Phonetic Characterization of a Complex Coronal System: Insights from Punjabi

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To my Family

Table of Contents

Declaration

The research conducted in this dissertation is my original work and it has not been submitted for a higher degree research in any other institution. In addition, I certify that all of the relevant sources and literature are cited. The experiments presented in this dissertation have gained ethics approval from Macquarie University (5201200770). Some of the results have already been published/submitted:

Papers:

- **Paper 1 (Chapter 2):** Hussain, Q., Harvey, M., Proctor, M., & Demuth, K. (revision submitted). Punjabi: illustration of the IPA. *Journal of the International Phonetic Association.*
- **Paper 2 (Chapter 3):** Hussain, Q. (2015). Temporal characteristics of Punjabi word-medial singletons and geminates. *Journal of the Acoustical Society of America, 138*(4), EL388-EL392.
- **Paper 3 (Chapter 4):** Hussain, Q., Proctor, M., Harvey, M., & Demuth, K. (revision submitted). Acoustic characteristics of Punjabi retroflex and dental stops. *Journal of the Acoustical Society of America.*
- **Paper 4 (Chapter 5):** Hussain, Q., Harvey, M., Proctor, M., & Demuth, K. (in preparation). Adaptation of English word-final alveolar stops into Punjabi.

I also certify that I was the first author of all the papers. The experiments conducted in this dissertation were designed in consultation with my supervisors, Katherine Demuth, Mark Harvey and Michael Proctor. All of the acoustic analyses, segmentation and data analyses were conducted by me.

Signed:

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Abstract

Punjabi is an Indo-Aryan language that has contrastive retroflex and dental series. However, very little is known about the phonetic and phonological properties of the retroflex and dental stops in Punjabi, and whether these are fully contrastive in all word-positions. The aim of this dissertation is therefore to investigate the phonetic properties of the Punjabi retroflex and dental stops across word-positions using temporal and spectral measures.

Among the world's languages, stops are the most frequently occurring manner of articulation (Schwartz, Boe, Badin, & Sawallis, 2012). Their acoustic cues in Indo-Aryan languages are yet to be fully investigated. Punjabi has a singleton vs. geminate opposition within the manner class of stops. In this dissertation, I examine the place contrasts only for the singleton retroflex and dental stops. However, I also provide an overview of the singleton vs. geminate opposition to show that the difference between these two classes of stops is one of duration, and not a manner opposition. Firstly, an introduction to the phonemic inventory of Punjabi is provided, followed by the temporal characteristics of the word-medial Punjabi singleton and geminate stops. After that, the contrast between Punjabi singleton retroflex and dental stops is investigated in detail, across word-positions (word-medial, word-initial and word-final positions). Finally, these insights are applied to better understand the nature of loanword adaptation, showing how English alveolar /t/ and Punjabi speakers' productions of source loanword /t/ align with Punjabi native retroflex and dental categories. For this purpose, Australian English (AusE) productions of alveolar stop /t/ and loanword /t/ were compared with native Punjabi retroflex and dental stops.

The findings suggest that Punjabi singletons differ from geminates in terms of both consonant duration and the duration of the following vowel. The results also suggest that Punjabi coronal place contrasts are signaled by the complex interaction of temporal and spectral cues. In the loanword study, the loanword /t/ was acoustically more similar to Punjabi retroflex

than dental stops. On the other hand, the comparisons of the AusE alveolar /t/ and Punjabi retroflex stop indicate no clear patterns of acoustic similarities. This suggests that AusE /t/ played little role in explaining the adaptation of English alveolar stops as retroflexes in Punjabi.

This dissertation will therefore help inform the phonetic and phonological processes underlying coronal contrasts in the native and loanword phonologies of Indo-Aryan languages. The detailed phonetic analyses of Punjabi will also contribute to the growing body of crosslinguistic literature on the phonetics of coronals.

Chapter 1: Introduction[1]

[1] Some of the literature review presented in this chapter will appear in the following chapters that have been submitted for publication.

Cross-linguistic studies have proposed three major place distinctions for speech sounds: labial, coronal and dorsal (Ladefoged & Maddieson, 1996; Rice, 2011; Sagey, 1986). Among these, the class of *coronals* is more diverse than the classes of labials and dorsals (Hall, 2011; Hamann, 2003; Paradis & Prunet, 1991). Some languages have a three or four-way coronal contrast as found in many Australian (Fletcher & Butcher, 2014), Indo-Aryan (predominantly three-way contrast; Arsenault, 2015; Pandey, 2014) and Dravidian languages (three or four-way contrast; Krishnamurti, 2003).[2] A major challenge in the current phonetic and phonological literature is how to characterize various types of coronals. Therefore, the acoustic analysis of Punjabi coronals will contribute to our understanding how these sounds function phonologically.

Coronals have been a focus of study in many areas of phonetics. One such area is the analysis of length differences between coronal singletons and geminates (e.g., see Yeou, Honda, & Maeda (2011) who investigated coronal singletons and geminates in Figuig Berber). Indo-Aryan languages have rich consonantal length contrasts (Pandey, 2014). However, there are very few studies looking at the acoustic characteristics of singleton and geminate stops (including coronals) in Indo-Aryan languages. Some studies examined singleton and geminate stops in Bengali (Lahiri & Hankamer, 1988), Dogri (Ghai, 1980) and Hindi (Ohala, 2007) and found that geminate stops have longer closure duration than singleton stops. One of the goals of this dissertation is therefore to extend these findings to better understand the temporal characteristics of Punjabi singleton and geminate stops.

The phonetic and phonological behaviour of coronals is also of interest in another research domain - the adaptation of non-native segments (Chang, 2012; Kang, 2011; Paradis, 2006; Peperkamp, 2005). Many studies have reported that English source alveolar stops are

[2] In a cross-linguistic survey only 16 languages were reported to have a four-way coronal contrast (UPSID: Maddieson, 1984).

adapted as retroflexes into Indo-Aryan languages (Lahndi or Western Punjabi: Bahri, 1962; Punjabi: Ghotra, 2006; Hindi: Koshal, 1978; Ohala, 1978; Siraiki: Shackle, 1976; Pahari: Sharma, 1980). For instance, Ghotra (2006) and Sharma (1980) compiled a corpus of English loanwords adapted into Punjabi and Pahari. Their results showed that English loanwords with alveolar stops are adapted as retroflexes rather than as dentals (e.g., /ruʈ/ *'route'*). However, to date there have been no acoustic studies exploring why English alveolar stops are adapted as retroflexes into Punjabi and other Indo-Aryan languages.

In Chapter 2, I first present a brief overview of the phonological structure of Punjabi that provides the larger context for understanding the phonology of coronals and other features of Punjabi. Chapter 3 then investigates the temporal properties of Punjabi singleton and geminate stops, including coronals. Chapter 4 provides a detailed analysis of the acoustic cues differentiating Punjabi retroflex and dental stops. In Chapter 4, the main focus is on the retroflex and dental stops because studies of other languages have shown that these two consonants are difficult to perceive for both native (Wubuy: Bundgaard-Nielsen, Baker, Kroos, Harvey, & Best, 2015) and non-native speakers (perception of Hindi retroflex and dental stops by English and Japanese listeners: Pruitt, Jenkins, & Strange, 2006).[3] The detailed acoustic analysis of the Punjabi retroflex and dental stops then provides a baseline from which to understand why English alveolar stops are adapted into Punjabi as retroflexes rather than as dentals (Chapter 5).

[3] Palatals are not included in this chapter because they are acoustically and articulatorily quite different from other coronals (c.f. Anderson, 1997; Ladefoged, 2001; Park, 2007; Tabain, 2012; Shalev, Ladefoged, & Bhaskararao, 1993).

Acoustic characteristics of coronals

There is a significant body of literature on coronals in Indo-Aryan languages (Benguerel & Bhatia, 1980; Berkson, 2012; Dave, 1977; Dutta, 2007; Maxwell, Baker, Bundgaard-Nielsen, & Fletcher, 2015; Mikuteit, 2009; Mikuteit & Reetz, 2007; Ohala & Ohala, 2001). Several acoustic cues have also been proposed to differentiate coronals (e.g., formant transitions, VOT, closure duration, total stop duration (closure + VOT/burst) and spectral moments of stop release bursts). Among various acoustic cues, the lowering of F3 on the preceding vowel is considered as a landmark of retroflex articulations (Anderson, 2000; Dart & Nihalani, 1999; Dave, 1977; Flemming, 2003; Hamann, 2003; Hamilton, 1996; Maxwell et al., 2015; Ohala & Ohala, 2001; Scholtz, 2009; Spajic, Ladefoged, & Bhaskararao, 1996; Stevens & Blumstein, 1975).

Engstrand, Frid, and Lindblom (2007) compared the formant frequencies of preceding vowels in various rhotics and found that retroflex rhotics are characterized by the lowest F3 formants among all places of articulation. McGregor (1999) demonstrated that F3 is the most important distinguishing feature of the apico-postalveolars (or retroflexes) in the Aboriginal language Gooniyandi. Feizollahi (2009) examined the retroflex and dental laterals of Norwegian and found that retroflex laterals show much lower F3 in the preceding vowels than dental laterals. Narayanan, Byrd, and Kaun's (1999) study of Tamil liquids also showed that retroflex laterals have lower F3 formant values in the preceding vowel than dental laterals. Retroflex stops in Malayalam were also found to lower the F3 formants (Dart, 1991). All these studies confirm the importance of F3 lowering in the preceding vowels as a reliable acoustic correlate of retroflex articulations.

However, there are also several inconsistent reports regarding the phonetic characterization of retroflexes and dentals in the context of preceding front vowels. Ramasubramanian and Thosar's (1971) study examined the formant transitions of the retroflex and dental stops of Tamil before/after vowels /i a u/. Their spectrographic illustrations of the preceding /a u/ vowels indicated that transitions into retroflex and dental stops were characterized by F3-F2 convergence (Figure 1). However, F3 and F2 were lowered when produced in the context of preceding front vowel /i/, suggesting that there was no F3-F2 convergence. In terms of formant transitions of the following vowels, Ramasubramanian and Thosar (1971) observed that both retroflex and dental stops were characterized by F3 raising into all following vowels /i a u/ but F2 lowering into /a u/. The F2 transitions of the following front vowel /i/ were slightly raised for both retroflex and dental stops. As there are no statistical analyses provided by Ramasubramanian and Thosar (1971), it is not clear if transitions into or out of retroflex and dental stops consistently differentiate these consonants.

Ohala and Ohala (2001) investigated the formant transitions of various places of articulation in Hindi (labial, dental, retroflex, palatal and velar). They argued that retroflex stops produced after vowels /i a u/ were characterized by F3-F2 convergence. Dental stops, on the other hand, showed raised F3 and F2 after /a u/, but lowering of both formants after the front vowel /i/. Dave (1977) compared the formant transitions of vowels /i e a o u/ into and out of Gujarati retroflex and dental stops (Figure 2). His findings indicated that retroflex stops produced after /a o u/ showed F3-F2 convergence. However, no F3-F2 convergence was found after the front vowels /i e/. Dave (1977) also found lowering of F4 for the retroflex stops produced after /a o u/ but not after the front vowels /i e/. Maxwell et al. (2015) examined the formant transitions of the Bengali voiceless aspirated retroflex /ʈʰ/ and dental /t̪ʰ/. Their results indicated that retroflex stops produced after the front vowel /i/ did not show F3-F2 convergence. All these studies agree that F3-F2 convergence occurs after vowels /a o u/. The main inconsistency appears for the front vowels /i e/. I address these issues by examining second and third formant trajectories as cues to place oppositions for Punjabi retroflex and dental stops.

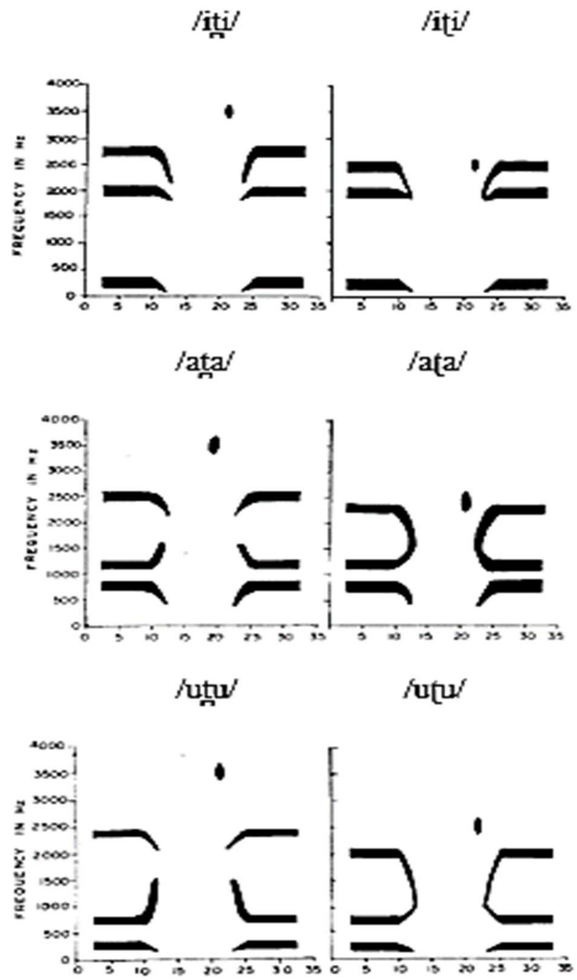

Figure 1. Tamil word-medial retroflex (right) and dental (left) stops across /i_i/, /a_a/ and /u_u/ vowels (Ramasubramanian & Thosar, 1971, pp. 83-84).

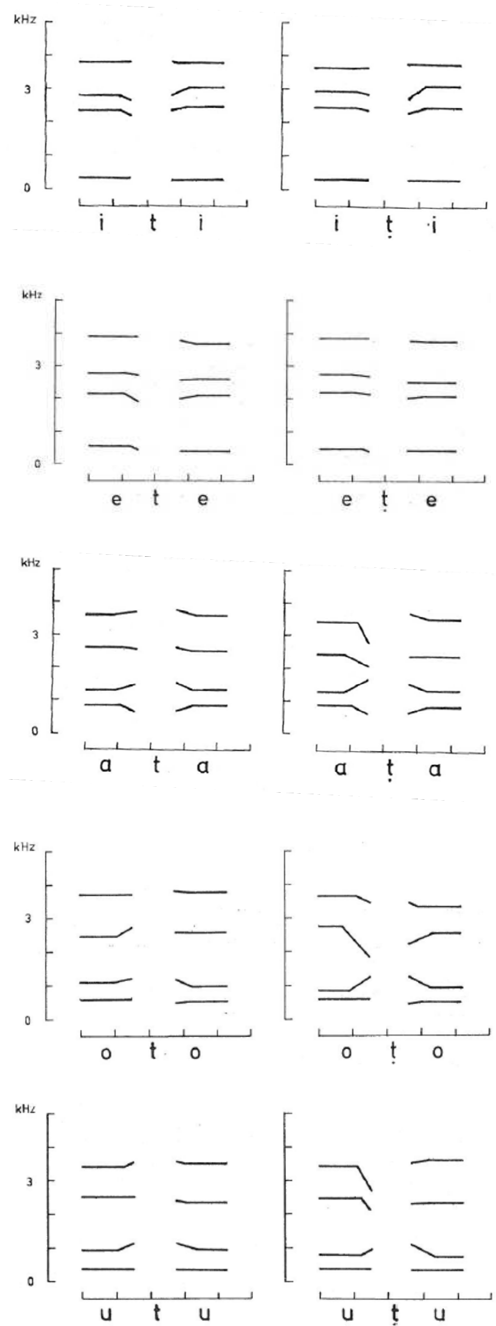

Figure 2. Schematic representations of the word-medial retroflex (right) and dental (left) stops of Gujarati across /i_i/, /e_e/, /a_a/, /o_o/ and /u_u/ vowels (Dave, 1977, pp. 99-104).

According to Hamann (2003), there are several languages where retroflexes pattern with the back vowels /o u/.[4] In Sinhala, retroflexes are produced as retroflexes in the context of preceding/following back vowels, but as alveolars elsewhere (Gair & Paolillo, 1997). This is due to the acoustic and articulatory similarities between back vowels and retroflexes. The tongue body during the production of back vowels and retroflexes is retracted.[5] The acoustic consequence of this retraction can be seen in the lowering of F3 in the preceding vowels (Hamann, 2003). Front vowels, unlike back vowels, can trigger de-retroflexion. This is evident from languages that disprefer retroflexes in the vicinity of front vowels. In Mandarin, retroflex fricatives do not occur before the front vowel /i/ (Duanmu, 2007; Lee-Kim, 2014). The co-occurrence restrictions between retroflexes and front/back vowels can also be explained by looking at the articulatory differences in oral cavity. The front vowel /i/ has the smallest front cavity, but it is longest for the back vowel /u/ (Sundberg & Lindblom, 1990). Similar to back vowel /u/, retroflex articulations involve a larger front cavity.

Some studies have also reported that retroflexes are more likely to be influenced by the surrounding vowel contexts than dentals. Dave (1977) conducted a static palataographic study on Gujarati coronals and found that retroflexes showed more variability across all vowels (i.e., fronted in the /i/ context, back in the /u/) but the articulation of the dental stops was in the dental area for all vocalic contexts. Unlike Dave (1977), Grainger's (1980) static palatographic study indicated more variation in Punjabi dental stops across the vowels /i a u/ but less variation in retroflex stops. The articulation of dental stops showed a lateral contact in the context of front vowel /i/ but a slight wipe-off in the alveolar region was observed for the back vowel /u/.

[4] Back vowels are also reported to trigger retroflexion (see Bhat, 1973).

[5] Tongue tip is also raised for retroflex articulations which results in a larger sublingual space. This has a lowering effect on F3 formant.

Retroflex stops, on the other hand, showed a wipe-off in the lateral direction for all vowels. From the above discussion, it can be concluded that there are considerable cross-linguistic differences in the acoustics and articulation of retroflexes.[6]

Locus equations (first proposed by Lindblom, 1963), have also been widely used as criteria for differentiating places of articulation (Brancazio & Fowler, 1998; Everett, 2008; Iskarous, Fowler, & Whalen, 2010; Martínez-Celdrán, Matas-Crespo, & Ortega-Escandell, 1999; Rhone & Jongman, 2012; Sussman, McCaffrey, & Matthews, 1991; Sussman & Shore, 1996; Tabain, 2002) and the coarticulation of stops in the context of preceding/following vowels (Bouferroum & Boudraa, 2015; Gibson & Ohde, 2007; Graetzer, Fletcher, & Hajek, 2015; Krull, 1988; Krull & Lindblom, 1996; Lindblom & Sussman, 2012; Modarresi, Sussman, Lindblom, & Burlingame, 2004; Yeou, 1997). However, within the class of coronals, no significant differences have been reported. Sussman, Hoemeke, and Ahmed (1993) demonstrated that the F2 locus equations of the retroflex and dental stops in Urdu are not statistically different from one another. This was further confirmed by a cross-linguistic study of the retroflex and dental stops of Swedish, Hindi and Tamil in the VC and CV contexts, which showed no statistically significant differences in the F2 locus equations of the retroflex and dental stops in all three languages (Krull & Lindblom, 1996). Tabain and Butcher (1999) also found that there are no clear patterns of locus equations among coronals.

Some studies postulated that the perceptibility of the coronal contrasts depends on the preceding and following transition cues (CV or VC). For example, Steriade (2008) conducted a cross-linguistic survey on the perceptual cues to coronals in different word-positions and found that retroflexes were better differentiated from other coronals in terms of VC transitions

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[6] See also Ladefoged and Bhaskararao (1983) for a detailed discussion about the differences in Indo-Aryan and Dravidian retroflexes.

compared to CV transitions. This claim is based on the Australian and a number of other languages that neutralize the coronal contrasts – apical alveolar vs. apical postalveolar or retroflex – in CV contexts, where there are no cues from a preceding vowel (Steriade, 2008; Hamilton, 1996). Steriade (2008) posits that these patterns derive from the absence of preceding transition cues, and that preceding transition cues are crucial for differentiating retroflexes from other coronals. Some European languages (e.g., Norwegian) allow retroflexes only in post-vocalic (VC) position (Johnsen, 2013). There are several perception studies as well confirming this general tendency of retroflexes to appear in VC contexts. A perceptual categorisation study of the coronal contrasts of Western Arrernte found that in a VCV context, the correct identification rate of retroflexes by native Arrernte speakers was 74%. However, this identification rate dropped significantly in a CV context (19%) (Anderson, 1997). As Arrernte does not contrast apicals in word-initial position, Anderson (1997) used CV stimuli excised from VCV stimuli. Bundgaard-Nielsen et al. (2015) found similar differences in perception of Wubuy coronals according to syllable position: Wubuy native speakers correctly discriminated retroflexes and dentals in intervocalic contexts (83%), dropping to 73% for word-initial consonants.

The perception of coronals is not only influenced by CV or VC cues, it might also be affected by different type of stimuli presented to the listeners (whole word, first half, second half or burst only) and vowel contexts (/i a u/). Krull (1990, p. 2561) tested the perception of Swedish voiced stops and concluded that the overall identification of retroflexes was difficult compared to other places of articulation. The correct identification rates of the retroflex stop in different conditions were 93.2% (whole word), 83.7% (first half), 92.7% (second half) and 69% (burst only). Ohala and Ohala (2001, p. 275) also conducted a perception experiment using the VC stimuli in whole word and gated (excluding the final burst) conditions with varying vowel contexts (/i a u/). The identification of the retroflex stops differed across gating conditions and vowels. In the /i/-gated condition, the retroflex stops were correctly identified in 36.5% of the cases. However, the identification increased in the /i/-whole condition (92.1%). In the /u/-gated condition, the correct identification rate of the retroflex stops was 66.7% but increased significantly in the /u/-whole condition with 95.2% correct identification. The highest correct identification of the retroflex stops was found in the /a/-gated (87.3%) and /a/-whole (95.2%) conditions. Ohala and Ohala (2001) concluded that the perception of retroflex stops in a VC context depends on different conditions (whole vs. gated) as well as on the nature of preceding vowels (/i a u/). A perception study of coronals is beyond the scope of this dissertation, but would be very interesting to pursue in further research.

Temporal cues (e.g., VOT/burst duration and closure duration) are also reported to differentiate coronals (Anderson & Maddieson, 1994). VOT has been widely used as a reliable descriptor of place oppositions (Abdiraman & Koffi, 2012; Helgason & Ringen, 2008; Kewley-Port & Preston, 1974; Li, 2013; Ogasawara, 2011; Riney, Takagi, Ota, & Uchida, 2007; Ringen & Suomi, 2012; Shimizu, 1989). Retroflexes are often characterized by shorter VOT compared to dentals (Arrernte: Tabain, 2012; Malayalam: Dart, 1991). Anderson and Maddieson (1994) reported that Tiwi word-medial postalveolars (or retroflexes) had the shortest VOT of all coronals. In Hindi, the mean VOT values of the voiceless unaspirated retroflex and dental stops were 8.5 ms and 13.1 ms, respectively (Sharma, Khan, & Farooq, 2014). Similarly, Marathi voiceless unaspirated retroflex stops (9.5 ms) were shorter in duration than dental stops (14.9 ms) (Karjigi & Rao, 2012). These patterns of VOT hold for geminate retroflex and dental stops as well. The VOT values of Malayalam retroflex geminate stops were shorter than geminate dental stops (retroflex: 15 ms; dental: 20) (Dart & Nihalani, 1999). VOT of stops also varies in different vowel contexts (Docherty, 1992; Morris, McCrea, & Herring, 2008; Nearey & Rochet, 1994; Smith, 1978). In Hindi, VOT of the voiceless unaspirated stops was longer in the context of intervocalic high vowels /i_i/ and /u_u/ compared to the low vowel /a_a/ (Ohala & Ohala, 1992). However, this pattern was consistent only for the velar and retroflex stops but not for dentals and labials.

