriction in /a/ context. There was no statistical difference in the Variability Index values among the three consonants. However, there was a statistical difference in the index values from speaker to speaker (see Appendix 2).

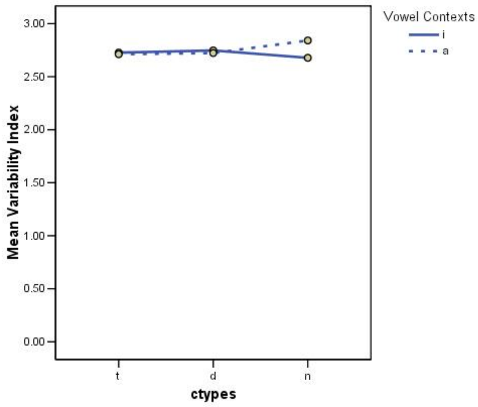


Figure 4. Mean Variability Index values for /t/, /d/ and /n/ in two vowel contexts (/I/ and /a/).

Discussion

The results showed that all alveolar stops, both oral and nasal, had similar EPG patterns, insofar as 99% had anterior constriction and zero contact in the posterior central region of the palate. Almost all the stops met the criteria relating to these articulatory features, despite considerable variability in the overall amount of contact that each person produced. These results are not surprising and are consistent with theories of phonetics that involve a notion of place of articulation (Ladefoged and Maddieson, 1996), which identifies the location within the oral cavity, in this case alveolar, at which major articulatory events occur.

Although normal adult speakers produced alveolar constriction for oral and nasal stops, there were some differences in the tongue palate contact for /t/ and /d/ compared to /n/ that have not been described previously. Specifically, speakers produced less contact for /n/ and overall there were fewer instances of bilateral constriction for /n/ compared to /t/ and /d/. The results showed that although over 80% of /t/ and /d/ production had bilateral constriction, less than half of /n/ productions in a low vowel context had bilateral constriction. The results show considerable inter speaker variability, however. For example, two participants (M1 and M3) produced all /t/, /d/ and /n/ with bilateral constriction, but one participant (F10) had no instances of bilateral constriction for any targets. The finding that some speakers do not have bilateral constriction for /n/ is consistent with EPG data reported in a recent study by McLeod (2006), which found that although most speakers' EPG patterns had alveolar constriction for /n/, some speakers did not produce lateral contact.

Traditional phonetic descriptions do not highlight the importance of lateral contact for the production of alveolar stops, although Fletcher (1992) emphasises the role of lateral contact in building up oral pressure for obstruent sounds and Stone et al. (1992) emphasised its role in providing stability to the tongue during speech production. The finding of more instances of bilateral constriction for /t/ and /d/ compared to /n/ may relate to the increased intra oral pressure requirements for oral stops (Subtelny, Worth and Sakuda, 1966). Subtelny et al. found that mean pressures in cm H_2O (averaged for males and females) were much higher for /t/ and /d/ compared to /n/ (6.8 for /t/, 5.6 for /d/ and 0.4 for /n/). The higher amount of tongue palate contact for oral stops may therefore be due to increased lingual pressure on the hard palate necessary to meet these requirements. McGlone, Proffit and Christiansen (1966) measured lingual pressure in adults producing /t/, /d/ and /n/ using strain gauge transducers placed in the lateral regions of the palate at the left and right maxillary first molars and the central incisors. Their study showed that the lateral transducers recorded higher pressures for /t/ and /d/ compared to /n/ and they concluded that “differing amounts of lingual pressure are used for consonant production” (p. 612). The finding from the present study of fewer instances of bilateral constriction for /n/ may therefore be due to the fact that /n/ does not require air to be impounded and therefore the need to produce a lateral seal is reduced.