Lisker and Abramson (1964) investigated VOT characteristics in a wide range of languages, including some Indo-Aryan languages. They compared the VOT values in utterance-initial and non-initial positions. The mean VOTs of Hindi and Marathi initial voiceless unaspirated retroflex and dental stops were 11 ms, showing no differences in VOT. However, in non-initial position, there were differences between both Hindi and Marathi voiceless unaspirated retroflex and dental stops (Hindi retroflex 8 ms vs. dental 14 ms; Marathi retroflex 3 ms vs. dental 15 ms). The data presented by Lisker and Abramson (1964) were based on one speaker of Hindi and Marathi. Therefore, the VOT values might differ if there are a large number of speakers.

Cho and Ladefoged (1999) argued that one of the factors contributing to the differences in VOT is "the extent of articulatory contact." Retroflexes have short VOT because their release involves tip of the tongue. The tongue tip is faster in velocity, compared to tongue body (Kuehn & Moll, 1976). Dentals are articulated with the tongue blade which results in a slower movement of the tongue and longer VOT (Ohala & Ohala, 1992).

Some studies report that retroflexes and dentals are not statistically different in terms of VOT (Hindi: Dutta, 2007). Hyslop (2009, 2011) recorded VOT data from two speakers of Kurtöp (a Tibeto-Burman language spoken in Bhutan). One of the speakers showed no differences in the VOT of voiceless unaspirated retroflex (22 ms) and dental (22 ms) stops.[7]

[7] Hyslop (2009) did not present statistical results comparing retroflex and dental stops but from the VOT values it can be assumed that both categories were not differentiated.

Another speaker had longer VOT for the retroflex (31 ms) than dental (26 ms) stops. Further studies with a larger number of speakers are desirable to better understand how VOT patterns in these languages.

Closure duration has also been found to significantly differ between retroflexes and other coronals. In Tiwi (Anderson & Maddieson, 1994) and Central Arrernte (Tabain, 2012), retroflexes were characterized by short closure duration. In terms of closure duration, Sindhi (an Indo-Aryan language) voiceless unaspirated retroflex stops were also smaller (185 ms) than dental stops (283 ms) (Keerio, 2010). There are several other languages showing inconsistent results in closure duration of retroflexes and dentals. In Bengali (Mikuteit, 2009; Mikuteit & Reetz, 2007) and Hindi (Benguerel & Bhatia, 1980; Dutta, 2007) there were no significant differences in closure duration of the retroflex and dental stops. These findings were also confirmed by Maxwell et al. (2015) where no differences in the closure duration of retroflexes and dentals were reported. The total stop duration (closure duration + VOT) also showed no difference. In Bengali real word productions, the total stop duration of the retroflex stops was longer than their dental counterparts (Maxwell et al., 2015). Dart and Nihalani (1999) also found similar patterns of closure duration in Malayalam. The retroflex geminate stop was 250 ms but dental geminate stop was only 165 ms long. Dart and Nihalani (1999) attributed these differences in closure duration to the duration of preceding vowels. Dental geminate stops were preceded by long vowels. In contrast, retroflex geminate stops were preceded by short vowels. These length differences in the preceding vowels affected the closure duration of the Malayalam geminate retroflex and dental stops. The above-mentioned varying and inconsistent results regarding the temporal properties of retroflexes and dentals call for a systematic investigation in another language that has similar coronal contrasts. Moreover, previous studies are based on the data from limited contexts (predominantly word-medially). In this dissertation, I therefore provide a detailed account of temporal properties (VOT/burst duration, closure duration, total stop duration (closure + VOT/burst) of the Punjabi retroflex and dental stops in different word-positions and vowel contexts.

In addition to spectral (formant transitions) and temporal analyses (VOT or burst duration, closure duration and total stop duration), spectral moments (spectral Centre of Gravity (CoG), spectral variance, spectral skewness, spectral kurtosis) have also been widely used to classify different places of articulation, for both fricatives (Al-Khairy, 2005; Forrest, Weismer, Milenkovic, & Dougall, 1988; Gordon & Applebaum, 2006; Gordon, Barthmaier, & Sands, 2002; Jones & Nolan, 2007; Jongman, Wayland, & Wong, 2000; Zygis, Pape, & Jesus, 2012) and stops (Eshghi, Zajac, Bijankhan, & Shirazi, 2013; Kirkham, 2011; Nissen, 2003; Nissen & Fox, 2009; Recasens, 2014; Stoel-Gammon, Williams, & Buder, 1994; Sundara, 2005; Sundara & Polka, 2007; Tabain, 2012).

Spectral moments are correlated with different articulatory configurations of the vocal tract. They therefore provide important information about the length of the oral cavity in the production of consonants (Li, Edwards, & Beckman, 2007, 2009). The first spectral moment (or spectral CoG (Hz)) indicates mean distribution of acoustic energy in the burst spectrum and correlates with the length of the front cavity. The second spectral moment (spectral variance (Hz)) corresponds to the distribution of acoustic energy on both sides of the mean (Li et al., 2009). The third spectral moment (spectral skewness) indicates whether the acoustic energy in the burst spectrum is skewed towards higher (positive skewness) or lower energies (negative skewness) and is correlated with the length of the front cavity (Li et al., 2009). The fourth spectral moment (spectral kurtosis) is a measure of ‘peakiness’ in the spectral envelope of the stop release burst. Retroflexes show peak spectrum and energy distribution around 3000 KHz, whereas dentals have flat or diffused spectra and burst energy distributed in higher frequency bands, around 4000 KHz (Stevens & Blumstein, 1975). Within the class of coronals, dentals and palatals show higher spectral CoG, spectral variance, and negative spectral skewness and spectral kurtosis (coronal stops: Tabain, 2012; fricatives: Gordon et al., 2002). Retroflexes have larger sublingual space, which results in lower spectral CoG, spectral variance, and positive spectral skewness and spectral kurtosis (Tabain, Butcher, Breen, & Beare, 2014). The spectral moments associated with a particular stop also differ across all vowel contexts (Nissen, 2003). In Mandarin, spectral CoG of the retroflex fricatives is significantly different across vowels /i a u/ (higher in the /i a/ than /u/: Y.-H. Chang, 2012). In the context of back vowel /u/, the constriction location is further back in the oral tract, which results in a very low spectral CoG values. Currently, there are no data available on the spectral moments of coronals in Indo-Aryan languages. Therefore, this dissertation also provides a detailed analysis of Punjabi retroflex and dental stops using spectral moments.

All the acoustic characteristics reported in this section might also be important for understanding the processes of loanword adaptation. Possible reasons for why Indo-Aryan languages adapt English alveolar stops as retroflexes rather than as dentals will also be investigated.

Loanword adaptation

Loanword adaptation is central to understanding the phonology of languages (LaCharité & Paradis, 2005). There are two approaches to loanword adaptations. The phonological view suggests that loanword adaptations are driven by the phonological grammar of the native language **(**e.g., phonotactic constraints and contrastive feature specifications) (Jacobs & Gussenhoven, 2000; LaCharité & Paradis, 2005; Paradis, 2006; Paradis & LaCharité, 1997). For instance, in Japanese, a language that does not allow complex clusters, English loanwords with complex onset or coda clusters are simplified through a process of vowel epenthesis ([desɯkɯ] ‘*desk’*) (see Paradis & LaCharité, 2011). Many other languages show similar processes of epenthesis during loanword adaptation (e.g., Italian: Repetti, 2012; Sesotho: Rose & Demuth, 2006).[8] According to the phonological view, loanword adaptations can also reveal the hidden knowledge of a native speaker's phonological grammar that is not apparent in surface level structures, and provides information about the underlying phonology when there is a clash between the source phonology and the borrowing language phonology (see Kang, 2011).

Others note the importance of perceptual contributions and suggest that loanword adaptation takes place at the level of perception (Boersma & Hamann, 2008; De Jong & Cho, 2012; Dupoux, 2003; Peperkamp, 2005, 2015; Peperkamp, Vendelin, & Nakamura, 2008). Both psycholinguistic and electrophysiological studies have demonstrated that Japanese listeners ‘hear’ epenthesis when given a nonsense word like [ebzo], interpreting it as [ebɯzo] (Dehaene-Lambertz, Dupoux, & Gout, 2000; Dupoux, Kakehi, Hirose, Pallier, & Mehler, 1999; Peperkamp, 2005). The perceptual view of loanword adaptation also suggests that loanword adaptation can sometimes create novel phonological structures that are neither reflected in the native language nor in source language. For example, in Korean native phonology, /s/ in coda position is realized as [t], but during the adaptation of English loanwords into Korean it undergoes epenthesis ([posɨ̱] ‘*boss’*; Kenstowicz & Sohn, 2001). This suggests that native and loanword phonology involve different processes.

Some studies support both perceptual and phonological approaches of loanword adaptation (Chang, 2012). Silverman (1992) argues that there are two levels of representations (Figure 3): a) the Perceptual level; and b) the Operative level.

[8] See also Uffmann (2007) for a cross-linguistic survey of epenthesis during loanword adaptation.

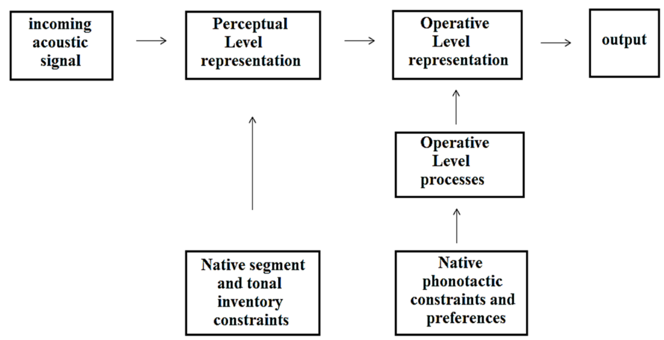

Figure 3. Model of loanword phonology (Silverman, 1992, p. 293).

At the Perceptual level, the constraints of the native segmental and tonal inventories are activated (perceptual approach). These segmental constraints are further shaped at the Operative level by the native phonotactic constraints (phonological approach). In loanword phonology, both levels play a significant role to shape an output form. Yip (1993) accepts Silverman’s two-level representations and argues that the phonological approach alone is conservative.

Rose and Demuth (2006) suggest that some of the controversy may be due to the use of different methodologies. Researchers favouring the perceptual approach tend to conduct experiments with monolingual speakers; researchers proposing the phonological approach tend to work with bilingual speakers. There are also various factors that can influence the way a loanword is adapted, for instance, the transmission of loanwords via different sources (i.e., the adaptation of English loanwords into Korean via Japanese; Kang, Kenstowicz, & Ito, 2008; see also Poplack & Sankoff, 1984; Poplack, Sankoff, & Miller, 1988) the degree of bilingualism (Lev-Ari, Giacomo, & Peperkamp, 2014), different phonological contexts (e.g., coronals in different vowel contexts; Crawford, 2008, 2009) and orthography (Vendelin & Peperkamp, 2007).

McCarthy, Evans, and Mahon (2013) tested monolingual and bilingual speakers in an immigrant community in the UK and found significant differences in the production of English stops. In their study, they focused on Sylheti, an indigenous language of Bangladesh that contrasts retroflexes and dentals (Gope & Mahanta, 2015). McCarthy et al. (2013) found that Sylheti speakers who had recently arrived in the UK had L1 phonetic cues in the production of L2 English labial /p b/, alveolar /t d/ and velar /k ɡ/ stops. However, those Sylheti speakers who were born in the UK, and had grown up there bilingually, had different realizations of the same consonants, producing English stops like native English speakers. This raises interesting questions about how loanwords are adapted in a non-immigrant situation. For example, in Pakistan, Punjabi speakers, whether they are monolinguals or trilinguals, predominantly speak Punjabi at home. The trilinguals speak Urdu with their friends. Urdu has a similar set of coronal contrasts as that found in Punjabi. English, on the other hand, has only alveolar stops, and has a limited role in the day to day life of Punjabi speakers. Therefore, Punjabi speakers, in speaking Punjabi, are less likely to be influenced by English phonetics/phonology. Keeping this in mind, we also examined whether bilingualism had an affect on the acoustic cues of English loanwords produced in a non-immigrant situation (i.e., Pakistan).

Aims of this dissertation

To date there has been no detailed investigation of the acoustic cues of coronals in Indo-Aryan languages across word-positions (word-medial, word-initial and word-final) and vowel (/i e a u o/) contexts. The aim of this dissertation is therefore to investigate the phonetic properties of the Punjabi retroflex and dental stops across word-positions and before/after vowels /i e a o u/, using temporal and spectral measures. Temporal characteristics of the Punjabi word-medial singleton and geminate stops are also investigated, showing that durational contrasts are important to understand stop oppositions. At the end, we then apply these insights to better understand the nature of loanword adaptation, showing how English alveolar /t/ produced by native English speakers and Punjabi speakers aligned with Punjabi retroflex and dental categories. This dissertation addresses the following research questions:

a. What is the phonology of coronals and other features of the Punjabi language (Chapter 2)?
b. What are the temporal characteristics of Punjabi word-medial singleton and geminate stops (Chapter 3)?
c. Which acoustic cues differentiate the contrast between Punjabi retroflex and dental stops in word-medial, word-initial and word-final positions, across all vowel contexts /i e a o u/ (Chapter 4)?
d. How do the temporal and spectral differences between Punjabi retroflex and dental stops help explain the adaptation of (Australian) English alveolar /t/ as a retroflex rather than a dental in Punjabi (Chapter 5)?

The remainder of this dissertation is organized as follows:

There are several detailed phonological descriptions of Punjabi (Arun, 1962; Bailey, 1914; Bhatia, 1993; Campbell, 1981; Dulai, 1989; Dulai & Koul, 1980; Gill & Gleason, 1962; Jain, 1934; Malik, 1995; Singh, 1971 among others). However, these descriptions are based primarily on impressionistic transcriptions. Currently, there is no illustration of the IPA for Punjabi. Chapter 2 therefore provides an overview of the phonological structure of Punjabi. This illustration will be helpful for linguists and students interested in working on the Punjabi language.

Chapter 3 investigates the temporal differences in Punjabi word-medial singleton and geminate stops in a $C_1V_1C_2V_2$ template. The main aim of this study is to examine how the duration of C_1, V_1 and V_2 vary depending on the duration of C_2 that is either a singleton or a geminate. Given previous findings from Hindi singletons and geminates (Ohala, 2007), we predicted that the duration of C_1 in a $C_1V_1C_2V_2$ template would differ significantly, depending on the durational properties of C_2 (singleton or geminate). It was also predicted that C_2 would be longer in geminates but shorter in singletons. Similarly, we expected that the duration of the preceding (V_1) and following (V_2) vowels would be shorter in geminates, but longer in singletons. The findings indicated that C_2 and V_2 durations are the most reliable acoustic cues distinguishing Punjabi singleton from geminate stops. C_1 and V_1 durations did not differ significantly for both singleton and geminate stops.

Chapter 4 focusses on the temporal and spectral characteristics of the Punjabi word-medial, word-initial and word-final retroflex and dental stops, before/after vowels /i e a o u/ (word-final stops were only investigated in the context of /i a u/). In particular, we consider the implications of Ohala and Ohala's (2001) claim that Hindi retroflex stops show F3-F2 convergence across all vowels /i a u/. In contrast, Dave (1977) argued that there is no F3-F2 convergence in the front vowels /i e/ for Gujarati retroflexes. This raises questions whether Punjabi retroflex stops show F3-F2 convergence in the front vowels /i e/. The goal of this paper is to explore the acoustic properties which characterize a rich coronal system, by examining in a new detail the spectral and temporal properties of Punjabi retroflex and dental stops. In particular, we sought to understand whether Punjabi retroflexes show F3-F2 convergence in the context of a preceding /i/ vowel, and how the acoustic properties of stop release bursts vary across all vowel and word-positions. The contrast between Punjabi retroflex and dental stops is investigated in both the maximally informative phonetic environment (word-medial position) and the less informative phonetic contexts (word-initial and word-final positions). The results suggested that Punjabi coronal place contrasts are signaled by the complex interaction of temporal and spectral cues. VOT and total stop duration consistently differentiated Punjabi word-medial, word-initial and word-final retroflex and dental stops across all vowels. The F3-F2 difference and spectral moments of stop release bursts failed to characterize both stops in various vocalic environments. However, spectral variance was a reliable cue in all but a few environments.

Having established that the temporal characteristics are the most reliable cues to the distinction between Punjabi retroflex and dental stops, Chapter 5 then extends these insights to better understand the adaptation of English word-final alveolar stops as retroflexes. To do this, we compared the acoustics of native English alveolar /t/ (produced by Australian English speakers) and adapted loanword /t/ (such as *'boot'*) with native Punjabi word-final retroflex and dental stops. To ensure that being bilingual would not be a factor, we tested two groups of speakers: Punjabi monolinguals (who only knew Punjabi) and trilinguals (who spoke Punjabi, Urdu and English). The Punjabi monolingual speakers were non-literate. Since this population could not read Punjabi, we used English loanwords that could be easily pictured to the monolingual group. Most of the high frequency picturable words that could be found in the corpus (Ghotra, 2006) across the three point vowel contexts had final /t/. We thus focussed on the adaptation of word-final /t/. It was hypothesized that Australian English (AusE) /t/ and loanword /t/ would be acoustically more similar to the native retroflex than dental stops. Given that Punjabi monolinguals and trilinguals have extensive exposure to Punjabi and Urdu (rather than English), we predicted that there would be no differences between monolingual and trilingual Punjabi speakers in the production of English loanwords. The findings suggested that the temporal and spectral characteristics of loanword /t/ are closer to Punjabi retroflex than dental stops. However, acoustic similarities between AusE /t/ and Punjabi retroflex stop were less clear.

Chapter 6 discusses the major findings and compares the data of this dissertation with other languages that possess the retroflex and dental contrast. The implications, limitations, and possible future research directions are then presented. The results of this dissertation will help inform various phonetic and phonological processes underlying coronal contrasts in the native and loanword phonologies of Indo-Aryan languages. Moreover, detailed phonetic analyses across all word-positions and vocalic contexts will help to address some of the inconsistencies in the current literature on the phonetics of coronals. This dissertation will thus provide a baseline for other phonetic studies on the typology of coronal contrasts in Australian, Indo-Aryan and Dravidian languages, and will raise many issues for further research regarding the loanword incorporation of coronals.

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Chapter 2: Punjabi (Lyallpuri variety): Illustrations of the IPA

This chapter is based on the following paper which is currently under review:

Hussain, Q., Harvey, M., Proctor, M., & Demuth, K. (revision submitted). Punjabi: illustration of the IPA. *Journal of the International Phonetic Association.*

Punjabi (Western, ISO-639-3 pnb (Lyallpuri (لایلپوری) variety)) is an Indo-Aryan language (Indo-European, Indo-Iranian) spoken in Pakistan and India, with a large number of immigrant speakers residing in the UK, Canada and America (Gill & Gleason 1962). In terms of number of speakers, it is ranked 10th among the world's languages (Lewis, Simons & Fennig 2016). The phonology of Punjabi is notable for rich coronal contrasts, geminate consonant contrasts, and the development of three contrastive tones. Aspects of the phonology of different varieties of Punjabi have been described in Arun (1961), Bhatia (1993), Dulai & Koul (1980), Gill & Gleason (1962), Jain (1934), Malik (1995) and Singh (1971).[9]

The lexicon of Punjabi includes loanwords from Arabic, English, Hindi-Urdu, Persian, Sanskrit and Turkish. The word *Punjabi* itself is a combination of two Persian words, /pəɲʤ/ پَنج'five' and /ab/ آب 'water', which literally means *the land of five rivers* (Shackle 2003). Punjabi is written in two different scripts: Gurmukhi (mainly used in India), and Shahmukhi, a modified Perso-Arabic script frequently employed by Punjabi speakers in Pakistan. The many dialects of Punjabi are broadly classified into two groups: Eastern and Western (also known as Lahnda or Lahndi).[10] The Eastern dialects are primarily spoken in the Indian state of Punjab, whereas the Western dialects cover the area of Punjab, Pakistan (Singh 1971); however, the distribution of speakers and varieties is more complicated (Shackle 1979). In 1947, during the partition of India and Pakistan, a large number of Punjabi speakers migrated from India to Pakistan and settled around Lahore, Sialkot, Sahiwal, Faisalabad and Gujranwala. Similarly, Punjabi speakers from the Punjab state of Pakistan moved to India. The current illustration is

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[9] For brief grammatical descriptions, see also Bahl (1969), Bailey (1914), Bailey & Cummings (1912), Campbell (1981), Carey (1812), Clivio (1966), Dulai (1989), Shackle (2003), Tisdall (1961) and Vatuk (1964).

[10] The classification of Punjabi into Eastern and Western dialects is still controversial. Readers are referred to Gill & Gleason (1962), Grierson (1916) and Shackle (1979) for a detailed discussion.

based on the speech of a native Punjabi speaker from Faisalabad (Punjab province), Pakistan.[11] This illustration describes a variety of Punjabi spoken in Faisalabad, known as Lyallpuri (originally from the old name of the city: Lyallpur; Campbell 1981; Gill & Gleason 1962). In addition to Lyallpuri, some people in the rural areas of Faisalabad speak Jangli, which is a distinct variety of Punjabi. Jangli speakers can also be found in other rural areas all across Punjab, Pakistan. One of the most distinctive features of Jangli is its retention of voiced aspirates.

In the Punjabi dialect chain, Lyallpuri is surrounded by the Majhi dialect in the North-East, and Lahndi (spoken in Multan and surrounding areas, now known as Siraiki) in the South-West (Gill & Gleason 1962). Lyallpuri shares a number of features with the Standard Majhi dialect, in particular a three-way laryngeal contrast (e.g. /p p^h b/).[12] On the other hand, Lyallpuri differs from Siraiki in terms of laryngeal contrast. Unlike Lyallpuri, Siraiki has a five-way laryngeal contrast (e.g., /p p^h b $b^ɦ$ ɓ/; Shackle 2003).[13] Figure 1 shows a map of Pakistan, with the city of Faisalabad where the Lyallpuri variety is spoken. The borderline between India and Pakistan (indicated with an arrow) shows the current division of Punjabi into Eastern and Western dialects.

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[11] The first author of this illustration.

[12] Detailed quantitative comparative studies of Lyallpuri and Lahore Majhi are needed to explore the differences and similarities in two varieties.

[13] Western dialects of Punjabi (Pakistan) can be categorized according to their laryngeal contrasts: three-way (Lyallpuri and Lahore Majhi: /p p^h b/); four-way (Jangli and Awankari: /p p^h b $b^ɦ$/ (Bahri 1962)); and five-way (Siraiki: /p p^h b $b^ɦ$ ɓ/ (Shackle 2003)). It should be noted that Siraiki is now considered a separate language (Shackle 1977).

Figure 1 (Colour online) Map of Pakistan.[14]

Consonants

	Labial	Dental	Alveolar	Retroflex	Palatal	Velar	Glottal
Plosive	p pʰ b	t̪ t̪ʰ d̪		ʈ ʈʰ ɖ	ʧ ʧʰ ʤ	k kʰ g	
Fricative	(f) (v)		s (z)		ʃ	(x) (ɣ)	h
Nasal	m		n	ɳ			
Lateral			l	ɭ			
Tap			r				
Flap				ɽ			
Approximant	ʋ				j		

[14] The World Factbook (Central Intelligence Agency (CIA), USA).

	Initial			Medial			Final		
p	par	پار	cross	ʧʰapa	چھاپا	raid	nap	ناپ	measurement
pʰ	pʰaɽ	پھاڑ	torn	nepʰa	نیپھا	waistband	pàpʰ	بھاپھ	steam
b	bar	بار	outside	baba	بابا	an old man	d̪ab	داب	bury
t̪	t̪al	تال	beat (n.)	kʰat̪a	کھاتا	ledger	bat̪	بات	talk
t̪ʰ	t̪ʰal	تھال	platter	hat̪ʰi	ہاتھی	elephant	sat̪ʰ	ساتھ	companionship
d̪	d̪al	دال	lentil	sad̪a	سادہ	simple	jad̪	یاد	remember
ʈ	ʈal	ٹال	stop	gaʈa	گاٹا	neck	ʧaʈ	چاٹ	fruit dish
ʈʰ	ʈʰər	ٹھر	cold	maʈʰa	ماٹھا	weak	baʈʰ	باٹھ	sixty-two
ɖ	ɖak	ڈاک	mail	saɖa	ساڈا	ours	laɖ	لاڈ	love
k	kal	کال	call	ɖaka	ڈاکا	robbery	pak	پاک	clean
kʰ	kʰad̪	کھاد	fertilizer	dakʰã	داکھاں	raisings (plu.)	rəkʰ	رَکھ	put
g	gal	گال	abuse	bagã	باگاں	garden (plu.)	sag	ساگ	name of a dish
ʧ	ʧal	چال	gait	gaʧa	گاچا	fodder	bəʧ	بَچ	save
ʧʰ	ʧʰal	چھال	jump	ʋəʧʰa	وَچھا	spread	kəʧʰ	کَچھ	armpit
ʤ	ʤal	جال	net	baʤa	باجا	tuba	kaʤ	کاج	buttonhole
s	sal	سال	year	masa	ماسا	little	mas	ماس	skin
ʃ	ʃal	شال	shawl	maʃa	ماشا	subunit of gram	laʃ	لاش	corpse
h	hal	حال	condition	-		-	-		-
m	mal	مال	stock	mama	ماما	maternal uncle	nam	نام	name
n	nal	نال	with	dana	دانا	bird food	pan	پان	betel leaf
ɳ	-		-	kaɳa	کانا	one-eyed	maɳ	مان	trust
l	lal	لال	red	ʤala	جالا	cobweb	pal	پال	raise
ɭ	-		-	paɭa	پالا	cold	məɭ	مَل	rub
r	rag	راگ	song	sara	سارا	a female name	ʧar	چار	four
ɽ	-		-	saɽa	ساڑا	jealousy	saɽ	ساڑ	burnt
ʋ	ʋaɽ	واڑ	push	paʋa	پاوا	cot leg	-		-
j	jar	یار	friend	maja	مایا	starch	-		-

*Lyallpuri has three tones: high (´), mid (¯) and low (`). Only high and low tones are marked in the wordlist.

The list of words presented above is based on the minimal or near minimal pairs of the Lyallpuri consonantal contrasts in word-initial, word-medial and word-final positions. There are a total 32 consonants, including 5 fricatives (in parentheses) that are only found in loanwords from Persian, Arabic and Urdu.

Obstruents

Lyallpuri has a three-way laryngeal contrast in plosives (e.g., voiceless unaspirated /p/, voiceless aspirated /pʰ/ and voiced unaspirated /b/) at five places of articulation (labial, dental, retroflex, palatal and velar). Plosives are contrastive in all word-positions. The contrast between voiced unaspirated and voiced aspirated plosives was lost in Lyallpuri (for more details, see the section on stress and tones). Other varieties of Punjabi (e.g., Jangli and Siraiki) still preserve the four or five-way laryngeal contrast (Shackle 2003). Figure 2 shows the waveforms and spectrograms of the three-way laryngeal contrast of labial plosives.

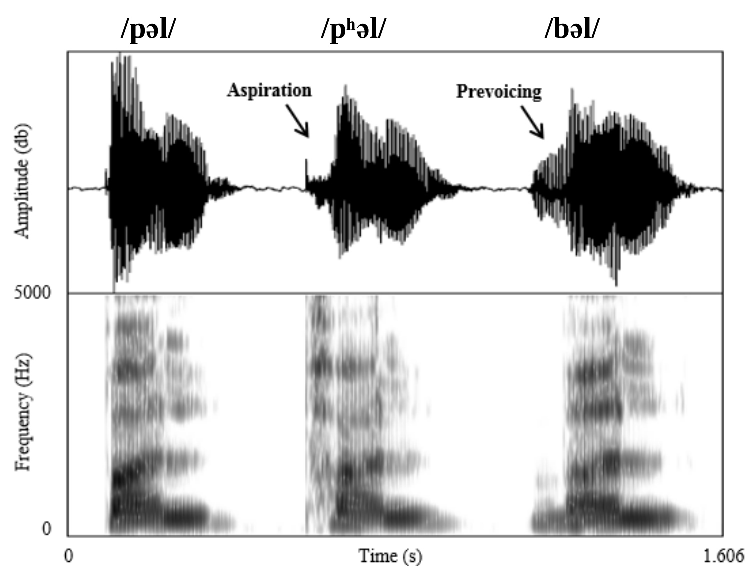


Figure 2 Waveforms and spectrograms of /pəl/ پَل ‘moment’ (left), /pʰəl/ پَھل ‘fruit’ (middle), and /bəl/ بَل ‘curl’ (right), respectively. The arrows indicate aspiration in voiceless aspirated /pʰ/ and prevoicing in voiced /b/.

There is a three-way coronal contrast in plosives (e.g., /t̪ ʈ ʧ/). The category of *palatals* is described as 'palatals' (Arun 1961; Bhatia 1993) or 'palatoalveolars' (Dulai & Koul 1980). These sounds belong to the broader category of *coronals* (see Arsenault 2008 for a detailed discussion about coronals in Indo-Aryan languages). The most important acoustic cue distinguishing Lyallpuri coronals is VOT. Retroflexes in Lyallpuri have the shortest VOT, followed by dentals and then by palatals (palatals have the longest VOT: Hussain, Harvey, Proctor & Demuth 2015). Figure 3 illustrates the three-way VOT contrast of Lyallpuri.

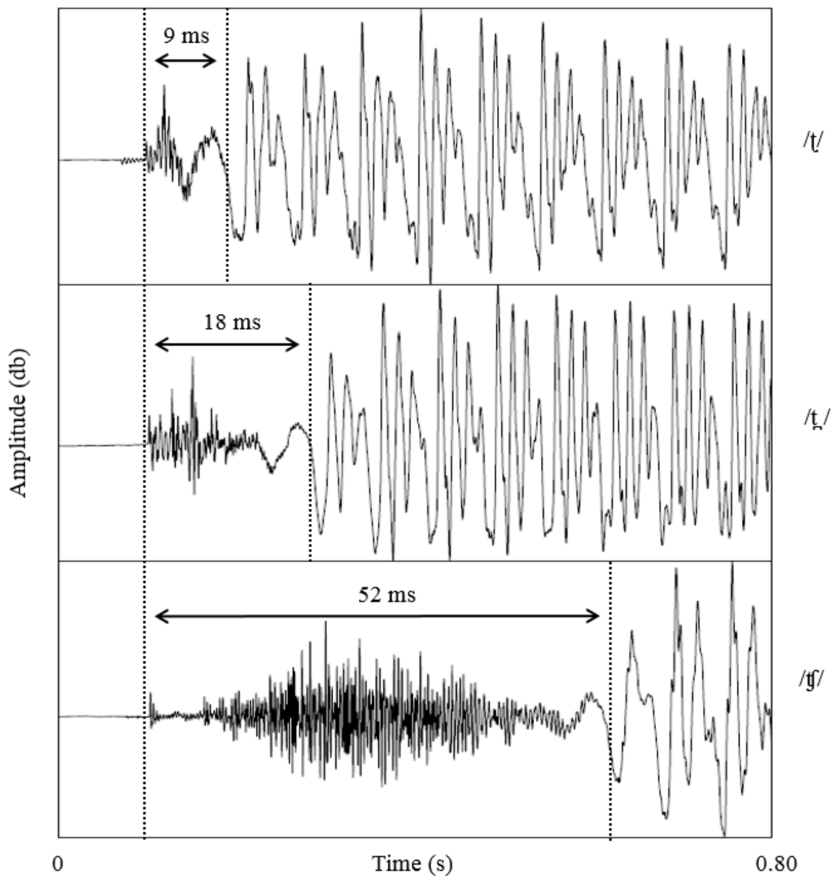


Figure 3 VOT (ms) of Punjabi voiceless unaspirated retroflex /ʈal/ ٹال 'stop', voiceless unaspirated dental /t̪al/ تال 'beat (n.)' and voiceless unaspirated palatal /ʧal/ چال 'gait'.

The fricatives /s/ and /ʃ/ are also contrastive in word-initial, medial and final positions. /h/ can occur word-initially but not word-medially and finally. The contrast among three fricatives /s ʃ h/ in word-initial position is illustrated in Figure 4.

Labial and velar fricatives (represented in parentheses in the consonant table) are only found in loanwords from Persian, Arabic, Urdu, and in the speech of literate Lyallpuri speakers (e.g., /zərurət/ ضَرورت 'need', /ɣar/ غار 'cave'). Non-literate speakers produce /z/ and /ɣ/ as /ʤ/ and /g/ (see Sharma 1971).

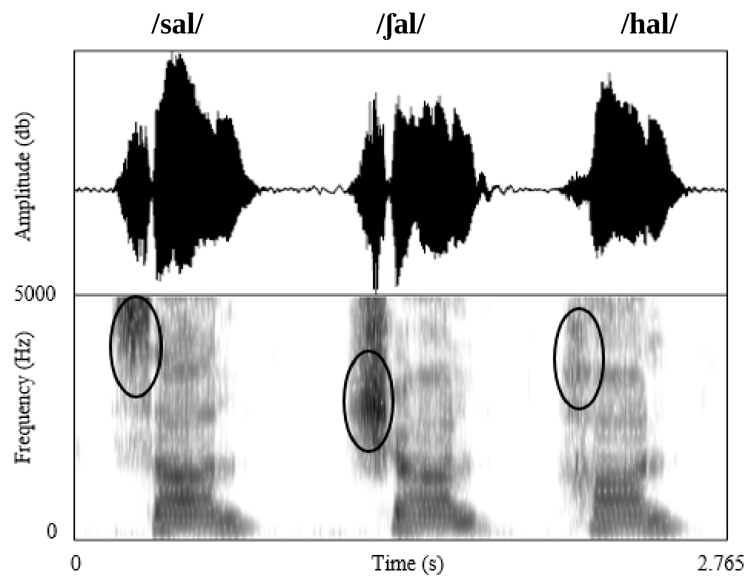


Figure 4 Waveforms and spectrograms of /sal/ سال 'year' (left), /ʃal/ شال 'shawl' (middle) and /hal/ حال 'condition' (right). The black circles indicate the concentration of acoustic energy in higher or lower frequencies.

Nasals

Lyallpuri contrasts nasals at three places of articulation: labial /m/, dental /n/ and retroflex /ɳ/. The first two can occur in all word positions, whereas retroflex /ɳ/ only occurs word-medially and finally. Palatal and velar nasals occur as allophones of /n/ and are found in homorganic clusters with palatal and velar stops (see the section on consonant clusters).

Liquids (laterals, tap and flap)

There is a four-way liquid contrast in Lyallpuri: /r/, /l/, /ɽ/ and /ɭ/, but only /r/ and /l/ can occur in all word positions. Thus, retroflex flap /ɽ/ and lateral /ɭ/ contrast with alveolar /r/ and /l/ word-medially and finally. The contrast between alveolar lateral /l/ and retroflex lateral /ɭ/ is neutralized in some dialects of Punjabi (Bhatia 1993). Figure 5 presents representative examples of alveolar tap /r/ and retroflex flap /ɽ/.

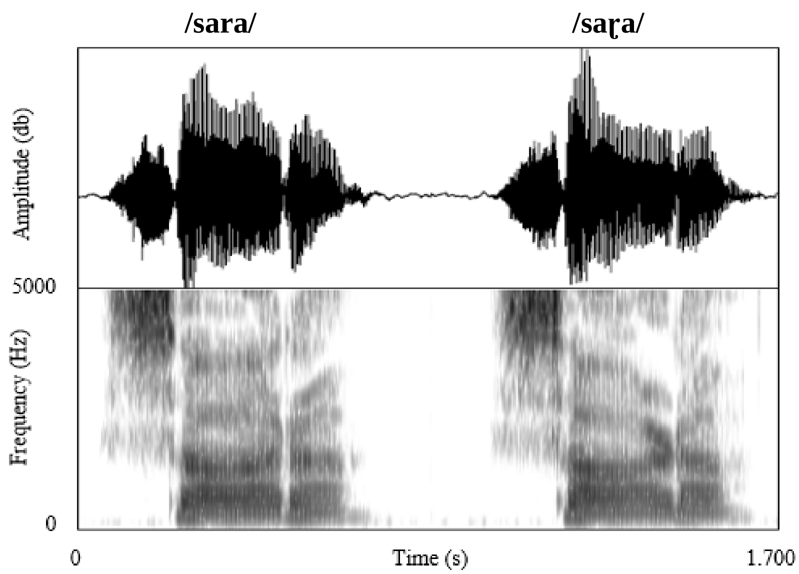


Figure 5 Waveforms and spectrograms of /sara/ سارا 'a female name' (left) and /saɽa/ ساڑا 'jealousy' (right).

Approximants

The labial approximant /ʋ/ and palatal /j/ are contrastive word-initially and medially. Urdu loanwords with word-initial /b/ (/bal/ بال 'hair') are sometimes produced as /ʋal/ or /val/ وال in Lyallpuri. This kind of variation only occurs in loanwords and is restricted to word-initial position.

Consonant clusters

Lyallpuri has a small set of consonant clusters. Word-initial clusters are rarely found; medial and final clusters are of limited types and there is much inter/intra-speaker variation in simplification of clusters.

Plosives can occur as the first or second member of the heterorganic word-medial clusters. If the first consonant is a plosive, the second consonant can be a plosive, liquid or nasal. The first member of the word-medial consonant clusters belongs to the first syllable and the second one to the second syllable. Some representative examples of the heterorganic word-medial clusters are presented in (1a-e).[15]

(1) Heterorganic word-medial clusters

(a) Plosives + plosives

/nək.d̪i/ نقدی cash

/bəʧ.d̪a/ بچدا escape

(b) Plosives + liquids

/nok.ri/ نوکری job

/pəd̪.ra/ پدرا level

(c) Plosives + nasals

/ʧʊk.na/ چُکنا lift

/bəd̪.nam/ بَدنام notorious

(d) Nasals + plosives

/ʧɪm.ʈa/ چِمٹا tong

/ʧəm.ʧa/ چَمچا spoon

---

[15] Readers are referred to Arun (1961), Gill & Gleason (1962) and Malik (1995) for a detailed discussion about the types of clusters.

(e) Fricatives + plosives

/ʧəs.ka/ چَسکا addicted

/kəʃ.t̪i/ کَشتی boat

Homorganic word-medial clusters are also permitted in Lyallpuri. The most commonly found homorganic clusters include nasals + plosives, and also laterals + plosives, as shown in (2a-b):

(2) Homorganic word-medial clusters

(a) Nasals + plosives

/gən.d̪a/ گندا dirty

/gəɳ.ɖa/ گنڈا onion

/məɲ.ʤa/ مَنجا cot

/kəŋ.ga/ کَنگا comb

/kʰəm.ba/ کھَمبا pole

(b) Laterals + plosives

/gəl.t̪i/ غَلطی fault

/ʤəl.d̪i/ جَلدی quickly

/həl.d̪i/ ہَلدی turmeric

Word-final clusters are not widespread in Lyallpuri, however, literate Lyallpuri speakers preserve word-final consonant clusters that are found in Persian, Urdu and Arabic loanwords. Monolingual Lyallpuri speakers and older generation speakers frequently epenthesize to break up clusters. The following types of word-final clusters are permitted in Lyallpuri (3a-b):[16]

(3) Word-final clusters

(a) Fricatives + plosives

/sʊst̪/ سُست lazy

[16] See Malik (1995) for a detailed list.

/gəʃt̪/	گشت	wander around

(b) Liquids + plosives

/mərd̪/	مَرد	man
/mɪrʧ/	مِرچ	pepper

Geminates

	Singleton			Geminate		
p	/ʈəpa/	ٹَپا	jump	/ʈəp:a/	ٹپّا	traditional song
b	/ləba/	لَبا	find	/ləb:a/	لَبّا	found
t̪	/pət̪a/	پَتا	address	/pət̪:a/	پَتّا	leaf
d̪	/səd̪i/	صَدی	century	/səd̪:i/	صَدّی	called (fem.)
ʈ	/kəʈa/	کَٹا	cut	/kəʈ:a/	کَٹّا	buffalo’s calf
ɖ	/ʋəɖa/	وَڈا	harvesting	/ʋəɖ:a/	وَڈّا	big
k	/ʧəka/	چَکا	carry	/ʧək:a/	چَکاّ	bicycle rim
kʰ	/pəkʰa/	پَکا	burn	/pəkʰ:a/	پَکاّ	fan
g	/ʤəga/	جَگا	wake up	/ʤəg:a/	جَگاّ	a nick name
ʧ	/bəʧa/	بَچا	save	/bəʧ:a/	بَچّہ	child
ʧʰ	/ʋəʧʰa/	وَچھا	spread	/ʋəʧʰ:a/	وَچھّا	cow’s calf
ʤ	/ʋəʤa/	وَجا	play instrument	/ʋəʤ:a/	وَجّا	hit
s	/kəsa/	کَسا	rub	/kəs:a/	کَسّا	jerk (n.)
m	/kəmi/	کَمی	shortage	/kəm:i/	کَمّی	low caste
n	/gəna/	گَنا	count	/gən:a/	گَنّا	sugarcane
l	/gəla/	گَلا	neck	/gəl:a/	غلّا	money box

In Lyallpuri, the following consonants can occur as geminates: /p b t̪ d̪ ʈ ɖ k kʰ ɡ ʧ ʧʰ ʤ s m n l/. Geminate consonants are always preceded by centralized vowels (/ɪ ə ʊ/). The difference between a singleton and geminate plosive lies in the closure duration (Hussain 2015). Geminate plosives are characterized by longer closure duration compared to singletons. There is no difference in the duration of the vowel preceding singletons and geminates. However, the following vowel is shorter in geminate than singleton plosives. Representative examples of Lyallpuri word-medial singleton and geminate plosives are presented in Figures 6 and 7.

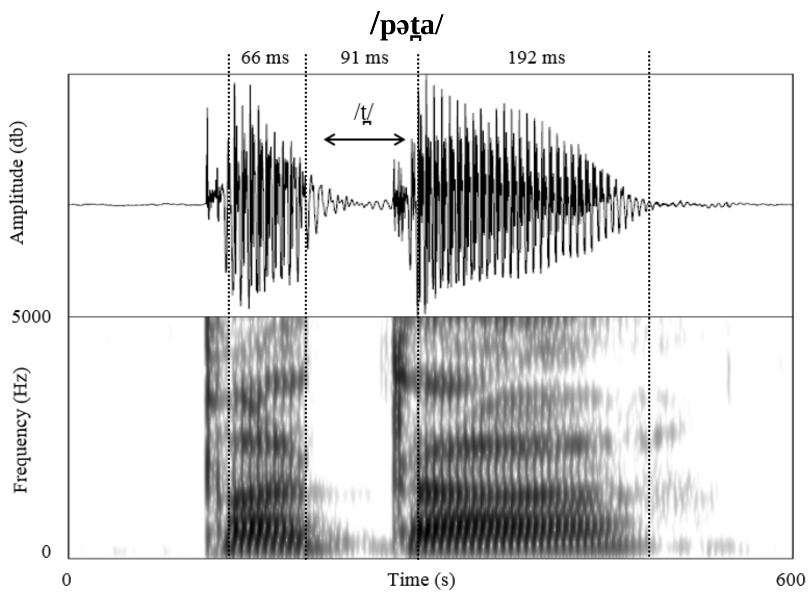


Figure 6 Waveform and spectrogram of voiceless unaspirated singleton /t̪/ in /pət̪a/ پَتا 'address'.

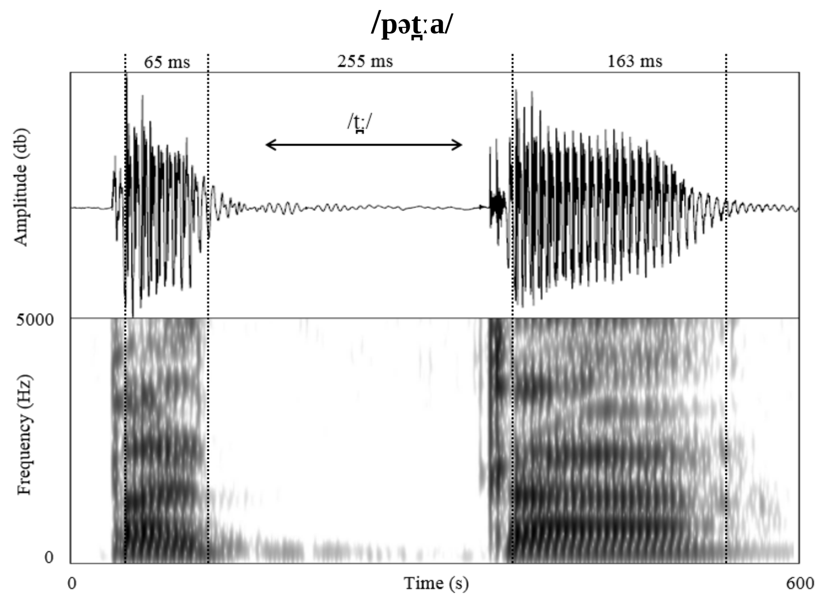
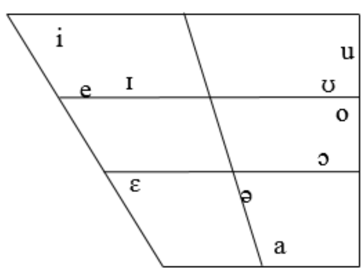


Figure 7 Waveform and spectrogram of voiceless unaspirated geminate /t̪ː/ in /pət̪ːa/ پَتّا 'leaf'.

Vowels



	Initial			Medial			Final		
i	id̪	عِید	Muslim festival	pir	پیر	Monday	pi	پی	drink
ɪ	ɪk	اِک	one	pʰɪr	پھر	retract	-	-	-
e	es	ایس	his	ber	بیر	berry	pe	پے	father
ɛ	ɛʃ	عیش	luxury	pɛr	پَیر	foot	pɛ	پَے	lie down
a	as	آس	hope	par	پار	cross	pa	پا	pour
ə	əsi	اَسی	we	pər	پَر	feather	-	-	-
ɔ	ɔkʰa	اَوکھا	difficult	ʧɔl	چَول	rice	bɔ	بَو	sit
o	os	اوس	dew	bol	بول	talk	bo	بو	smell

ʊ	ʊd̪as	اُداس	sad	pʊr	پُر	town	-	-	-
u	uɳa	اُونا	low	pur	پُور	fill	su	سُو	calved

The list of Lyallpuri vowels above contains minimal or near minimal pairs. Figure 8 presents the F1 and F2 formants of Lyallpuri vowels produced in word-medial position (based on five repetitions). The vowel system of Lyallpuri is similar to the Punjabi dialects spoken in India (Dulai 1989; Gill & Gleason 1962). Lyallpuri vowels can be categorized into centralized /ɪ ə ʊ/ and peripheral vowels /i e ɛ a o ɔ u/. Only peripheral vowels occur in all word-positions. There is a contrast in vowel height (/i/ vs. /a/) and backness (/i/ vs. /u/). In the Lyallpuri dialect, the contrast between /ɪ/ and /e/ is sometimes neutralised. For instance, the word for 'head' varies between /sɪr/ سِر and /ser/ سر . This can also be observed in Figure 8 below where /ɪ/ and /e/ are close to each other in terms of height.

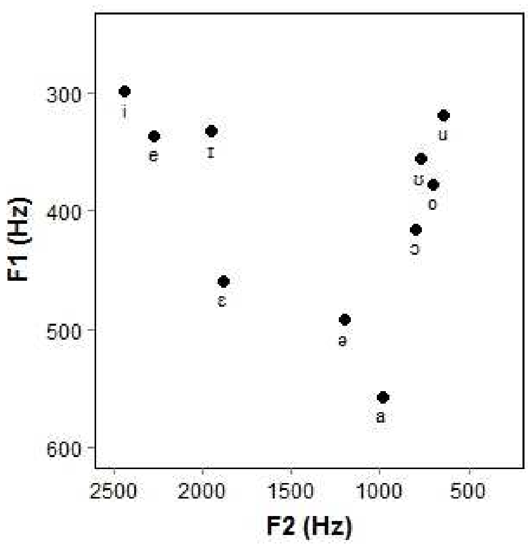


Figure 8 F1 and F2 plot of Punjabi vowels in word-medial position.