The importance of the lateral seal is evident, but making judgements about its presence or absence from EPG data alone is not straightforward or reliable. On the one hand, even when the EPG data indicates bilateral seal, it is possible that air is escaping behind the back row of electrodes into the buccal cavity and that there is not in fact a complete oral seal. This situation may arise during the production of lateral fricatives, for example, or during lateral release of lingual plosives. On the other hand, when the EPG patterns do not show bilateral constriction, it may be that there is lateral seal at a lower level than can be recorded by the lateral electrodes. Although EPG provides useful data about the actions of the sides of the tongue against the palate, it is not possible to know from EPG data alone whether a speaker has produced a lateral seal. As a result of these procedural limitations of EPG, it is important to recognise that the data is only indicative of lateral seal and is not a reliable measure of this articulatory feature.

There were considerable differences in the amount of contact that speakers produced, with some speakers having almost twice the amount of contact as others. One explanation for this variation is to do with speaker differences in palatal shape. More precisely, individuals with flatter palates are more likely to have higher amounts of contact than those whose palates are steeply arched (Hiki and Itoh, 1986). There are other possible explanations for the inter speaker variation in amount of contact, however. Shockey (1991) suggested that reduced spatial patterns may be due to lower long term jaw and tongue settings and it may be that some speakers have lower habitual settings than others. Another factor could be overall amount of effort, with some speakers responding to the speech material as citation forms and as a result exerting more effort and therefore higher pressures during production. Other speakers could have articulated the speech material in a more relaxed way, more like conversational speech, and this could have resulted in reduced EPG contacts (Shockey, 1991). Although these are possible reasons for the inter speaker variation in the amount of tongue contact, the present study did not investigate these factors, so the contribution of each to the overall findings remains speculative.

The results of this study give normative adult data for /t/, /d/ and /n/ that can be used for identifying abnormal EPG patterns produced by individuals with speech disorders. However, caution is needed when comparing EPG data from normal adults to patterns produced by children, particularly those with cleft palate. Previous studies have shown that the EPG patterns recorded from older school age children are similar to younger children, but older children have somewhat less contact overall (Dagenais and Critz-Crosby, 1991; Fletcher, 1989). In addition, the hard palates of cleft speakers (at least those who have a cleft of the alveolus) tend to be smaller, narrower, and more irregular in shape than those of normal speakers. Furthermore, abnormal dental conditions (e.g. maxillary collapse, dental malalignment, missing teeth, ectopic eruption of teeth, supernumerary teeth and protrusion of the maxilla) as well as malocclusion are frequent in people with cleft palate. These factors will have direct effects on tongue-palate contact patterns (Peterson-Falzone, Hardin-Jones and Karnell, 2001) and it is important to bear these in mind when using EPG in diagnosis and therapy. The above points highlight the importance of taking into account individuals' age and craniofacial anatomy as well as normal tongue contact patterns when interpreting EPG data.

In terms of therapy, normative data provide helpful guides when using EPG for visual feedback to remediate articulation errors affecting alveolar stops, particularly /t/ and d/. More specifically, the normal EPG patterns will serve as targets that speakers with articulation errors will attempt to reproduce in order to produce alveolar stops with normal place of articulation. Furthermore, the similarities in EPG patterns for oral and nasal stops suggest that speech and language therapists can use /n/ as a facilitating context in situations where children can produce this sound with correct placement. The aim of contextual facilitation is to place the target sound in a specific phonetic context so that components of a preceding or following sound facilitate production of that target (Kent, 1982). For /n/ to facilitate /t/ or /d/, it may be helpful to use specific vowel contexts to encourage lateral contact. One approach would be to use /n/ in a high vowel context, for example in the following contexts: mint tea, windy etc. In these sequences, for successful production of /t/ or /d/, the high vowel will encourage bilateral constriction and in addition the child needs to hold constant the alveolar placement (facilitated by /n/) during production of the following oral stop. This approach to intervention requires systematic study in the future to establish whether it is effective in practice. It is also important to gather more normative data from typically developing children in order to know precisely what constitutes normal tongue palate contact patterns at different stages of speech, motor control and anatomical development and how these differ from adult EPG patterns.