Both /e/ and /ɛ/ are peripheral vowels (/t̪eɽ/ تیڑ 'crack' vs. /t̪ɛr/ تَیر 'swim'). /ə/ is higher than /a/ (/ʧəl/ چَل 'lets go' vs. /ʧal/ چال 'gait'). The distinction between /ɔ/ and /o/ is neutralized for some speakers who produce the word for ‘one hundred’ as /sɔ/ سَو or /so/ سو .[17] /ʊ/ is lowered and more central than /u/ (/sur/ سُور ‘pig’ vs. /sʊr/ سُر ‘rhythm or tune’).

In addition to oral vowels, Lyallpuri has a contrastive set of nasal vowels. Only peripheral nasalized vowels contrast with oral vowels (Bhatia 1993; Shackle 2003). Representative examples of contrastive nasalized peripheral vowels are presented in (4) (Shackle 2003).[18]

(4) Oral vs. nasal vowels in Lyallpuri

	Oral			Nasal	
/hɛ/	ہے	is	/hɛ̃/	ہیں	you are (2nd sg.)
/ɡa/	گا	sing	/ɡã/	گاں	cow
/ʧo/	چو	milking	/ʧõ/	چوں	from
/sɔ/	سَو	hundred	/sɔ̃/	سَوں	sleep

Diphthongs

Lyallpuri variety has a rich inventory of diphthongs. Representative examples of minimal or near minimal pairs of Lyallpuri diphthongs are presented in (5). /ɛ ɔ/ do not occur as a first or second member of the diphthongs. Central vowels /ɪ ə ʊ/ do not occur as a second member of the diphthongs.

(5) Lyallpuri diphthongs

/sui/	سُوئی	small needle	/sue/	سُوئے	big needle
/soi/	سوئی	slept (3rd sin.)	/lau/	لاؤ	will remove
/məi/	مئی	May	/ləu/	لَؤ	will take
/mai/	مائی	old lady	/kʰou/	کھوؤ	will snatch

[17] /ɔ/ is slightly diphthongized.

[18] Nasalized vowels have important grammatical functions (Shackle 2003).

/soe/	سوئے	slept (3rd plu.)	/ʈoa/	ٹوا	hole
/sae/	سائے	shade	/ʤua/	جُوا	gambling

Prosodic features

Syllable structure

In Lyallpuri, syllables consist maximally of two onset consonants and two coda consonants (C)(C)V(C)(C).[19] The vast majority of Lyallpuri words are monosyllabic or disyllabic. Some representative examples of Lyallpuri syllables are presented in (6).

(6) Lyallpuri syllables

V	/a/	آ	come
CV	/kʰa/	کھا	eat
CVC	/giʈ̪/	گِیت	song
CV.CV	/si.ʈi/	سِیٹی	whistle
V.CV	/a.ri/	آری	chainsaw
VC.CV	/aɳ.ɖa/	آنڈا	egg

Stress and tone

Stress is not contrastive in Lyallpuri. However, Lyallpuri and other dialects of Indian Punjabi are known for the development of three contrastive tones: high (´), mid (¯) and low (`) (Gill 1960).[20] Minimal pairs of all three tones in monosyllabic and disyllabic words are given in (7). Figure 9 illustrates the differences in F0 and durations of high, mid and low tones.

[19] Words with initial and final consonant clusters are very rare and only found in Persian, Urdu and Arabic loanwords.

[20] See also Bahl (1957).

(7) Three-way tonal contrast in Lyallpuri

	Monosyllabic			Disyllabic		
High	/ʧá/	چا	tea	/kóɽa/	کوڑھا	leper
Mid	/ʧā/	چا	enthusiasm	/kōɽa/	کوڑا	whip
Low	/ʧà/	چا	peek	/kòɽa/	گھوڑا	horse

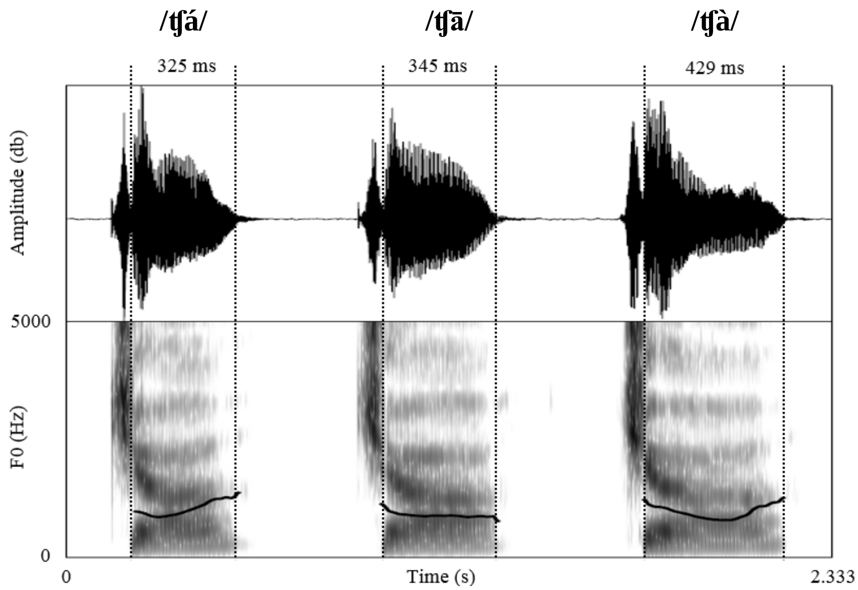


Figure 9 Waveforms and spectrograms of /ʧá/ چا 'tea' (left), /ʧā/ چا 'enthusiasm' (middle) and /ʧà/ چا 'peek' (right), representing high, mid and low tones, respectively. The black solid lines indicate the F0.

In high tone, the pitch is raised near the offset. The mid tone is the default tone and occurs on the vowels where there is no tone specification at the phonetic level (Bhatia 1975). Low tone generally has a falling-rising contour (Campbell 1981). There are some temporal differences in three tones. Low tones have the longest duration, followed by mid and high tones (Gill 1960).

The emergence of contrastive tones in Lyallpuri (also in Standard Majhi) is generally associated with the loss of aspiration and voicing in voiced aspirated plosives (Gill 1960;

Kanwal & Ritchart 2015; Shackle 2003; Sharma 1971; Yip 2002). Hindi-Urdu words with word-initial voiced aspirated plosives (i.e., /bʱ d̪ʱ ɖʱ ʤʱ ɡʱ/) lost their aspiration/voicing in Lyallpuri, and the following vowel is produced with low tone (Purcell, Villegas & Young 1978), as shown in (8). Word-medial and final /h/ has also been lost, resulting in high tone on the preceding vowel (9).

(8) Loss of voiced aspirates and voicing

Hindi-Urdu			Lyallpuri		
/ɡʱoɽa/	گھوڑا	→	/kòɽa/	گھوڑا	horse
/ɖʱol/	ڈھول	→	/ʈòl/	ڈھول	drum

(9) Deletion of glottal fricative /h/ in word-medial and final positions

Hindi-Urdu			Lyallpuri		
/pehla/	پہلا	→	/péla/	پہلا	first
/rah/	راہ	→	/rá/	راہ	path

For further discussion on tonogenesis, readers are referred to Bhatia (1975), Hombert, Ohala & Ewan (1979) and Ohala (1973).

Transcription of The North Wind and The Sun

This passage was translated from English to Lyallpuri and presented here using phonetic transcription. Only high (´) and low (`) tones are marked.

[ʃʊmal d̪i həʋa t̪e surəʤ ʋɪʧ rəpʰəɽ peja si pəi kon bót̪a t̪akət̪ʋər e]

[t̪e fer ɪk mʊsafər aja jinẽ kəmbəl d̪i bʊkːəl mari hoi si]

[onã ne ʃərt̪ la ləi pəi ʤéɽa pélã mʊsafər d̪a kəmbəl lʊʋa d̪eve o bót̪a t̪akət̪ʋər hoʋe ɡa]

[fer ʃʊmal d̪i həʋa pura zor la ke ʧəlːi] [pər o ʤɪnːa zor la ke ʧəld̪i si mʊsafər əpna kəmbəl onã i kəs ke bʊkːəl mar lɛ̃d̪a si]

[axər ʃʊmal d̪i həʋa ne har ke bəs kit̪i] [fer surəʤ ɡərmi nal ʧəmkeya t̪e mʊsafər ne ʧʰet̪i nal əpna kəmbəl lá d̪ɪt̪ːa]

[t̪e ɛ̃ʤ ʃʊmal d̪i həʋa nũ mənəna peja pəi d̪onã ʋɪʧːõ surəʤ bót̪a t̪akət̪ʋər e]

Orthographic version (Shahmukhi script)

شُمال دی ہَوا تے سُورج وِچ رَپھڑ پیا سی پَئی کون بوہتا طاقتور اے۔ تے فیر اِک مُسافر آیا جینیں کَمبل دی بُکّل ماری ہوئی سی۔ اوناں نے شرط لا لئی پئی جیہڑا پہلاں مُسافر دا کَمبل لُوا دیوے او بوہتا طاقتور ہووے گا۔ فیر شُمال دی ہوا پُورا زور لا کے چلّی، پر او جِنّاں زور لا کے چلدی سی مُسافر اپنا کَمبل اوناں ای کَس کے بُکّل مار لیندا سی۔ آخر شُمال دی ہَوا نے ہار کے بس کیتی۔ فیر سُورج گرمی نال چمکیا تے مُسافر نے چھیتی نال اپنا کَمبل لا دِتّا۔ تے اینج شُمال دی ہَوا نوں مَننا پیا پَئی دوناں وِچّوں سُورج بوہتا طاقتور اے۔

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Chapter 3: Temporal characteristics of Punjabi word-medial singletons and geminates

This chapter is based on the following published paper:

Hussain, Q. (2015). Temporal characteristics of Punjabi word-medial singletons and geminates. *Journal of the Acoustical Society of America, 138*(4), EL388-EL392.

Abstract

Many studies have investigated the temporal characteristics of the word-medial singletons and geminates in Indo-Aryan languages. However, little is known about the acoustic cues distinguishing between the word-medial singletons and geminates of Punjabi. The present study examines the temporal characteristics of Punjabi word-medial singleton and geminate stops in a $C_1V_1C_2V_2$ template. The results from five Punjabi speakers showed that, unlike previous studies of Indo-Aryan languages, the durations of C_2 and V_2 are the most important acoustic correlates of singleton and geminate stops in Punjabi. These findings therefore point towards the cross-linguistic differences in the acoustic correlates of singletons and geminates.

PACS Numbers: 43.70.Fq, 43.70.Kv.

1. Introduction

Cross-linguistic studies have demonstrated that languages with a singleton and geminate contrast are relatively rare. In a database containing 317 languages, only 11 languages exhibit singleton and geminate consonants (Maddieson, 1984). Geminate consonants show a wide-range of diversity and appear in word-initial (Swiss German: Lahiri and Hankamer, 1988), intervocalic (Italian: Esposito and Benedetto, 1999) and word-final positions (Maltese: Hume et al., 2014). Some languages allow all types of geminates (Tashlhiyt Berber: Ridouane, 2010).

Word-medial geminates are frequently found across languages. Punjabi, like many other Indo-Aryan languages, contrasts word-medial singleton and geminate consonants. There are ten vowels in Punjabi: three centralized vowels /ɪ ə ʊ/ and seven peripheral vowels /i e ɛ u o ɔ a/. Geminate consonants are always preceded by centralized vowels and are followed by peripheral vowels (Dulai and Koul, 1980). In the Lyallpuri dialect of Punjabi, the following consonants can occur as geminates: /p b t̪ d̪ ʈ ɖ k kʰ g ʧ ʧʰ ʤ s m n l/. Substantial research efforts have been made in order to investigate the acoustic correlates of singleton and geminate consonants in Indo-Aryan languages (Ghai, 1980; Ohala, 2007). The most essential cue distinguishing singletons from geminates is the closure duration (Lahiri and Hankamer, 1988). Geminates are characterized by longer closure duration, compared to singletons. Ridouane (2007) found that geminates in Tashlhiyt Berber consistently show longer consonant durations than singletons, regardless of the position of geminates in a word (initial, intervocalic, final) and types of obstruents (stops, fricatives). This is also manifested in the EPG (electropalatography) contact data. Geminates have a larger linguopalatal contact than their singleton counterparts. Kraehenmann and Lahiri (2008) reported that the linguopalatal contact of the word-initial geminates in Swiss German is longer in geminates (167 ms) but shorter in singletons (112 ms).

Other acoustic correlates of singletons and geminates are duration of the preceding and following vowels. In Italian, the duration of the preceding vowel is shorter when the following consonant is a geminate (Esposito and Benedetto, 1999). Japanese lengthens the preceding vowel before geminates and shortens the following vowel after geminates (Han, 1994).

Phonetic studies of singletons and geminates have also established that the duration of C_1 in a $C_1V_1C_2V_2$ template is longer when C_2 is a geminate. In Hindi (Ohala, 2007), the duration of C_1 is longer when C_2 is a geminate but shorter when C_2 is a singleton. Han (1994) reported similar results for the Japanese geminates. Turco and Braun (2014) associated this lengthening effect of C_2 on C_1 with the long-distance anticipatory effects.

The aim of the current study is therefore to investigate the temporal characteristics of Punjabi singletons and geminates in a $C_1V_1C_2V_2$ template. Given previous findings from Hindi (Ohala, 2007) singletons and geminates, we predicted that the duration of C_1 in a $C_1V_1C_2V_2$ template would differ significantly, depending on the durational properties of C_2 (singleton or geminate). It is also predicted that C_2 would be longer in geminates but shorter in singletons. Similarly, it is expected that the duration of the preceding vowel would be shorter in geminates, but longer in singletons (Ohala, 2007). Most of the studies on singletons and geminates do not report the duration of following vowels. It is also predicted that the duration of following vowels would be shorter after geminates and longer after singletons.

2. Methods

2.1 Participants

Five male Punjabi speakers (21-29 years old, Mean: 23.8 years) participated in the experiments. The native language of the participants was Punjabi but they were fluent in English and Urdu as well. The participants reported normal speaking and hearing abilities. All of the speakers were residing in Faisalabad, Pakistan and shared the same dialect of Punjabi.

2.2 Speech material

The target words consisted of five pairs of singleton and geminate stops, with $C_1V_1C_2V_2$ template. C_1 was one of the following stops /ʈ p k b/; V_1 was /ə/; C_2 was either a singleton /p t̪ ʈ tʃ k/ or a geminate /pː t̪ː ʈː tʃː kː/; and V_2 was /a/. All words were real Punjabi words. The target words were elicited in an utterance-medial position, enu_____ke, which can be literally translated as *say it*_____.

2.3 Procedure

The participants were invited into a quiet room at the University of Agriculture, Faisalabad. Before the experiment, a practice session was conducted to familiarize participants with the task. Target words were written in Punjabi orthography (Shahmukhi script) and presented on a computer screen. Participants were asked to read the words in an utterance-medial position. Each item was repeated five times (Broad and Clermont, 2014) resulting in a total of 250 tokens (5 singletons + 5 geminates × 5 repetitions × 5 participants = 250 items). The recordings were made using a Zoom H2 digital voice recorder with a built-in microphone at a sampling rate of 44.1 KHz.

2.4 Acoustic segmentation

A total of 250 items were acoustically segmented using Praat. Four items were excluded due to mispronunciations. The vowels (V_1 and V_2) were segmented as clear F2 energy in the spectrogram. Closure durations and VOTs were segmented together for the C_1 and C_2 durations

(Ridouane, 2007). Fig. 1 presents a representative example of the acoustic segmentation of the target items.

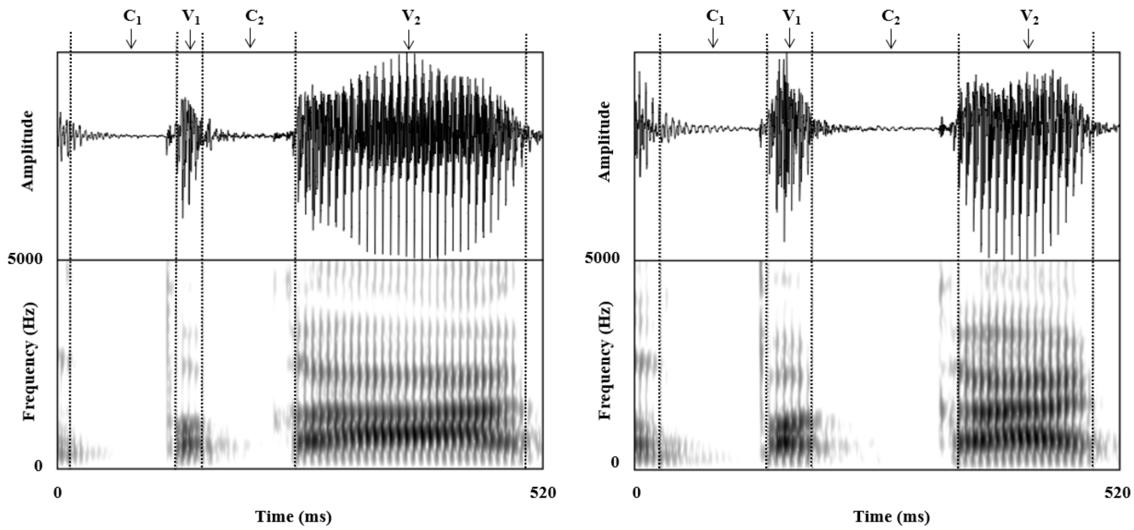

Fig. 1. Acoustic waveform and spectrum showing the segmentation of the target items (left: /pəka/ '*cook*'; right: /pəkːa/ '*firm or strong*'). Acoustic landmarks, $C_1V_1C_2V_2$, are indicated with the dotted lines.

3. Results

Separate repeated-measure analyses of variance (ANOVA) were conducted for each acoustic measurement, with C_1, V_1, C_2 and V_2 as dependent variables, place (labial, dental, retroflex, palatal, and velar) and consonant type (singleton vs. geminate) as within-subject factors. The alpha value was set at 0.05.

3.1 Consonant durations (C_1 and C_2)

It was predicted that the duration of C_1 would be longer when C_2 is a geminate. Furthermore, the duration of C_2 was anticipated to be longer in geminates and shorter in singletons. The results of C_1 duration indicated that there was a significant effect of place [F (4, 16) = 10.322, p<0.001], but unexpectedly, there was no significant effect of consonant type [F (1, 4) = 4.203,

p=0.110] and no significant interaction between the place and consonant type [F (4, 16) = .170, p=0.950]. This suggests that the duration of C_1 varied significantly across different places of articulation but C_1 duration did not differ significantly when the C_2 was one of the singleton or geminate stops. The results of C_2 duration showed a significant effect of place [F (4, 16) = 13.359, p<0.001] and consonant type [F (1, 4) = 44.346, p=0.003] but no significant interaction between the place and consonant type [F (4, 16) = 1.357, p=0.292]. This indicates that C_2 duration was significant across different places of articulation and C_2 duration, as expected, was significantly longer for geminates, compared to singletons. Table 1 presents the mean $C_1V_1C_2V_2$ durations across different places of articulation. The mean values of C_1 and C_2 are plotted in Fig. 2.

Table 1. Mean $C_1V_1C_2V_2$ durations (ms) in singletons and geminates, across different places of articulation. The first value in each cell represents the mean value and second value in parentheses shows the SD.

Place	**Consonant**	**C_1**	**V_1**	**C_2**	**V_2**
Labial	/p/	100 (10)	39 (11)	111 (19)	210 (33)
	/pː/	113 (16)	46 (5)	143 (10)	128 (33)
Dental	/t̪/	111 (19)	45 (10)	101 (10)	173 (54)
	/t̪ː/	116 (22)	45 (7)	149 (10)	130 (29)
Retroflex	/ʈ/	110 (34)	45 (10)	87 (14)	199 (41)
	/ʈː/	117 (23)	47 (6)	125 (17)	122 (19)
Palatal	/tʃ/	81 (27)	47 (11)	102 (18)	205 (37)
	/tʃː/	85 (24)	53 (8)	140 (16)	130 (37)
Velar	/k/	109 (17)	39 (12)	102 (12)	207 (24)
	/kː/	118 (11)	52 (10)	142 (15)	143 (26)

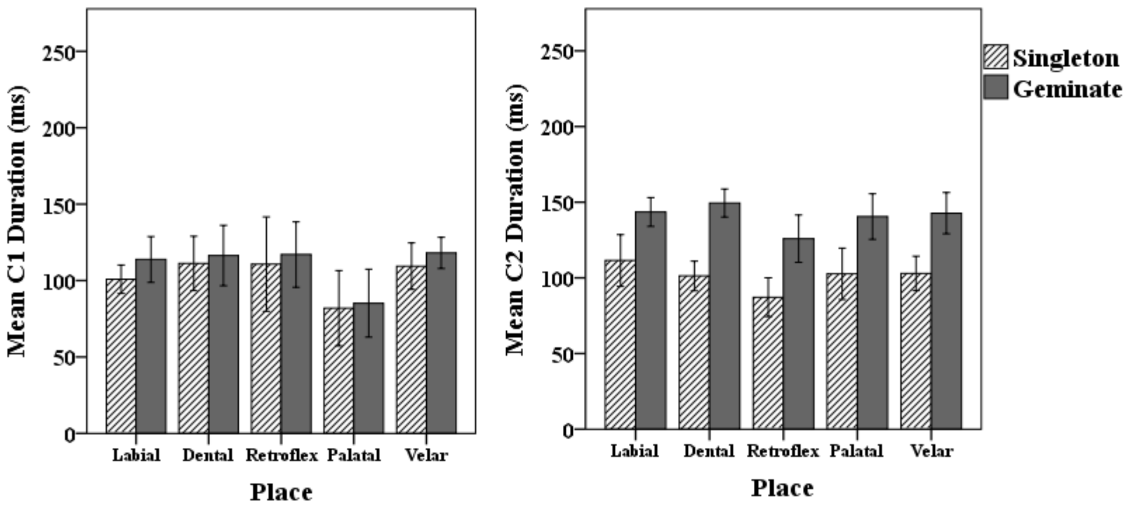

Fig. 2. Mean C_1 (left) and C_2 (right) durations (ms) in singletons and geminates, across different places of articulation. Error bars indicate standard error of the mean.

Although there were no statistically significant differences in C_1, but C_1 was slightly longer when C_2 was a geminate. For the labial, C_1 was on average 13 ms longer in geminates than singletons. This minor difference in singletons and geminates was also reflected in other places of articulation (dental: 5 ms; retroflex: 7 ms; palatal: 4 ms; velar: 9 ms). C_2 showed longer durations in geminates but shorter in singletons.

3.2 Vowel durations (V_1 and V_2)

It was expected that the duration of the preceding vowels would be shorter in geminates, but longer in singletons. On the other hand, the duration of the following vowels would be shorter after geminates and longer after singletons. The results of repeated-measures ANOVA suggested that place [F (4, 16) = 1.765, p=0.185] and consonant type [F (1, 4) = 1.106, p=0.352] had no significant effect on V_1 duration and there was no significant interaction between the place and consonant type [F (4, 16) = 1.316, p=0.306]. This suggests that V_1 duration was not significantly different in both singletons and geminates. However, as predicted, the repeated-measures ANOVA indicated that there was an effect of consonant type on V_2 duration [F (1, 4) = 170.844, p<0.001], with geminates showing shorter V_2 duration, and singletons are characterized by the longer V_2 duration. The effect of place on V_2 duration was not significant [F (4, 16) = 1.873, p=0.165] and there was no significant interaction between place and consonant type [F (1.586, 6.344) = 1.618, p=0.265]. Figure 3 illustrates the mean vowel durations of singletons and geminates across different places of articulation.

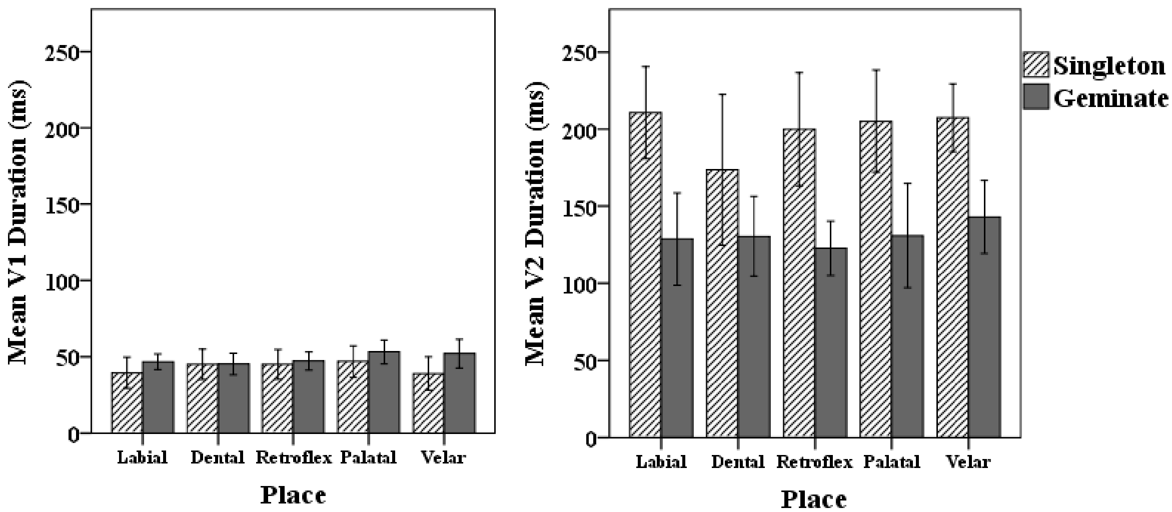

Fig. 3. Mean V_1 (left) and V_2 (right) durations (ms) in singletons and geminates, across different places of articulation. Error bars indicate standard error of the mean.

V_1 duration was not significant in singletons and geminates but it was slightly longer in geminate labial, retroflex, palatal and velar, compared to singletons. V_2 duration was consistently longer in singletons but shorter in geminates. On average, the difference between the V_2 duration of labial, dental, retroflex, palatal and velar was 82, 43, 77, 75, and 63 ms, respectively.

4. Discussion

The present study investigated the temporal characteristics of Punjabi word-medial singleton and geminate stops across different places of articulation. The findings suggest that consonant duration of C_2 and vowel duration of V_2 are the primary acoustic correlates of Punjabi geminates. The durational correlates of C_2 are in line with the previous studies (Ohala, 2007; Lahiri and Hankamer, 1988), however, the results of C_1 do not match with other studies on singletons and geminates. It is argued that, unlike what has been reported for Italian (Turco and Braun, 2014), Hindi (Ohala, 2007), and Japanese (Han, 1994) geminates, there are no anticipatory effects of C_2 lengthening on C_1 duration in Punjabi.

Languages exhibit three types of durational patterns when talking about the duration of preceding vowel (V_1): (a) languages that shorten the preceding vowel when the following consonant is a geminate (Italian: Esposito and Benedetto, 1999; Tashlhiyt Berber: Ridouane, 2007); (b) languages that lengthen the preceding vowel (Japanese: Han, 1994); and (c) languages that show no difference in the duration of preceding vowel (Turkish: Lahiri and Hankamer, 1988). Punjabi falls under the category of type (c) languages that show no difference in V_1 duration.

The duration of the following vowel (V_2) is not widely reported in the literature. However, for the Japanese geminates Han (1994) shows that the duration of the following vowel (V_2) is shorter when the preceding consonant (C_2) is a geminate. The results of V_2 duration in the current study are similar to Japanese (Han, 1994). The duration of V_2 is shorter in geminates, compared to singletons.

The results of this study depart from other Indo-Aryan languages. As reported by many studies, for the geminate consonants, the duration of preceding vowel (V_1) is shorter in Hindi (Ohala, 2007), Dogri (Ghai, 1980), and Bengali (Lahiri and Hankamer, 1988), than their singleton counterparts. These languages share the same language family and their phonological systems closely resemble with Punjabi. The findings of this study also confirm that languages belonging to the same language family might behave differently in terms of the temporal characteristics of singleton and geminate stops.

Acknowledgements

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Chapter 4: Acoustic characteristics of Punjabi retroflex and dental stops

This chapter is based on the following paper that is currently being revised:

Hussain, Q., Proctor, M., Harvey, M., & Demuth, K. (in revision). Acoustic characteristics of Punjabi retroflex and dental stops. *Journal of the Acoustical Society of America.*

Abstract

The place category "retroflex" is found in many Indo-Aryan languages; however, it has not been clearly established which acoustic characteristics reliably differentiate retroflexes from other coronals. This study investigates the acoustic phonetic properties of Punjabi retroflex /ʈ/ and dental /t̪/ in word-medial and word-initial contexts across /i e a o u/, and in word-final context across /i a u/. Formant transitions, closure and release durations, and spectral moments of release bursts are compared in 2,280 stop tokens produced by thirty speakers. Although burst spectral measures and formant transitions do not consistently differentiate retroflexes from dentals in some vowel contexts, stop release duration and total stop duration reliably differentiate Punjabi retroflex and dental stops across all word contexts and vocalic environments. These results suggest that Punjabi coronal place contrasts are signaled by the complex interaction of temporal and spectral cues.

Keywords: Punjabi; coronal; retroflex; dental; formant transitions

I. INTRODUCTION

Languages which have a contrastive set of retroflex consonants are comparatively rare (Ladefoged and Maddieson, 1996). Donohue et al. (2013) estimate that only 14% of languages in the world contrast retroflex stops with other coronal stops. Several studies have reported data on retroflexes in Indo-Aryan languages, but results are not entirely consistent. Ohala and Ohala (2001) reported that retroflex stops in Hindi are characterized by F3-F2 convergence after vowels /i a u/. Dave (1977) found that there is no F3-F2 convergence for Gujarati retroflex stops produced after /i/ and /e/. This raises the question whether F3-F2 convergence is a reliable acoustic correlate of retroflex articulations. It should also be noted that Ohala and Ohala (2001) and Dave (1977) reported data from only a few participants (ten Hindi speakers and only one Gujarati speaker) and did not provide any quantitative analysis on formant transitions. Therefore, more data are required to fully understand the phonetic characteristics of coronal stop contrasts in Indo-Aryan languages.

Punjabi is an Indo-Aryan language spoken in Pakistan and India, and in expatriate communities throughout the world. Despite the large number of speakers (>100 million; 10th in speaker numbers globally (Lewis et al., 2015)), Punjabi remains relatively understudied, with little or no data available on many aspects of the phonological system. Punjabi has a three-way coronal contrast: dental /t̪/, retroflex /ʈ/, and palatal /ʧ/ (see Appendix A). These stops are contrastive in all word contexts (medial, initial, and final). In this paper we examine the Punjabi /ʈ/-/t̪/ contrast, because studies of other languages have shown that the contrast between retroflex and dental stops is difficult to perceive for both native (Wubuy: Bundgaard-Nielsen et al., 2015) and non-native speakers (perception of Hindi retroflex and dental stops by English and Japanese listeners: Pruitt et al., 2006). Palatal /ʧ/ is not included as it is acoustically and articulatorily quite different from other coronals (c.f. Anderson, 1997; Park, 2007; Shalev et al., 1993; Tabain, 2012).

Formant transitions have been a particular focus of the research on place oppositions (Halle et al., 1957; Delattre et al., 1962; Iskarous et al., 2010; Rhone and Jongman, 2012, etc.). Lowering of F3 in preceding vowels has been argued to be the most important acoustic correlate of retroflex articulations (Hamann, 2003; Hamilton, 1996), as F2 may be raised or lowered before a retroflex, depending on the vowel context. In Australian indigenous languages, palatals are clearly differentiated from other coronals (Central Arrernte: Tabain, 2012; Pitjantjatjara: Tabain and Beare, 2011); however, acoustically, dentals, alveolars, and retroflexes are not as clearly differentiated. In Wubuy, an Australian language with a four-way coronal contrast, F2 transitions from the preceding vowel in an intervocalic /aCa/ context do not robustly distinguish dental, alveolar, and retroflex, but F3 transitions from the preceding vowel differentiate all three places. In /Ca/ contexts, the F2 onset of the following /a/ vowel differentiates retroflex vs. dental and retroflex vs. alveolar stops, but not alveolar vs. dental stops; however, F3 transitions do not differentiate Wubuy dentals, alveolars, and retroflexes (Bundgaard-Nielsen et al., 2012). Unlike Wubuy, Central Arrernte (Tabain, 2012) does not maintain a four-way coronal contrast word-initially, with the contrast between alveolar and retroflex being neutralized (Tabain, 2012).

The perceptibility of some coronal contrasts may depend also on the type and direction of transition cues. Steriade's (2008) cross-linguistic survey of perceptual cues to coronals in different word contexts found that retroflexes were better differentiated from other coronals in terms of VC transitions compared to CV transitions. This claim is based on data from Australian and other languages that neutralize coronal contrasts – apical alveolar vs. apical postalveolar or retroflex – in CV contexts, where there are no cues from a preceding vowel (Hamilton, 1996;

Steriade, 2008). Steriade (2008) posits that these patterns derive from the absence of preceding transition cues, and that preceding transition cues are crucial for differentiating retroflexes from other coronals. Steriade's (2008) observations are further confirmed by perception studies. A perceptual categorization study of the coronal contrasts of Western Arrernte found that in a VCV context, the correct identification rate of retroflexes by native Arrernte speakers was 74%. However, this identification rate dropped significantly in a CV context (19%) (Anderson, 1997). As Western Arrernte does not contrast apicals in word-initial context, Anderson (1997) used CV stimuli excised from VCV stimuli. Bundgaard-Nielsen et al. (2015) found similar differences in perception of Wubuy coronals according to syllable position: Wubuy native speakers correctly discriminated retroflexes and dentals in intervocalic context (83%), dropping to 73% for word-initial context.

In word-initial context, formant transitions do not distinguish retroflexes from dentals. However, VOT may distinguish the two coronals. Lisker and Abramson (1964) investigated VOT characteristics in a wide range of languages, including some Indo-Aryan languages, in utterance-initial and non-initial contexts. Mean VOTs of Hindi and Marathi initial voiceless unaspirated retroflex and dental stops were 11 ms, showing no differences in VOT. However, in non-initial context, there were differences between both Hindi and Marathi voiceless unaspirated retroflex and dental stops (Hindi retroflex 8 ms vs. dental 14 ms; Marathi retroflex 3 ms vs. dental 15 ms). The data presented by Lisker and Abramson (1964) were based on one speaker each of Hindi and Marathi. It is possible that VOT values might differ in a larger population of speakers. In Tiwi, word-medial retroflex/postalveolars are characterized by shorter VOT compared to dentals (Anderson and Maddieson, 1994). Comparisons of VOT between retroflexes and dentals do not consistently report that retroflexes have longer VOT. Hyslop (2009) recorded VOT data from two speakers of Kurtöp (a Tibeto-Burman language spoken in Bhutan). One of the speakers showed no differences in VOT of the voiceless unaspirated retroflex (22 ms) and dental (22 ms) stops, while another speaker had longer VOT for retroflex (31 ms) than dental (26 ms) stops.

Closure duration has also been found to significantly differ between retroflexes and other coronals. In Tiwi (Anderson and Maddieson, 1994) and Central Arrernte (Tabain, 2012), retroflexes were characterized by shorter closure duration. In terms of closure duration, Sindhi (an Indo-Aryan language) voiceless unaspirated retroflex stops were also shorter (185 ms) than dental stops (283 ms) (Keerio, 2010). In Bengali (Mikuteit and Reetz, 2007) and Hindi (Benguerel and Bhatia, 1980; Dutta, 2007), there were no significant differences in closure duration of the retroflex and dental stops. Maxwell et al. (2015) investigated the closure duration and total stop duration (closure + VOT) of the Bengali word-medial retroflex and dental stops and found no significant differences.

Other acoustic cues that have been reported to differentiate retroflexes from dentals are energy distribution in the burst spectrum and burst amplitude (Anderson and Maddieson, 1994), such that retroflexes show peak spectrum and energy distribution around 3000 Hz, whereas dentals have flat or diffused spectra and burst energy distributed in higher frequency bands, around 4000 Hz (Stevens and Blumstein, 1975). These acoustic differences might be associated with the differences in constriction location and the part of the tongue that makes contact with the hard palate. Retroflexes are articulated with the tongue tip and tend to have faster release and intense bursts (Gordon and Maddieson, 1999).

Apart from formant transitions, VOT or burst duration, closure duration, and total stop duration, spectral moments (Center of gravity (CoG), variance, skewness, kurtosis) have been widely used to classify different places of articulation (e.g., retroflex and dental fricatives: Gordon et al., 2002; and stops in general: Eshghi et al., 2013; Nissen and Fox, 2009; Tabain, 2012, etc.). Spectral moments are correlated with different articulatory configurations of the vocal tract and therefore provide important information about the length of the oral cavity in the production of consonants (Li et al., 2009). The first spectral moment (or spectral CoG) indicates mean distribution of energy in the burst spectrum, and correlates with the length of the front cavity. The second spectral moment (spectral variance) corresponds to the distribution of acoustic energy on both sides of the mean (Li et al., 2009). The third spectral moment (spectral skewness) indicates whether the acoustic energy in the burst spectrum is skewed towards higher (positive skewness) or lower energies (negative skewness), and is correlated with the length of the front cavity (Li et al., 2009). The fourth spectral moment (spectral kurtosis) is a measure of 'peakiness' in the spectral envelope of the burst release. Within the class of coronals, dentals and palatals show higher spectral CoG, spectral variance, and negative spectral skewness and spectral kurtosis in some languages (Gordon et al., 2002; Tabain, 2012; Tabain et al., 2016). Retroflexes tend to have larger sublingual space, which results in lower spectral CoG, spectral variance, and positive spectral skewness and spectral kurtosis (Bundgaard-Nielsen et al., 2016; Tabain et al., 2014). Spectral moments of alveolars more closely match those of retroflexes than dentals (Tabain, 2012).

The formant transitions, VOT or burst duration, closure duration, and spectral moments associated with a particular stop are also expected to differ across vowel contexts (Nissen, 2003). For instance, retroflexes show higher spectral CoG in the context of following /i/, than /u/ (Tabain and Butcher, 2015) which might be due to the articulatory incompatibility of retroflexes with /i/ (Hamann, 2003). This is evident from languages which show a dispreference for retroflexes in the vicinity of front vowels. In Mandarin, retroflex fricatives do not occur before the front vowel /i/ (Lee-Kim, 2014). Previous studies of Indo-Aryan coronal stops have mainly addressed only temporal cues (Berkson, 2012; Benguerel and Bhatia, 1980) or formant transitions (Dave, 1977; Ohala and Ohala, 2001). Maxwell et al. (2015) investigated temporal characteristics and formant transitions of Bengali word-medial retroflex and dental stops, but no data on spectral moments were reported. Very little is known about the influence of vowels and word contexts on the temporal and spectral properties of retroflex and dental stops in Punjabi.

The goal of this paper is to examine the acoustic properties of Punjabi coronal stops more closely than has previously been examined in an Indo-Aryan language, to better understand the realization of dental-retroflex contrasts. We focused on voiceless unaspirated stops /ʈ/ and /t̪/, produced across a full range of word contexts (medial, initial, final), and vocalic /i e a o u/ environments. We examined key temporal and spectral cues that have been widely used to classify coronals: stop closure, release, and total stop duration; formant trajectories, and spectral moments of stop release bursts (Berkson, 2012; Benguerel and Bhatia, 1980; Bundgaard-Nielsen et al., 2016; Dave, 1977; Maxwell et al., 2015; Mikuteit and Reetz, 2007; Ohala and Ohala, 2001; Tabain, 2012; Tabain and Butcher, 2015). In particular, we examined formant transitions to see if F3 reliably differentiates coronal place, and whether Punjabi retroflexes are cued by F3-F2 convergence after high front vowels.

II. METHOD

A. Participants

Word-medial and word-initial stop contrasts were examined in the speech of twelve male speakers of Punjabi (20 to 29 years of age, mean 22.6 years). All informants were trilinguals with some knowledge of Urdu and English. Coronal contrasts were elicited in word-final context from another eighteen male Punjabi speakers (ten trilinguals and eight monolinguals; 22 to 30 years old, mean 26.4 years). Two additional speakers were excluded from the analysis:

one speaker consistently resyllabified the target words with the carrier sentence, and a second participant produced atypical vowels compared to other speakers. Our initial analyses showed that the temporal and spectral properties of Punjabi word-final retroflex and dental stops do not differ significantly across Punjabi trilinguals and monolinguals. Therefore, we collapsed the word-final data from both groups. None of the participants had speech or hearing difficulties. Speakers were recruited from Faisalabad, Pakistan, and all spoke the Lyallpuri dialect of Punjabi, which closely resembles the Majhi dialect of Punjabi spoken in Lahore (Gill and Gleason, 1962).

B. Speech material

The word-medial and word-initial target words consisted of ten disyllabic ($\boldsymbol{C_1}V_1\boldsymbol{C_2}V_2$) nonsense words (see Appendix B). The target consonants (C_1 or C_2) were either a retroflex /ʈ/ or a dental /t̪/. V_1 and V_2 were selected from the five vowels /i e a o u/. The word-final target words consisted of twelve monosyllabic ($C_1V_1\boldsymbol{C_2}$) real Punjabi words with the target consonant (C_2) in word-final context, preceded by a vowel (V_1) selected from the three maximally contrastive vowels /i a u/ (see Appendix C). Punjabi allows coronals in all word contexts, preceded or followed by peripheral or central vowels. All speech materials used in this study (real or nonsense words) contained peripheral vowels, to reduce the influence of vowel length on consonant duration, and followed the phonotactic restrictions of Punjabi.

Word-medial and word-initial consonants were elicited using a reading task in which participants were presented with nonsense words written in the Shahmukhi script of Punjabi (10 word-medial items × 10 word-initial items × 12 participants × 5 repetitions = 1200 tokens). The word-final consonant data were recorded using an elicited imitation task. All word-final target words were matched with a picture (accompanied by an auditory prompt produced by a female Punjabi speaker), pseudo-randomized, and presented in five different blocks (12 word-final items × 5 repetitions × 18 speakers = 1080 items). The target words were embedded in a Punjabi carrier sentence [kɛ___əʤ] (*'Say___today'*). Given that there were two different methods of elicitation (single word productions for word-medial and initial contexts and in a carrier phrase for word-final context), we expected that there may be task-related temporal differences. We consider these differences in the discussion section.

C. Procedure

The procedure for recording the word-medial, word-initial, and word-final data was similar. The participants were invited into a quiet room at the University of Agriculture, Faisalabad (Pakistan). Before the experiment, a practice session was conducted to familiarize participants with the task. Because the data were collected in Pakistan, a portable Zoom H2 digital recorder with in-built microphone (122 dB bidirectional max. sound pressure input, +39 dB input gain) was used to make audio recordings. All speech was recorded in stereo mode, at 44.1 kHz and encoded in 16 bit, uncompressed WAV format. The stereo recordings were converted to mono in Praat.

D. Acoustic analyses

A total of 2,280 lexical items were recorded, containing target stops in three different word contexts: word-medial (600 items), word-initial (600 items), and word-final (1080 items). We used the same criteria to identify temporal landmarks in all stops. For consonants elicited in word-medial context, 5 temporal landmarks were located: (1) preceding vowel onset, (2) preceding vowel offset (stop closure onset), (3) release burst onset, (4) voice onset of following vowel, and (5) following vowel offset (see Figure 1). Landmarks (1), (2), (4), and (5) defining vowel intervals were manually located by visual inspection of the waveform and spectrogram, making reference to periodicity and formant energy bands. Landmarks (2) and (3) represent closure duration that was located at the point of maximum attenuation of F2 energy in the transition from adjacent vocalic intervals. Voice onset time (VOT) was calculated as the duration of interval (4-3). In word-medial context, total stop duration (closure + VOT) was calculated as the duration of the interval from the closure onset (2) to VOT offset (4). In word-final context, where VOT cannot be measured, we used burst release duration as an equivalent parameter. Total stop duration therefore provides a consistent measure of closure + release duration for stops produced in word-medial and word-final contexts, because all stops examined in this study are voiceless. Because closure duration cannot be reliably measured word-initially, we only reported VOT for initial stops.

To validate the placement of temporal landmarks, another trained phonetician segmented 10% of the data containing stops produced in word-medial context (60 items). The average differences between closure durations calculated by the two analysts were 8 ms in retroflex stops, and 1 ms for dental stops; for VOT, the average differences were 3 ms (retroflexes) and 1 ms (dentals).

Formant analyses of the Punjabi retroflex and dental stops were conducted, focusing on the first three formant trajectories (F1, F2, F3) into and out of each target stop. For each consonant of interest, a Praat script was used to identify F1, F2, and F3 values at six sample time points in the preceding (50, 60, 70, 80, 90 and 100% total vowel duration) and following (0, 10, 20, 30, 40 and 50% total vowel duration) vowels (see Figure 1). These sample time points were then used to extract formants with LPC analysis over a sliding 25 ms analysis window with a 50 db dynamic range (Boersma and Weenink, 2014). Formants were estimated in Praat, and subsequently validated in a custom graphical user interface implemented in Matlab. The automatic formant tracker in Praat did not always correctly identify the formants near the offset of the preceding vowels. Therefore, the extracted formants were checked at each time step by visually comparing them with an additional set of formant estimates superimposed on the target spectrogram. Formants were re-estimated using an alternative algorithm (14th order LPC, 25 ms 50% overlapping analysis window, max search frequency: 4000 Hz), and manually corrected only where needed, in cases where the original Praat estimates deviated excessively from the validation estimates. Final analyses were based on the corrected formant trajectories.

The first four spectral moments (spectral CoG, spectral variance, spectral skewness, and spectral kurtosis) of stop release bursts were also measured in Praat from FFT spectra generated over a single 20 ms Hamming analysis window centered at the beginning of the stop release bursts (landmark (3), Figure 1) (Forrest et al., 1988). Unlike word-final context, stop release bursts in word-medial and word-initial contexts were followed by vowels. Therefore, we might expect some differences in spectral moments across word contexts (see section IV. Discussion).

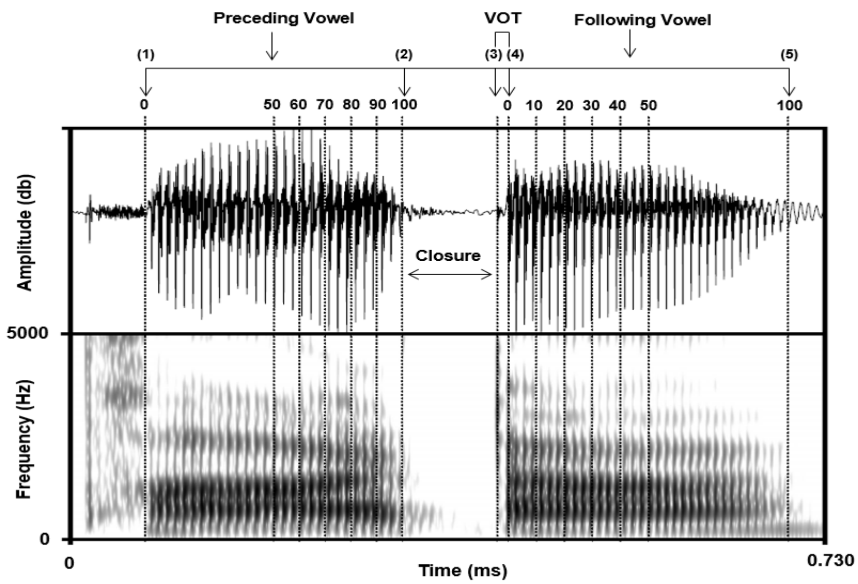

FIG. 1. Spectral and temporal analysis of Punjabi word-medial coronal stops: acoustic waveform and wideband spectrogram for the nonsense word /pʰaʈa/. Temporal landmarks indicated at: (1) preceding vowel onset, (2) preceding vowel offset (stop closure onset), (3) release burst onset, (4) voice onset of following vowel, and (5) following vowel offset. Voice onset time (VOT) is calculated as the duration of interval (4-3). Formants are measured at six sample time points in the second half of the preceding vowel (50, 60, 70, 80, 90, 100% total vowel duration) and at six sample time points in the first half of the following vowel (0, 10, 20, 30, 40, 50% total vowel duration).