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References

Dagenais, P.A., & Critz-Crosby, P. (1991). Consonant lingual-palatal contacts produced by normal-hearing and hearing-impaired children. *Journal of Speech and Hearing Research,* 34, 1423-1435.

Dagenais, P.A., Lorendo, L.C., & McCutcheon, M.J. (1994). A study of voicing and context effects upon consonant linguapalatal contact patterns. *Journal of Phonetics*, 22, 225-238.

Farnetani, E., & Provaglio, A. (1991). Assessing variability of lingual consonants in Italian. *Quaderni del Cantro di Studio per le Ricerche di Fonetica del C.N.R., X,* 117-145.

Farnetani, E., & Recasens, D. (1993). Anticipatory consonant-to-vowel coarticulation in the production of VCV sequences in Italian. *Language and Speech*, 36, 279-302.

Fletcher, S.G. (1989). Palatometric specification of stop, affricate and sibilant sounds. *Journal of Speech and Hearing Research*, 32, 736-748.

Fletcher, S.G. (1992). *Articulation: A Physiological Approach.* California: Singular Publishing Group.

Gibbon, F. E. (1999). Undifferentiated lingual gestures in children with articulation/phonological disorders. *Journal of Speech, Language, and Hearing Research*, 42, 382-397.

Gibbon, F., Dent, H., & Hardcastle, W. (1993). Diagnosis and therapy of abnormal alveolar stops in a speech-disordered child using EPG. *Clinical Linguistics and Phonetics*, 7, 247-268.

Gibbon, F., Stewart, F., Hardcastle, W.J., & Crampin, L. (1999). Widening access to electropalatography for children with persistent sound system disorders. *American Journal of Speech-Language Patholog*y, *8,* 319-334.

Goozée, J.V., Murdoch, B.E., & Theodoros, D.G.. (1999). Electropalatographic assessment of articulatory timing characteristics in dysarthria following traumatic brain injury. *Journal of Medical Speech-Language Pathology,* 7, 209-222.

Hardcastle, W.J., & Gibbon, F.E. (1997). Electropalatography and its clinical applications. In M.J. Ball and C. Code (Eds.), *Instrumental clinical phonetics.* (London: Whurr Publishers), pp 149-193.

Hiki, S., & Itoh, H. (1986). Influence of palate shape on lingual articulation. *Speech Communication, 5*, 141-158.

Houston, C. A. (2002). An investigation of the lingual assist theory in the production of /t/ and /n/ by children with cleft palate. *Unpublished Honours Project*, Queen Margaret University College, Edinburgh.

Howard, S. (2004). Compensatory articulatory behaviours in adolescents with cleft palate: Comparing the perceptual and instrumental evidence. *Clinical Linguistics and Phonetics*, 18, 313-340.

Hutters, B., & Bronsted, K. (1987). Strategies in cleft palate speech – with special reference to Danish. *Cleft Palate Journal, 24*, 126-136.

Kent, R.D. (1982). Contextual facilitation of correct sound production. *Language, Speech, and Hearing Services in Schools*, 13, 66-76.

Kohler, K., & Hardcastle, W.J. (1974). The instability of final alveolars in English and German. *Proceedings of Stockholm Speech Communication Seminar.* Uppsala. Almqvist and Wiksell, 95-98.

Ladefoged, P., & Maddieson, I. (1996). *Sounds of the World's Languages*. Blackwell Publishers: Oxford.

McAuliffe, M., Ward, E., & Murdoch, B. (2001). Tongue-to-palate contact patterns and variability of four English consonants in an /i/ vowel environment. *Logopedics Phoniatrics Vocology*, 26, 4, 165-178.

McGlone, R.E., Proffit, W.R., & Christiansen, R.L. (1967). Lingual pressures associated with alveolar consonants. *Journal of Speech and Hearing Research, 10*, 606-615.