III. RESULTS

A. Word-medial stop properties

1. Formant measures of word-medial stops

We first describe the acoustic properties of the Punjabi word-medial retroflex and dental stops, and how these are encoded in the preceding and following vowels. Figures 2a-b show mean formant trajectories of context vowels /i e a o u/ and their characteristic transitions into and out of Punjabi word-medial retroflex and dental stops. The figures show the last 50% of the preceding vowels and first 50% of the following vowels. To examine the influence of Punjabi word-medial retroflex and dental stops on formant trajectories in context vowels, separate repeated-measure ANOVAs for each vowel context were conducted, with consonant type (two levels: retroflex and dental), vowels (/i e a o u/), and sample time points (six levels corresponding to the six sample time points) from preceding (50% to 100%) and following (0% to 50%) vowels as within-subject factors, and F3-F2 difference as a dependent variable. Statistical results are presented in Table I.

For word-medial retroflex and dental stops produced after vowels /e a o u/, the effect of consonant type and sample time points was significant. However, the interaction between consonant type and sample time points was only significant for /a/ and /o/, which indicates that the F3-F2 difference in vowels /a/ and /o/ vary in both retroflex and dental stops. There were no significant interactions between consonant type and sample time points for preceding /e/ and /u/ vowels, suggesting that the F3-F2 difference in vowels /e/ and /u/ did not vary significantly for the retroflex and dental stops. In the context of preceding /i/, there was no effect of consonant type, but a significant effect of sample time points was found. The interaction between consonant type and sample time points was not significant. This suggests that the relationship between second and third formants did not systematically vary with place in the transition from a preceding /i/ into retroflex vs. dental stops. Overall, mean F3-F2 difference from the offset (100%) of the preceding vowels /i e a o u/ was smaller for the retroflex (/i/: 498 Hz (240); /e/: 520 Hz (69); /a/: 352 Hz (135); /o/: 1099 Hz (273); /u/: 1329 Hz (285)) than dental stops (/i/: 592 Hz (147); /e/: 715 Hz (99); /a/: 1352 Hz (118); /o/: 1676 Hz (136); /u/: 1517 Hz (169)). The smallest F3-F2 difference was found for the retroflex stop near the offset of the preceding vowel /a/.

For the F3-F2 difference in vowels /a o u/ produced after word-medial retroflex and dental stops, there was a main effect of consonant type, sample time points, and a significant interaction between consonant type and sample time points, which indicates a significant difference in 2nd and 3rd formant spacing for both retroflex and dental stops in the transitions into these post-consonantal vowels. For post-consonantal /i/, there was no significant effect of consonant type and sample time points; however, the interaction between consonant type and sample time points was significant, which indicates that the higher formant trajectories out of Punjabi retroflex and dental stops into high front vowel /i/ differed significantly. Similarly, there was no main effect of consonant type on F3-F2 difference for coronals produced before vowel /e/. The effect of sample time points was significant, but no significant interaction between consonant type and sample time points was found. This indicates that the F3-F2 difference did not vary significantly across retroflex and dental stops in mid-front vowel context. Mean F3-F2 difference from the onset (0%) of the following vowels /e a o u/ was smaller for the retroflex (/e/: 674 Hz (84); /a/: 994 Hz (179); /o/: 1141 Hz (269); /u/: 1149 Hz (264)) than dental stops (/e/: 694 Hz (137); /a/: 1320 Hz (153); /o/: 1466 Hz (172); /u/: 1391 Hz (141)), but F3-F2 difference from the onset of a following /i/ vowel was larger in retroflexes (630 Hz (98)) than in dental stops (601 Hz (75)).

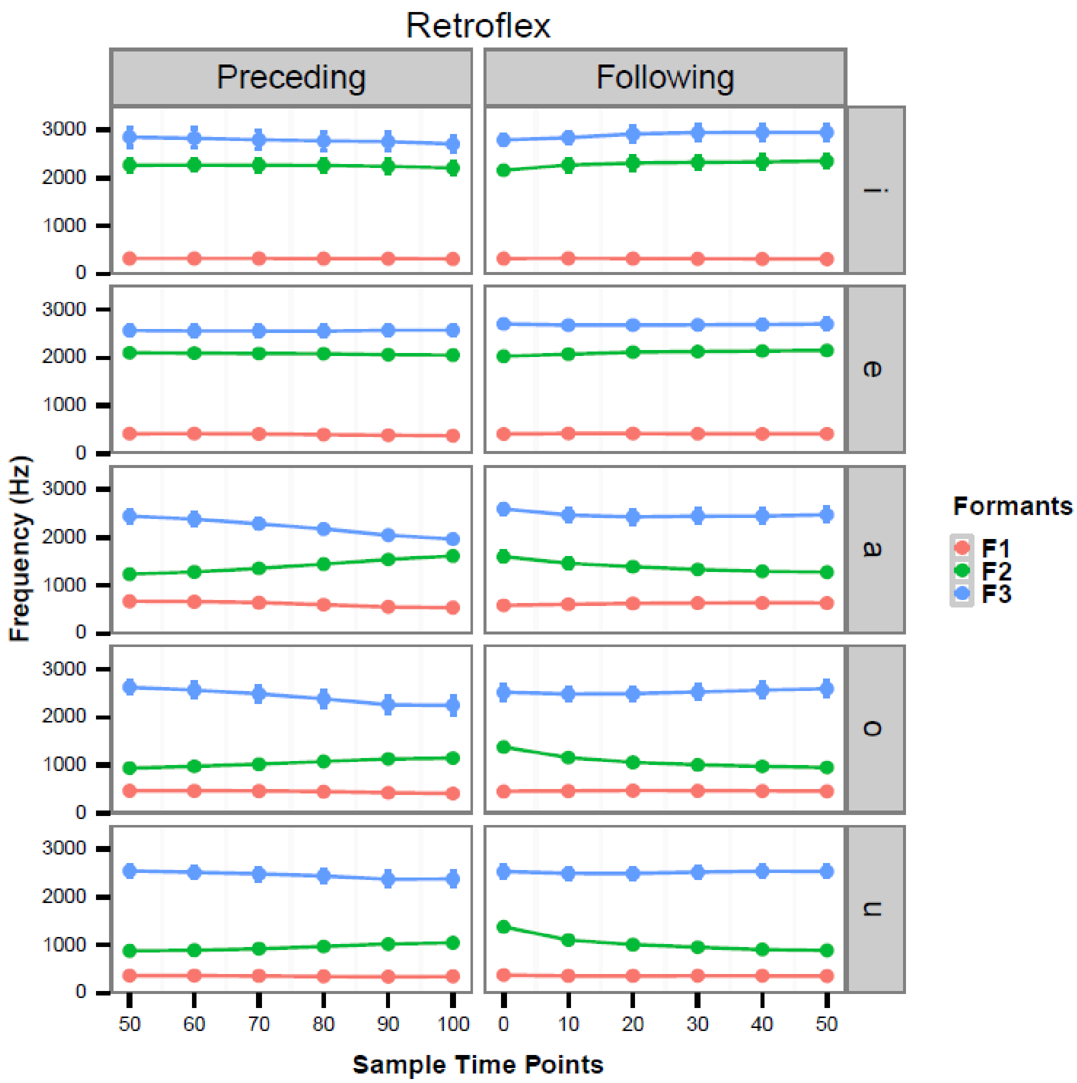

FIG. 2a. (Color online) Mean vowel trajectories (Hz) of /i e a o u/ preceding and following word-medial retroflex stops (all speakers, all items). Formants averaged at six sample time points for each context vowel. Error bars show standard deviation of mean frequencies (Hz).

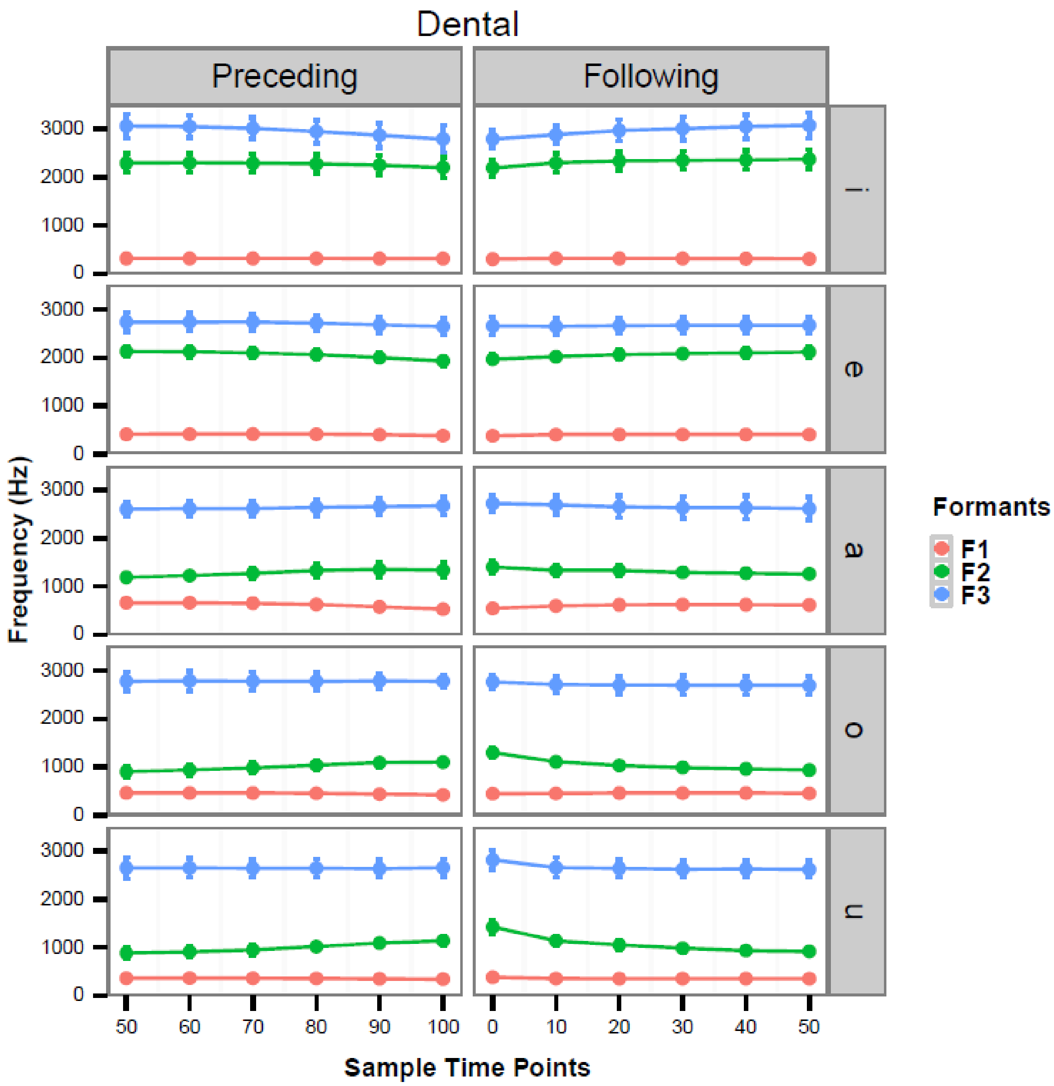

FIG. 2b. (Color online) Mean vowel trajectories (Hz) of /i e a o u/ preceding and following word-medial dental stops (all speakers, all items). Formants averaged at six sample time points for each context vowel. Error bars show standard deviation of mean frequencies (Hz).

Table I. F3-F2 difference in word-medial stops: results of separate repeated-measure ANOVAs with consonant type (two levels: retroflex and dental), vowels (/i e a o u/), and sample time points (six levels corresponding to the six sample time points) from preceding (50% to 100%) and following (0% to 50%) vowels as within-subject factors; F3-F2 difference as a dependent variable. Values inside the parentheses represent degrees of freedom (df) and values on the right side show the *p* values. * indicates statistical significance with alpha value of $p = 0.05$.

	F3-F2 Difference				
Factors	**/i/**	**/e/**	**/a/**	**/o/**	**/u/**
	Preceding Vowel				
Consonant type (CT)	(1, 11) = 0.077	(1, 11) < 0.001*	(1, 11) = 0.001*	(1, 11) < 0.001*	(1, 11) = 0.026*
Time Points (TP)	(5, 55) < 0.001*	(5, 55) < 0.001*	(5, 55) < 0.001*	(5, 55) < 0.001*	(5, 55) < 0.001*
CT*TP	(1.28, 14.13) = 0.147	(5, 55) = 0.185	(5, 55) < 0.001*	(5, 55) < 0.001*	(5, 55) = 0.263
	Following Vowel				
Consonant type (CT)	(1, 11) = 0.229	(1, 11) = 0.435	(1, 11) = 0.001*	(1, 11) < 0.001*	(1, 11) = 0.025*
Time Points (TP)	(5, 55) = 0.129	(5, 55) < 0.001*	(5, 55) < 0.001*	(5, 55) < 0.001*	(5, 55) < 0.001*
CT*TP	(5, 55) = 0.001*	(5, 55) = 0.954	(5, 55) < 0.001*	(5, 55) = 0.012*	(5, 55) < 0.001*

In addition to F3-F2 difference, separate analyses were also run to investigate if third formant trajectories in vowels produced before Punjabi word-medial retroflex and dental stops reliably differentiated the two coronals. Repeated-measure ANOVAs were conducted using consonant type (retroflex and dental), vowels (/i e a o u/), and six sample time points in the preceding vowels (50% to 100%) as within-subject factors, with F3 as a dependent variable. The results showed that F3 transitions into retroflex and dental stops are not significantly different in preceding /i/ context [F (1, 11) = 3.909, p = 0.074]; however, F3 transitions from preceding vowels /e a o u/ did differ significantly (/e/: [F (1, 11) = 18.019, p = 0.001]; /a/: [F (1, 11) = 104.472, p < 0.001]; /o/: [F (1, 11) = 23.392, p = 0.001]; /u/: [F (1, 11) = 14.577, p = 0.003]). These data suggest that F3 may only provide a robust cue to place for coronal stops produced after non high-front vowels in Punjabi.

2. Temporal properties of word-medial stops

Figure 3 presents the boxplots of closure duration, VOT, and total stop duration of the Punjabi word-medial retroflex and dental stops. Separate repeated-measure ANOVAs in each vowel context were conducted using consonant type (retroflex and dental) and vowels (/i e a o u/) as within-subject factors; closure duration, VOT, and total stop duration as dependent variables. The ANOVA results indicated that there were significant differences in closure duration of the Punjabi word-medial retroflex and dental stops, but only in the context of /i_i/ [F (1, 11) = 25.710, p < 0.001], /e_e/ [F (1, 11) = 32.568, p < 0.001], and /a_a/ [F (1, 11) = 15.537, p = 0.002]. In the context of back vowels, /o_o/ [F (1, 11) = 2.840, p = 0.120] and /u_u/ [F (1, 11) = 2.162, p = 0.169], closure duration did not differentiate word-medial stops.

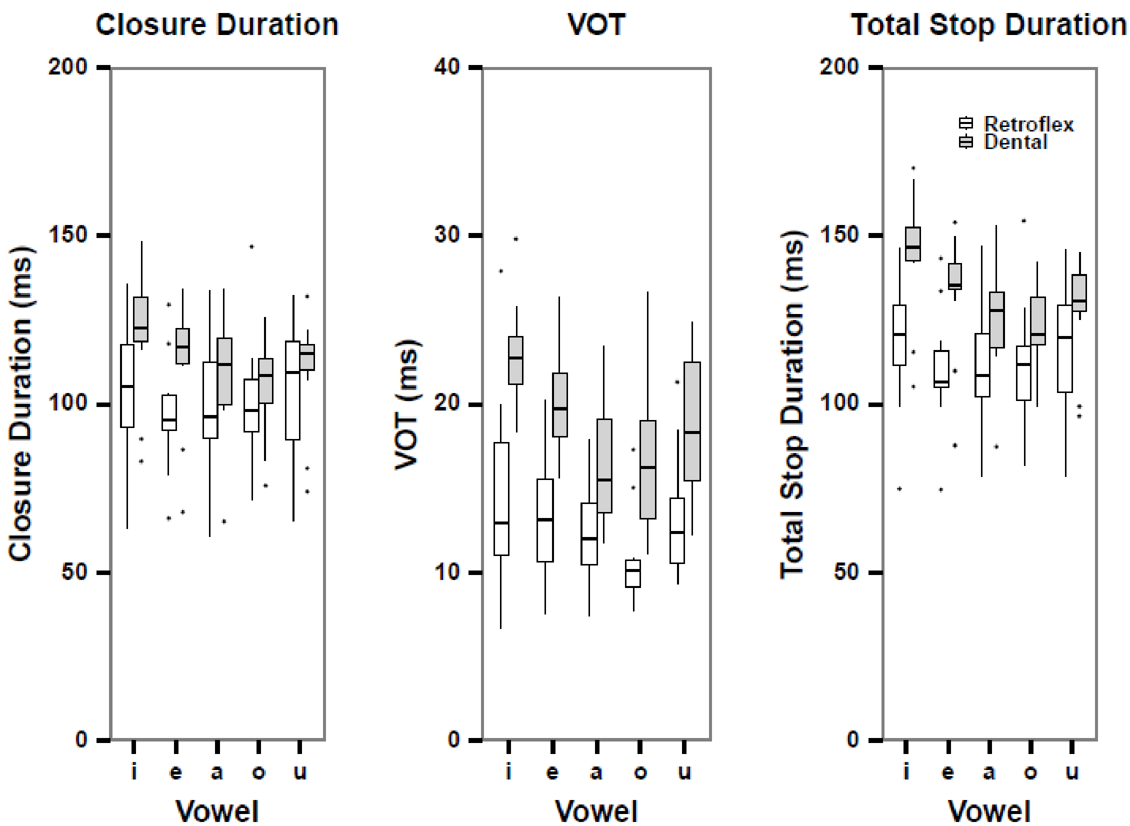

FIG. 3. Boxplots of closure duration (ms), VOT (ms), and total stop duration (ms) of Punjabi word-medial retroflex and dental stops produced in /i_i/, /e_e/, /a_a/, /o_o/, and /u_u/ contexts (all speakers, all items).

VOT reliably differentiated the Punjabi word-medial retroflex and dental stops in all vowel contexts (/i_i/: [F (1, 11) = 33.524, p < 0.001]; /e_e/: [F (1, 11) = 33.559, p < 0.001]; /a_a/: [F (1, 11) = 8.381, p = 0.015]; /o_o/: [F (1, 11) = 16.176, p = 0.002]; /u_u/: [F (1, 11) = 13.170, p = 0.004]). Similarly, total stop duration also differentiated the word-medial retroflex and dental stops in all vowel contexts (/i_i /: [F (1, 11) = 54.392, p < 0.001]; /e_e/: [F (1, 11) = 60.171, p < 0.001]; /a_a/: [F (1, 11) = 42.261, p < 0.001]; /o_o/: [F (1, 11) = 10.625, p = 0.008]; /u_u/: [F (1, 11) = 6.269, p = 0.029]).

Retroflex stops were characterized by shorter mean closure duration and VOT (closure duration: 101 ms (20); VOT: 13 ms (4)), averaged across all vowel contexts). In contrast, dental stops showed longer mean closure duration and VOT (closure duration: 112 ms (18); VOT: 19 ms (4)). The total stop duration of the retroflex stops was also shorter (113 ms (19)) than that of the dental stops (131 ms (17)). Having examined their temporal properties, we will now address the spectral characteristics of stop release bursts of Punjabi word-medial retroflex and dental stops.

3. Spectral properties of word-medial stop releases

Figure 4 depicts the boxplots of spectral moments (spectral CoG, spectral variance, spectral skewness, and spectral kurtosis) of stop release bursts of Punjabi word-medial retroflex and dental stops produced in all five vowel /i e a o u/ contexts. Separate repeated-measure ANOVAs in each vowel context were conducted using consonant type (retroflex and dental) and vowels (/i e a o u/) as within-subject factors; spectral CoG, spectral variance, spectral skewness, and spectral kurtosis as dependent variables. The results of repeated-measure ANOVAs in each vowel context indicated that spectral CoG differentiated the Punjabi retroflex and dental stops in the context of the back vowels (/o_o/: [F (1, 11) = 27.746, $p < 0.001$]; /u_u/: [F (1, 11) = 45.814, $p < 0.001$]). However, spectral CoG did not differentiate the Punjabi word-medial retroflex and dental stops in the context of /i_i/ [F (1, 11) = .041, $p = 0.843$], /e_e/ [F (1, 11) = .333, $p = 0.575$], and /a_a/ [F (1, 11) = .178, $p = 0.681$]. There were no consistent patterns in the spectral CoG values across the two stops in /i_i/, /e_e/, and /a_a/ contexts. However, in the context of back non-low vowels, retroflex stops (/o_o/: 835 Hz (174); /u_u/: 728 Hz (171)) consistently showed smaller spectral CoG values compared to dental stops (/o_o/: 1493 Hz (353); /u_u/: 1565 Hz (468)). Mean spectral CoG collapsed across all vowel contexts was 1070 Hz (242) for retroflex stops and 1371 Hz (385) for dental stops, suggesting that the concentration of acoustic energy in the burst spectrum is characteristically lower for retroflexes than dentals.

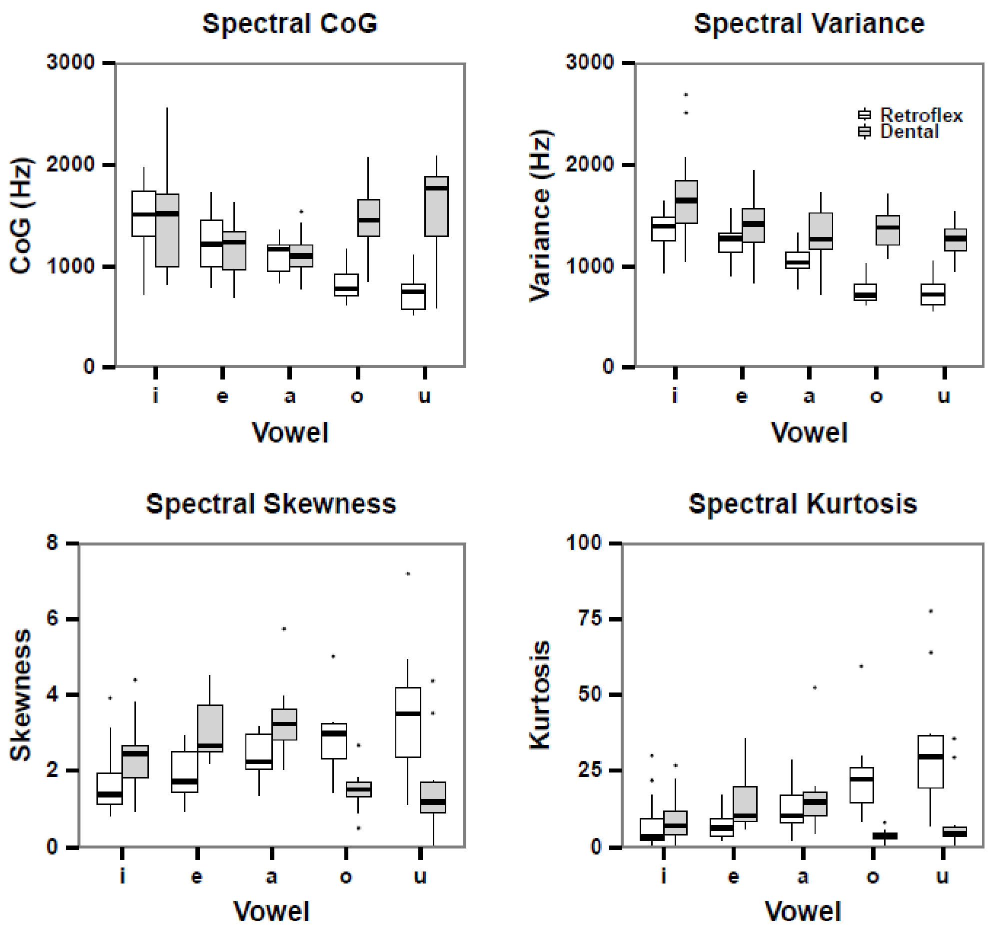

FIG. 4. Boxplots of spectral CoG (Hz), spectral variance (Hz), spectral skewness, and spectral kurtosis of stop release bursts of Punjabi word-medial retroflex and dental stops produced in /i_i/, /e_e/, /a_a/, /o_o/, and /u_u/ contexts (all speakers, all items).

Spectral variance reliably distinguished the Punjabi word-medial retroflex and dental stops in the context of /i_i/ [F (1, 11) = 5.748, p = 0.035], /a_a/ [F (1, 11) = 24.098, p < 0.001], /o_o/ [F (1, 11) = 98.043, p < 0.001], and /u_u/ [F (1, 11) = 65.011, p < 0.001]. However, the coronals were not differentiated in the context of /e_e/ [F (1, 11) = 3.711, p = 0.080]. Two speakers produced dental stops with very low spectral variance (SP9: 830 Hz; SP10: 940 Hz) in the /e_e/ context, even lower than retroflex stops (SP9: 905 Hz; SP10: 1078 Hz). This is probably why spectral variance did not reach statistical significance. After excluding these two speakers, spectral variance was significant for both retroflex and dental stops [F (1, 9) = 5.670, p = 0.041]. Spectral variance was lowest for the word-medial retroflex stops (/i_i/: 1357 Hz (194); /e_e/: 1246 Hz (179); /a_a/: 1057 Hz (156); /o_o/: 764 Hz (149); /u_u/: 739 Hz (148)), compared to dental stops (/i_i/: 1718 Hz (506); /e_e/: 1398 Hz (331); /a_a/: 1304 Hz (277); /o_o/: 1375 Hz (199); /u_u/: 1259 Hz (181)). Averaged across all vowels, overall spectral variance was 1033 Hz (165) for retroflex stops and 1411 Hz (299) for dental stops.

Spectral skewness differentiated the Punjabi word-medial retroflex and dental stops across all vowel contexts, except /i_i/ (/i_i/: [F (1, 11) = 2.144, p = 0.171]; /e_e/: [F (1, 11) = 13.047, p = 0.004]; /a_a/: [F (1, 11) = 15.035, p = 0.003]; /o_o/: [F (1, 11) = 17.969, p = 0.001]; /u_u/: [F (1, 11) = 14.908, p = 0.003]). There were no significant differences in spectral skewness of stop release bursts of the retroflex and dental stops in the context of /i_i/, but the retroflex stops showed much smaller spectral skewness in the context of /i_i/ (1.75 (1)), compared to dental stops (2.42 (.97)). In back vowel contexts, retroflex stops were characterized by higher spectral skewness (/o_o/: 2.86 (.93); /u_u/: 3.55 (1.60)) than dental stops (/o_o/: 1.49 (.53); /u_u/: 1.52 (1.25)).

Spectral kurtosis distinguished the Punjabi word-medial retroflex and dental stops in the context of /e_e/, /o_o/, and /u_u/, but not in the context of /i_i/ and /a_a/ (/i_i/: [F (1, 11) = .091, p = 0.768]; /e_e/: [F (1, 11) = 5.929, p = 0.033]; /a_a/: [F (1, 11) = 2.809, p = 0.122]; /o_o/: [F (1, 11) = 26.587, p < 0.001]; /u_u/: [F (1, 11) = 15.970, p = 0.002]). The highest spectral kurtosis values were observed for the retroflex stops produced in back vowel contexts (/o_o/: 23.51 (13);

/u_u/: 32.30 (20)). In contrast, dental stops showed the lowest spectral kurtosis values in /o_o/ and /u_u/ contexts (/o_o/: 3.83 (1); /u_u/: 8.81 (11)).

B. Word-initial stop properties

1. Formant measures of word-initial stops

Mean formant trajectories of following vowels /i e a o u/ produced after the Punjabi word-initial retroflex and dental stops are illustrated in Figure 5. To evaluate the behavior of higher formant transitions out of Punjabi word-initial retroflex and dental stops, separate repeated-measure ANOVAs for each vowel context were conducted, with consonant type (two levels: retroflex and dental), vowels (/i e a o u/), and sample time points (six levels corresponding to the six sample time points) from following vowels (0% to 50%) as within-subject factors, and F3-F2 difference as a dependent variable. Statistical results are presented in Table II.

The results showed that there was a significant effect of consonant type and sample time points for stops produced before /i/, but no significant interaction between consonant type and sample time points was found. This indicates that 2^{nd} and 3^{rd} formant spacing did not systematically differ in the transition from retroflex vs. dental stops to a following high front vowel. For stops produced before /e/, no significant effect of consonant type was observed on higher formant spacing. There was a significant effect of sample time points for following /e/ but no significant interaction between consonant type and sample time points. This indicates that F3-F2 difference does not contrast significantly for Punjabi retroflex and dental stops produced before /e/. For the following /a o u/ vowels, the effect of consonant type and sample time points was significant. However, the interaction between consonant type and sample time points was only significant for /a/ and /o/, showing significant F3-F2 differences for retroflex and dental stops produced before low back vowels. Mean F3-F2 difference from the onset (0%)

of the following vowels /e a o u/ was shorter for the retroflex (/e/: 664 Hz (119); /a/: 1035 Hz (203); /o/: 1181 Hz (248); /u/: 1231 Hz (251)) than dental stops (/e/: 670 Hz (109); /a/: 1319 Hz (158); /o/: 1526 Hz (196); /u/: 1469 Hz (207)). However, the F3-F2 difference from the onset of following /i/ vowel was larger in retroflex (672 Hz (149)) than dental stops (543 Hz (123)).

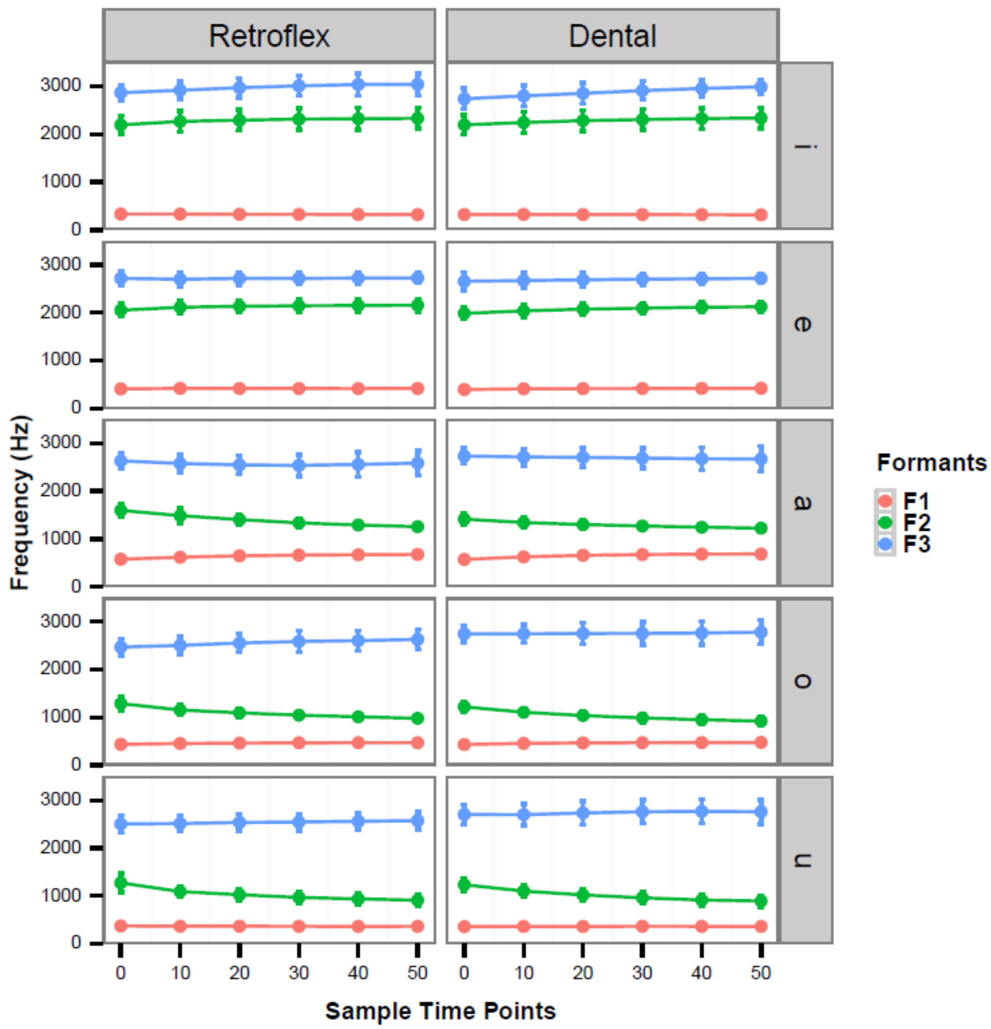

FIG. 5. (Color online) Mean vowel trajectories (Hz) of /i e a o u/ produced after word-initial retroflex (left) and dental (right) stops (all speakers, all items). Formants averaged at six sample time points for each context vowel. Error bars show standard deviation of mean frequencies (Hz).

Table II. F3-F2 difference in word-initial stops: results of separate repeated-measure ANOVAs with consonant type (two levels: retroflex and dental), vowels (/i e a o u/), and sample time points (six levels corresponding to the six sample time points) from following vowels (0% to 50%) as within-subject factors; F3-F2 difference as a dependent variable. Values inside the parentheses represent the df and values on the right side show the *p* values. * indicates statistical significance with alpha value of *p* = 0.05.

	F3-F2 (Hz) of Following Vowel				
Factors	**/i/**	**/e/**	**/a/**	**/o/**	**/u/**
Consonant type (CT)	(1,11) = 0.057*	(1, 11) = 0.239	(1, 11) = 0.017*	(1, 11) < 0.001*	(1, 11) = 0.001*
Time Points (TP)	(5, 55) = 0.002*	(5, 55) < 0.001*	(5, 55) < 0.001*	(5, 55) < 0.001*	(5, 55) < 0.001*
CT*TP	(5, 55) = 0.275	(5, 55) = 0.408	(5, 55) < 0.001*	(5, 55) < 0.001*	(5, 55) = 0.522

2. Temporal properties of word-initial stops

Figure 6 presents boxplots of VOT for the Punjabi word-initial retroflex and dental stops. Separate repeated-measure ANOVAs were conducted with consonant type (retroflex and dental) and vowels (/i e a o u/) as within-subject factors, and VOT as a dependent variable. The ANOVA results showed that VOT significantly distinguished word-initial retroflex and dental stops across all vowel contexts (/i/: [F (1, 11) = 200.476, p < 0.001]; /e/: [F (1, 11) = 54.851, p < 0.001]; /a/: [F (1, 11) = 7.129, p = 0.022]; /o/: [F (1, 11) = 12.936, p = 0.004]; /u/: [F (1, 11) = 29.306, p < 0.001]), which suggests that VOT is a robust acoustic correlate of place for Punjabi word-initial retroflex and dental stops. Longer VOTs can be observed for dentals (/i/: 25 ms (3); /e/: 21 ms (4); /a/: 18 ms (3); /o/: 17 (3); /u/: 22 ms (4)) produced in all vowel contexts, compared to the shorter VOTs that characterize retroflex stops (/i/: 15 ms (3); /e/: 14 ms (3); /a/: 15 ms (4); /o/: 14 (4); /u/: 16 ms (3)) produced before the same vowels. Mean VOT for retroflexes collapsed across all vowels was shorter (15 ms (3)) than the grand mean VOT for dentals (21 ms (4)).

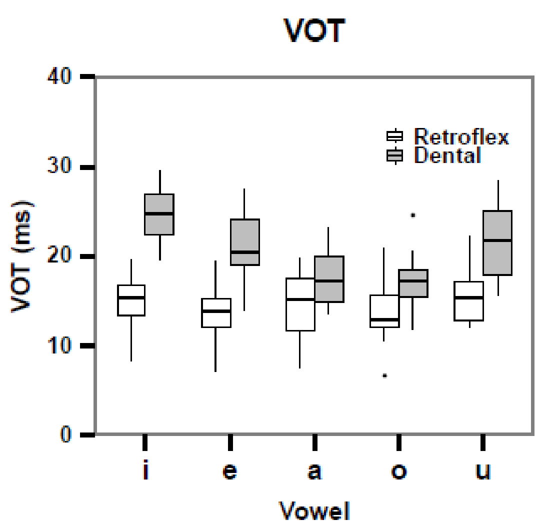

FIG. 6. Boxplot of VOT (ms) of Punjabi word-initial retroflex and dental stops produced before vowels /i e a o u/ (all speakers, all items).

3. Spectral properties of word-initial stop releases

Boxplots of the first four spectral moments (spectral CoG, spectral variance, spectral skewness, and spectral kurtosis) characterizing stop release bursts of the Punjabi word-initial retroflex and dental stops are compared in Figure 7. Separate repeated-measure ANOVAs in each vowel context were conducted using consonant type (retroflex and dental) and vowels (/i e a o u/) as within-subject factors; spectral CoG, spectral variance, spectral skewness, and spectral kurtosis as dependent variables. The results of repeated-measure ANOVAs in each vowel context indicated that spectral CoG differentiated the Punjabi word-initial retroflex and dental stops only before /o u/, but not before /i e a/ contexts (/i/: [F (1, 11) = 1.203, p = 0.296]; /e/: [F (1, 11) = .052, p = 0.823]; /a/: [F (1, 11) = .395, p = 0.542]; /o/: [F (1, 11) = 44.922, p < 0.001]; /u/: [F (1, 11) = 65.193, p < 0.001]). In the context of back vowels, retroflex stops showed much smaller spectral CoG (/o/: 886 Hz (166); /u/: 777 Hz (227)) compared to dental stops (/o/: 1723 Hz (337); /u/: 1728 Hz (430)). When collapsed across all vowels, the mean spectral CoG of the word-initial retroflex and dental stops was 1128 Hz (256) and 1550 Hz (417), respectively.

Spectral variance distinguished the Punjabi word-initial retroflex and dental stop bursts before all vowels except /e/ (/i/: [F (1, 11) = 8.859, p = 0.013]; /e/: [F (1, 11) = 3.080, p = 0.107]; /a/: [F (1, 11) = 10.972, p < 0.007]; /o/: [F (1, 11) = 91.717, p < 0.001]; /u/: [F (1, 11) = 64.329, p < 0.001]). Similar to the word-medial data, in the context of /e/, SP9 and SP10 produced dental stops with lower spectral variance (1014 Hz and 1124 Hz, respectively) than retroflex stops (1109 Hz and 1335 Hz). After excluding these two speakers, spectral variance was significant for both dental and retroflex stops [F (1, 9) = 5.283, p = 0.047]. The word-initial retroflex stops showed the lowest spectral variance across all vowels (/i/: 1388 Hz (202); /e/: 1315 Hz (137); /a/: 1098 Hz (135); /o/: 765 Hz (150); /u/: 722 Hz (121)) than dental stops (/i/:

1748 Hz (361); /e/: 1471 Hz (316); /a/: 1444 Hz (337); /o/: 1567 Hz (330); /u/: 1410 Hz (299)). The overall spectral variance collapsed across all vowels was 1058 Hz (149) for retroflex stops and 1528 Hz (329) for dental stops.

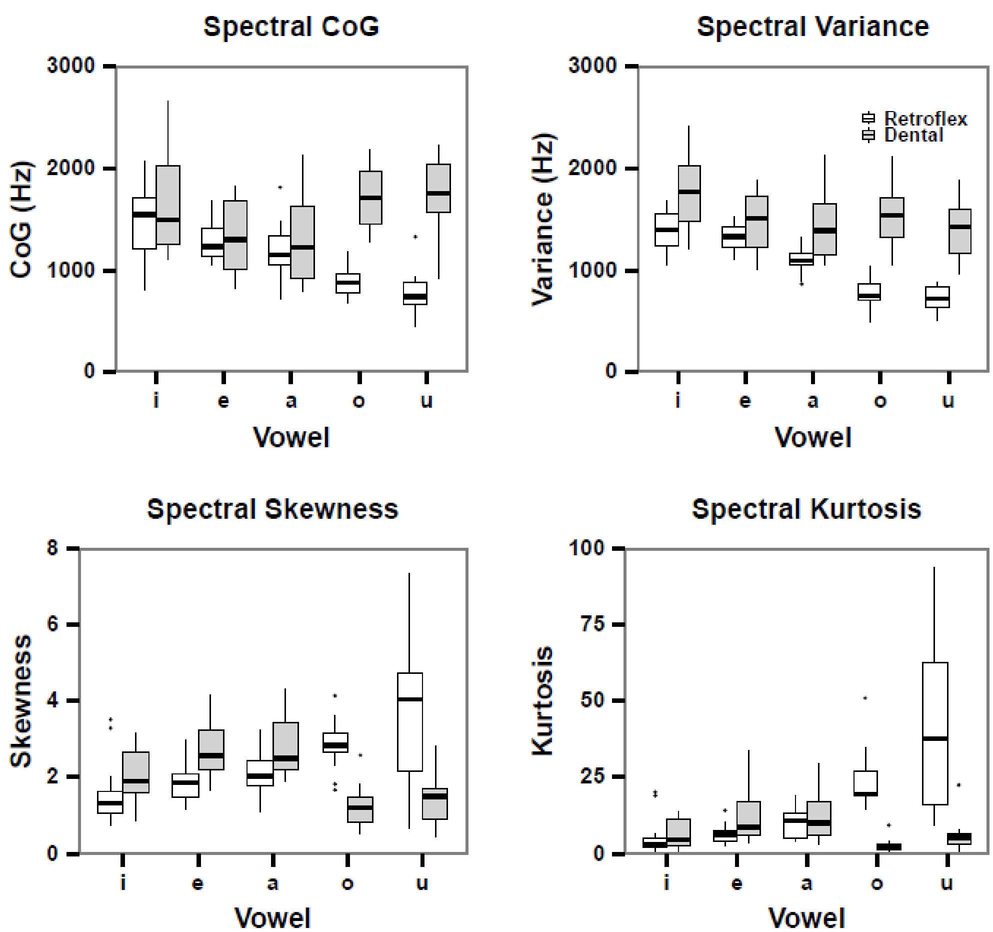

FIG. 7. Boxplots of spectral CoG (Hz), spectral variance (Hz), spectral skewness, and spectral kurtosis of stop release bursts of Punjabi word-initial retroflex and dental stops produced before /i/, /e/, /a/, /o/, and /u/ contexts (all speakers, all items).

Word-initial coronal release bursts were differentiated by spectral skewness but only before /e o u/ (/i/: [F (1, 11) = 1.458, p = 0.253]; /e/: [F (1, 11) = 9.301, p = 0.011]; /a/: [F (1, 11) = 4.391, p = 0.060]; /o/: [F (1, 11) = 38.177, p < 0.001]; /u/: [F (1, 11) = 18.907, p = 0.001]).

Spectral skewness of the Punjabi word-initial retroflex stop releases was higher in the context of the back vowels /o u/ (/o/: 2.88 (.71); /u/: 3.80 (1)) compared to dental stops in the same vocalic contexts (/o/: 1.25 (.58); /u/: 1.39 (.68)). Spectral skewness collapsed across all vowels was 2.45 (.94) for the retroflex stops and 2.04 (.71) for the dental stops.

Release burst spectral kurtosis distinguished the Punjabi word-initial retroflex and dental stops only before /e o u/ (/i/: [F (1, 11) = .045, p = 0.837]; /e/: [F (1, 11) = 4.532, p = 0.057]; /a/: [F (1, 11) = .763, p = 0.401]; /o/: [F (1, 11) = 59.527, p < 0.001]; /u/: [F (1, 11) = 17.038, p = 0.002]). Spectral kurtosis of word-initial retroflex stops produced before back vowels /o u/ was higher (/o/: 23.91 (10); /u/: 40.87 (29)) than for dental stops produced in the same contexts (/o/: 2.74 (2); /u/: 6.07 (5)). Mean spectral kurtosis collapsed across all vowel contexts was 17.41 (10.82) for retroflex stops and 8 (5.94) for dental stops.

C. Word-final stop properties

1. Formant measures of word-final stops

Figure 8 presents the mean formant trajectories of the vowels /i a u/ produced before the Punjabi word-final retroflex and dental stops. A repeated-measures ANOVA was conducted with consonant type (two levels: retroflex and dental), vowels (/i a u/), and sample time points (six levels corresponding to the six sample time points) from preceding vowels (50% to 100%) as within-subject factors, and F3-F2 difference as a dependent variable. Statistical results are presented in Table III.

The ANOVA results indicated that there was a significant effect of consonant type for word-final stops produced after /i/ (showing larger F3-F2 difference for dental than retroflex stops) but neither sample time points nor the interaction between consonant type and sample time points were statistically significant. This suggests that F3-F2 difference did not vary across sample time points for both retroflex and dental stops. A main effect of consonant type and sample time points on F3-F2 difference was found for stops produced after /a/ and /u/ vowels, with a significant interaction between consonant type and sample time points. This indicates that F3-F2 difference varied significantly across time points and two stop types. Mean F3-F2 difference from the offset (100%) of the preceding vowels /i a u/ was shorter for retroflex (/i/: 473 Hz (84); /a/: 331 Hz (88); /u/: 1039 Hz (283)) than dental stops (/i/: 612 Hz (102); /a/: 1190 Hz (171); /u/: 1441 Hz (158)).

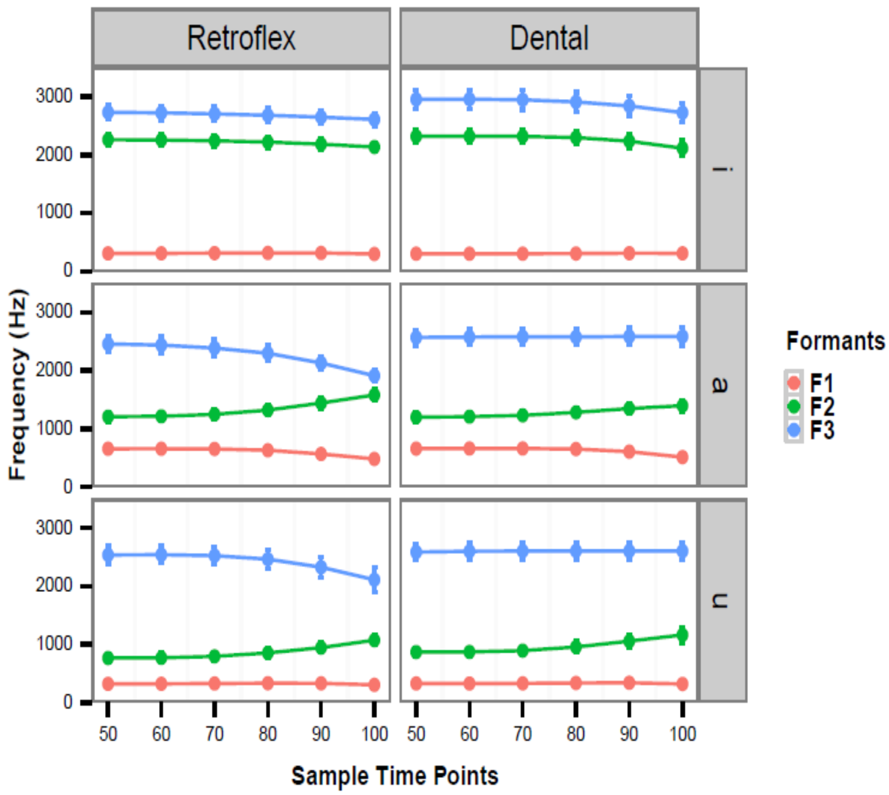

FIG. 8. (Color online) Mean vowel trajectories (Hz) of /i a u/ produced before Punjabi word-final retroflex (left) and dental (right) stops (all speakers, all items). Formants averaged at six sample time points for each vowel. Error bars show standard deviation of mean frequencies (Hz).