McLeod, S. (2006). Australian adults' production of /n/: an EPG investigation. *Clinical Linguistics and Phonetics, 20*, 99-107.

McLeod, S., & Roberts, A. (2005). Templates of tongue/palate contact for speech sound intervention. In C. Heine & L. Brown (Eds) *Proceedings of the Speech Pathology Australia National Conference*. Melbourne: Speech Pathology Australia.

McWilliams, B.J., Morris, H.L., & Shelton RL. (1990). *Cleft Palate Speech,* 2nd Edition. Philadelphia: B.C. Decker.

Morley, M.E. (1970). *Cleft Palate and Speech,* 7th Edition. Edinburgh, Scotland: Churchill Livingstone.

Peterson-Falzone, S.J., Hardin-Jones, M.A., & Karnell, M.P. (2001). *Cleft Palate Speech,* 3rd Edition. St. Louis: Mosby.

Recasens, D. (1984). Vowel-to-vowel coarticulation in Catalan VCV sequences. *Journal of the Acoustical Society of America, 76*, 1624-35.

Shockey, L. (1991). Electropalatography of conversational speech. *Proceedings of the XIIth International Congress of Phonetic Sciences, Aix-en-Provence, France, August 19th-24th*, Vol. 3, 10-13.

Smit, A.B., Hand, L., Freilinger, J., Bernthal, J.B., & Bird, A. (1990). The Iowa articulation norms project and its Nebraska replication. *Journal of Speech and Hearing Disorders, 55*, 779-798.

Smit, A.B. (1993). Phonologic error distributions in the Iowa-Nebraska Articulation Norms Project: consonant singletons. *Journal of Speech and Hearing Research, 36*, 533-47.

Stone, M., & Lundberg, A. (1996). Three-dimensional tongue surface shapes of English consonants and vowels. *Journal of the Acoustical Society of America, 99*, 3728-3737.

Stone, M., Faber, A., Raphael, L.J., & Shawker, T.H. (1992). Cross-sectional tongue shape and linguopalatal contact patterns in [s], [ʃ], and [l]. *Journal of Phonetics, 20,* 253-270.

Subtelny, J.D., Worth, J.H., & Sakuda, M. (1966). Intraoral pressure and rate of flow during speech. *Journal of Speech and Hearing Research,* 9, 498-518.

Trost, J.E. (1981). Articulatory additions to the classical description of the speech of persons with cleft palate. *Cleft Palate Journal,* 18, 193-203.

Waters, D., Nicolaidis, K., Hardcastle, W.J., & Gibbon, F. (1995). Variability of lingual stops in English - an EPG study. *Proceedings of the XIIIth International Congress of Phonetic Science, Stockholm, Sweden, 13-19 August 1995, 3,* 456-458.

Wrench, A.A., Gibbon, F.E., McNeill, A.M., & Wood, S.E. (2002). An EPG therapy protocol for remediation and assessment of articulation disorders. In J.H.L. Hansen and B. Pellom (Eds.) *Proceedings of ICSLP-2002*, 965-968. Also on CD-ROM.

Appendix 1.

Univariate ANOVA with Percent Contact as a dependent variable.

Independent Variables	*F*	*df*	*p*
Consonant-types	194.045	2	< 0.0001
Speakers	282.803	14	< 0.0001
Speakers * Consonant-types	14.367	28	< 0.0001
Vowel Contexts	8.801	1	< 0.003
Vowel Contexts * Speakers	1.742	14	< 0.043
Vowel Contexts * Speakers * Consonant-types	1.731	28	< 0.011

Appendix 2.

Univariate ANOVA with Variability Index as a dependent variable.

Independent Variables	*F*	*df*	*p*
Speakers	46.816	14	< 0.0001
Speakers * Consonant-types	5.733	28	< 0.0001