Table III. F3-F2 difference in word-final stops: results of separate repeated-measure ANOVAs with consonant type (two levels: retroflex and dental), vowels (/i a u/), and sample time points (six levels corresponding to the six sample time points) from preceding vowels (50% to 100%) as within-subject factors; F3-F2 difference as a dependent variable. Values inside the parentheses represent the df and values on the right side show the *p* values. * indicates statistical significance with alpha value of $p = 0.05$.

	F3-F2 (Hz) before Word-Final Stop		
Factors	**/i/**	**/a/**	**/u/**
Consonant type (CT)	(1, 17) < 0.001*	(1, 17) < 0.001*	(1, 17) = 0.002*
Time Points (TP)	(5, 85) = 0.542	(5, 85) < 0.001*	(5, 85) < 0.001*
CT*TP	(5, 85) = 0.437	(5, 85) < 0.001*	(5, 85) < 0.001*

In addition to F3-F2 difference, separate analyses were also run to investigate if third formant trajectories in vowels produced before Punjabi word-final retroflex and dental stops reliably differentiated the two coronals. Repeated-measure ANOVAs were conducted using consonant type (retroflex and dental), vowels (/i a u/), and six sample time points (corresponding to the six sample time points) from preceding vowels (50% to 100%) as within-subject factors, with F3 as a dependent variable. The results showed that F3 transitions into retroflex and dental stops are significantly different across vowel contexts (/i/: [F (1, 17) = 56.261, $p < 0.001$]; /a/: [F (1, 17) = 167.553, $p < 0.001$]; /u/: [F (1, 17) = 81.750, $p < 0.001$]). The reason F3 achieved statistical significance in the context of front vowel /i/ because F3 is slightly higher for the dental than retroflex stops (see Figure 8).

2. Temporal properties of word-final stops

Figure 9 shows boxplots of closure duration, burst duration, and total stop duration of the Punjabi word-final retroflex and dental stops. To evaluate whether these temporal characteristics robustly distinguished the Punjabi word-final retroflex and dental stops across all vowels /i a u/, separate repeated-measure ANOVAs in each vowel context were conducted using consonant type (retroflex and dental) and vowels (/i a u/) as within-subject factors; closure duration, burst duration, and total stop duration as dependent variables. The ANOVA results showed that there was a closure duration difference between the Punjabi word-final retroflex and dental stops produced after all three vowels (/i/: [F (1, 17) = 29.092, p < 0.001]; /a/: [F (1, 17) = 44.068, p < 0.001]; /u/: [F (1, 17) = 31.420, p < 0.001]). The burst duration of the word-final retroflex and dental stops was also significant for each vowel context (/i/: [F (1, 17) = 17.630, p = 0.001]; /a/: [F (1, 17) = 23.549, p < 0.001]; /u/: [F (1, 17) = 25.999, p < 0.001]). Significant contrasts were also found for total stop durations (/i/: [F (1, 17) = 49.672, p < 0.001]; /a/: [F (1, 17) = 67.941, p < 0.001]; /u/: [F (1, 17) = 53.415, p < 0.001]).

The retroflex stops were consistently produced with smaller closure and burst durations (closure duration: 86 ms (21); burst duration: 10 ms (2), averaged across all vowel contexts), compared to dental stops (closure duration: 101 ms (20); burst duration: 15 ms (4)). The total stop duration also appeared to maintain the contrast between retroflex (96 ms (22)) and dental (116 ms (20)) stops. The findings suggest that in word-final context, all temporal cues consistently differentiated Punjabi retroflex and dental stops produced after all vowels.

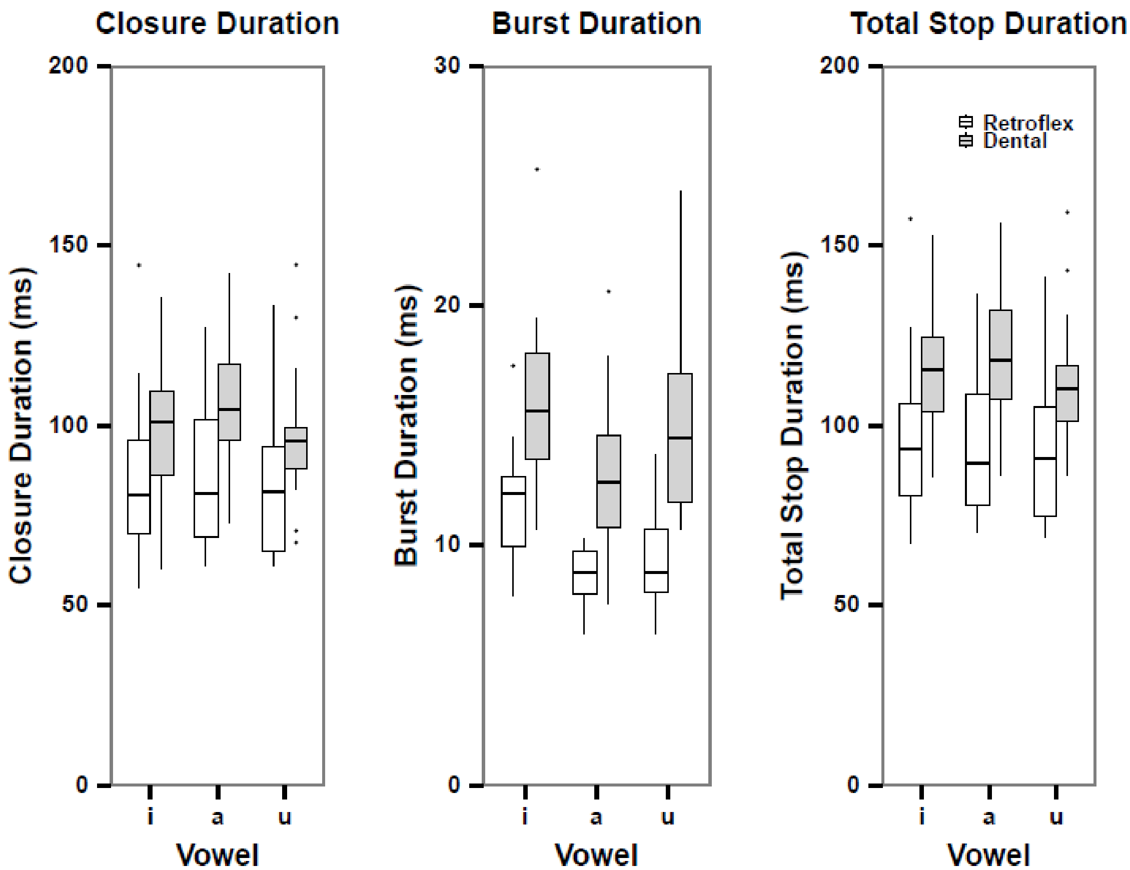

FIG. 9. Boxplots of closure duration (ms), burst duration (ms), and total stop duration (ms) of Punjabi word-final retroflex and dental stops produced after /i a u/ (all speakers, all items).

3. Spectral properties of word-final stop releases

Figure 10 presents the boxplots illustrating the first four spectral moments (spectral CoG, spectral variance, spectral skewness, and spectral kurtosis) of the Punjabi word-final retroflex and dental stops produced after the vowels /i a u/. To investigate whether spectral moments of stop release bursts consistently distinguished the Punjabi retroflex and dental stops in all vocalic environments, separate repeated-measure ANOVAs in each vowel context were conducted using consonant type (retroflex and dental) and vowels (/i a u/) as within-subject factors; spectral CoG, spectral variance, spectral skewness, and spectral kurtosis as dependent variables.

The ANOVA results showed that spectral variance reliably differentiated the retroflex and dental stops in all three vocalic environments (/i/: [F (1, 17) = 53.463, p < 0.001]; /a/: [F (1, 17) = 65.087, p < 0.001]; /u/: [F (1, 17) = 75.866, p < 0.001]). Spectral CoG also differentiated retroflexes and dentals but only in the context of /u/ (/i/: [F (1, 17) = .322, p = 0.578]; /a/: [F (1, 17) = 1.945, p = 0.181]; /u/: [F (1, 17) = 40.153, p < 0.001]). Spectral skewness distinguished the two stops after /i/ and /a/, but not /u/ (/i/: [F (1, 17) = 19.104, p < 0.001]; /a/: [F (1, 17) = 8.536, p = 0.010]; /u/: [F (1, 17) = .636, p = 0.436]). Spectral kurtosis only distinguished the word-final retroflex and dental stops produced after /u/, but not in /i/ and /a/ contexts (/i/: [F (1, 17) = 3.959, p = 0.063]; /a/: [F (1, 17) = .728, p = 0.405]; /u/: [F (1, 17) = 5.741, p = 0.028]).

Overall, dental stops were characterized by higher spectral CoG (1689 Hz (484), collapsed across vowels), spectral variance (1677 Hz (309)), spectral skewness (2.06 (1.14)), and spectral kurtosis (8.30 (9.43)). Retroflex stops, on the other hand, showed small spectral CoG (1484 Hz (372)), spectral variance (1154 Hz (198)), spectral skewness (1.41 (.77)), and spectral kurtosis (7.06 (5.13)). In the context of /i/, retroflex stops showed highest spectral CoG (1863 Hz (398)) and spectral variance (1332 Hz (205)). However, lowest spectral CoG (1218 Hz (323)) and spectral variance (1014 Hz (190)) were observed in the context of back vowel /u/. This suggests that the place of articulation of the retroflex is fronted after /i/, but is retracted following /u/. These results are consistent with coarticulatory factors, if the retroflex stop was produced with a more anterior posture in the context of /i/ compared to those produced after /u/. Dental stops showed an increase in the spectral CoG of their release bursts when produced after /u/ (1797 Hz (449)), compared to /i/ (1791 Hz (542)), but the lowest spectral CoG for dental stops was found in the context of /a/ (1479 Hz (460)).

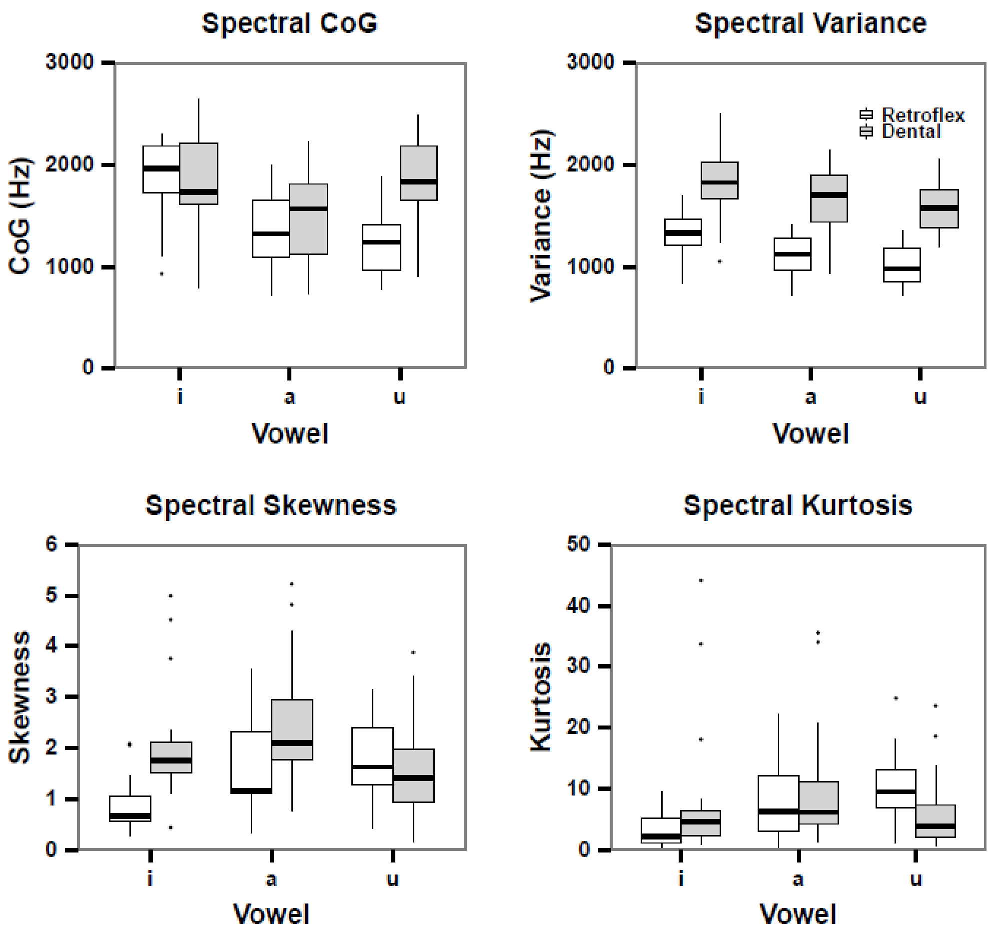

FIG. 10. Boxplots of spectral CoG (Hz), spectral variance (Hz), spectral skewness, and spectral kurtosis of stop release bursts of Punjabi word-final retroflex and dental stops produced after /i a u/ contexts (all speakers, all items).

IV. DISCUSSION

In this study, we investigated the acoustic phonetic properties of Punjabi retroflex and dental stops in word-medial, word-initial, and word-final contexts. The findings suggest that Punjabi coronal place contrasts are signaled by the complex interaction of temporal and spectral cues.

In word-medial context, VOT and total stop duration consistently differentiated the Punjabi retroflex and dental stops. Spectral variance was also significant for all speakers in all vocalic environments, except /e_e/. Two speakers (SP9 and SP10) had very low spectral variance for dental stops in /e_e/ context (lower than retroflex stops), which affected the overall spectral variance. However, after excluding these two speakers, spectral variance of medial stop release bursts differed significantly for the remaining speakers in all word-medial contexts (and also in word-initial context; see the discussion below). Spectral skewness in /i_i/ and spectral kurtosis in /i_i/ and /a_a/ contexts failed to characterize the Punjabi word-medial retroflex and dental stops. Similarly, the F3-F2 difference of the preceding vowel /i/ was not significantly different for retroflex and dental stops (suggesting no F3-F2 convergence), which is consistent with the findings of Gujarati retroflexes (Dave, 1977). However, F3-F2 difference reliably differentiated the word-medial stops in /a o u/ contexts. Third formant trajectories of preceding vowels /e a o u/ reliably distinguished retroflex and dental stops, but F3 did not vary significantly for stops produced after /i/. These findings showed that word-medial context is the maximally informative phonetic environment in which to encode coronal contrasts, but not all acoustic properties provide robust cues to coronal place contrasts.

Word-initially, VOT consistently differentiated both retroflex and dental stops. Similar to the word-medial context, spectral variance of the Punjabi word-initial retroflex and dental stops was significant before /i a o u/ but not before /e/. After excluding the two speakers (SP9 and SP10), spectral variance achieved statistical significance across all vowels. Spectral CoG of the word-initial stop bursts was significant in /o u/ contexts; spectral skewness and spectral kurtosis differentiated the Punjabi word-initial retroflex and dental stops but only in the contexts of /e o u/. All acoustic properties distinguished word-initial retroflex and dental stops produced before back non-low vowels /o u/. The F3-F2 difference failed to characterize Punjabi word-initial retroflex and dental stops produced before /e/.

Word-finally, all temporal characteristics examined differed significantly between retroflex and dental stops. Third formant trajectories, and F3-F2 differences were also significantly different for stops produced after all context vowels /i a u/; however, F3-F2 difference did not vary systematically and categorically for stops following the high-front vowel /i/. Among the four spectral characteristics of stop release bursts examined, only spectral variance consistently differentiated the retroflex and dental stops in all vocalic environments.

In all word contexts, VOT (or burst duration) and total stop duration of the Punjabi retroflex and dental stops produced by these Punjabi speakers pattern consistently with data from other languages showing that retroflexes are characterized by short VOTs, compared to dentals (Tiwi: Anderson and Maddieson, 1994; Wubuy: Bundgaard-Nielsen et al., 2016; Central Arrernte: Tabain, 2012). On the other hand, our results differ from other studies that found no difference in VOT of the retroflex and dental stops in Bengali (Maxwell et al., 2015). These differences might be due to the types of target words used in our study and other related studies. For instance, Maxwell et al. (2015) used word-medial voiceless aspirated retroflex and dental stops of Bengali in the context of /i/ and /a/ vowels and found no differences between the closure duration, VOT, and total stop duration of the retroflex and dental stops across all vowels. Interestingly, their findings suggested that the dental stop had shorter total stop duration than the retroflex stop (at least in real words). The use of voiceless aspirated stops might be a confounding factor for the quantification of release cues to place oppositions. Voiceless aspirated stops have a very long aspiration phase which masks the actual duration of the stops (Mikuteit and Reetz, 2007). Furthermore, Maxwell et al. (2015) did not measure the spectral moments of stop release bursts. In contrast, our study measured both temporal cues and spectral moments of the voiceless unaspirated retroflex and dental stops.

Cho and Ladefoged (1999) argued that VOT is affected by the extent of articulatory contact. The reason Punjabi retroflex stops have short VOT might be due to their small tongue contact with the palate and faster release of the tongue tip (Kuehn and Moll, 1976). Long VOTs of dental stops reflect their slow tongue movement. Our results of VOT in word-initial context differ from Lisker and Abramson (1964) who found no differences in VOTs of word-initial voiceless unaspirated retroflex and dental stops of Hindi and Marathi. However, they reported differences in VOTs of both stops in non-initial context.

Some differences among the temporal and spectral characteristics of the Punjabi retroflex and dental stops were observed across word contexts. For instance, closure duration of the Punjabi retroflex stops was smaller in word-final context (86 ms (21)) than when produced word-medially (101 ms (20)). This might be due to the different elicitation methods. The word-final stops were elicited in a carrier sentence which compressed the closure duration. The word-medial stops were elicited in citation form which might have lengthened the closure duration. On the other hand, mean spectral CoG and spectral variance of the retroflex stops in word-final context (CoG: 1484 (372); variance: 1154 (198)) was higher than both word-medial (CoG: 1070 (242); variance: 1033 (165)) and word-initial (CoG: 1128 (256); variance: 1058 (149)) contexts. There were minor differences in VOT (or burst duration) of the Punjabi retroflex stops across word contexts (word-medial: 13 ms (4); word-initial: 15 ms (3), and word-final: 10 ms (2)).

We also found that a number of acoustic cues (spectral CoG, skewness, and kurtosis) did not differentiate the Punjabi retroflex and dental stops in the vicinity of front vowels. This raises the question of the articulatory constraints which a high front vowel might impose on an adjacent retroflex (Dixit and Flege, 1991; Hamann, 2003; Krull and Lindblom, 1996). High front vowels are typically produced with bunched lingual posture (Jackson and McGowan, 2012; Takemoto et al., 2006), but retroflex consonant production involves tongue-retraction and raising of the tongue tip (Bhat, 1973; Narayanan et al., 1999; Smith et al., 2013). Many of the goals of production of the high-front vowels therefore appear to be articulatorily incompatible with those of retroflex production. Tabain and Butcher (2015) found similar effects in Pitjantjatjara, where retroflex stop release before the /i/ vowel was more anterior than the alveolar stop release. They proposed that these findings may account for the cross-linguistic scarcity of retroflexes in the context of high front vowel /i/.

Overall, the results of spectral moments indicated lower spectral CoG and spectral variance for retroflexes but higher for dentals. This is consistent with previous studies showing that retroflexes have concentration of acoustic energy in the lower regions of burst spectrum, compared to dentals (Bundgaard-Nielsen et al., 2016; Stevens and Blumstein, 1975; Tabain, 2012). The results also showed that spectral CoG of stop release bursts did not characterize the Punjabi retroflex and dental stops in the context of front vowels /i e/. Spectral CoG is correlated with the length of front cavity. This indicates that front cavity length may not differ systematically for Punjabi retroflex and dental stops produced before front vowels /i e/. Surprisingly, spectral CoG also failed to distinguish the Punjabi retroflex and dental stops in the context of low vowel /a/, which is considered to be a neutral and optimal vowel for studying the coronal contrasts of a language (Kochetov et al., 2014).

The data presented in this paper offer new details of the properties of the complex coronal system of Punjabi, which should contribute to the broader understanding of phonetic and phonological processes underlying coronal contrasts in other Indo-Aryan languages. The phonetic analyses of Punjabi coronals across word and vocalic contexts will help to address some of the inconsistencies in the current literature on the phonetics and phonology of coronals.

The acoustic results presented here can be used to further explore the types of cues that listeners might use during the perception of coronals.

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APPENDIX A. Phonemic inventory of Punjabi (adapted from Gill and Gleason, 1962). Segments occurring only in loanwords are indicated in parentheses.

	Labial	**Dental**	**Alveolar**	**Retroflex**	**Palatal**	**Velar**	**Glottal**
Plosive	p pʰ b	t̪ t̪ʰ d̪		ʈ ʈʰ ɖ	ʧ ʧʰ ʤ	k kʰ g	
Fricative	(f) (v)		s (z)		ʃ	(x) (ɣ)	h
Nasal	m		n	ɳ			
Lateral			l	ɭ			
Tap			r				
Flap				ɽ			
Approximant	ʋ				j		

APPENDIX B. Punjabi nonsense target words contrasting /ʈ/-/t̪/ in word-medial and word-initial contexts, preceded/followed by each of the five vowels /i e a o u/.

		Preceding/following vowels				
Context	**Target**	**/i/**	**/e/**	**/a/**	**/o/**	**/u/**
Word-medial	**Retroflex**	/pʰiʈi/	/pʰeʈe/	/pʰaʈa/	/pʰoʈo/	/pʰuʈu/
	Dental	/pʰit̪i/	/pʰet̪e/	/pʰat̪a/	/pʰot̪o/	/pʰut̪u/
Word-initial	**Retroflex**	/ʈipʰi/	/ʈepʰe/	/ʈapʰa/	/ʈopʰo/	/ʈupʰu/
	Dental	/t̪ipʰi/	/t̪epʰe/	/t̪apʰa/	/t̪opʰo/	/t̪upʰu/

APPENDIX C. Punjabi real target words contrasting /ʈ/-/t̪/ in word-final context after vowels /i a u/.

	Preceding vowels					
Target	**/i/**		**/a/**		**/u/**	
Retroflex	/pʰiʈ/	*'village officer'*	/pʰaʈ/	*'torn'*	/kuʈ/	*'mountain top'*
	/ʧʰiʈ/	*'type of cloth'*	/ʧaʈ/	*'fruit dish'*	/ɡuʈ/	*'short man'*
Dental	/ɡit̪/	*'song'*	/bat̪/	*'talk'*	/sut̪/	*'thread'*
	/bit̪/	*'passed'*	/ʧʰat̪/	*'roof'*	/ʧʰut̪/	*'impure'*

APPENDIX D. Mean (SD) durations in ms of vowels in elicitation items (all speakers, all items).

		Vowels preceding coronal stops					Vowels following coronal stops				
Context	**Target**	/i/	**/e/**	**/a/**	**/o/**	**/u/**	**/i/**	**/e/**	**/a/**	**/o/**	**/u/**
Medial	**Retroflex**	127 (40)	137 (36)	136 (34)	127 (40)	128 (39)	172 (32)	193 (46)	183 (45)	186 (42)	182 (41)
	Dental	113 (41)	125 (38)	127 (36)	124 (40)	119 (40)	174 (41)	181 (35)	187 (39)	190 (40)	178 (36)
Initial	**Retroflex**	-	-	-	-	-	121 (35)	129 (33)	132 (30)	129 (35)	127 (35)
	Dental	-	-	-	-	-	117 (34)	118 (30)	132 (27)	127 (35)	123 (36)
Final	**Retroflex**	194 (21)	-	221 (15)	-	213 (22)	-	-	-	-	-
	Dental	199 (18)	-	215 (16)	-	190 (15)	-	-	-	-	-

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Chapter 5: Adaptation of English word-final alveolar stops into Punjabi

This chapter is based on the following paper:

Hussain, Q., Harvey, M., Proctor, M., & Demuth, K. (in preparation). Adaptation of English word-final alveolar stops into Punjabi.

Abstract

Alveolar stops are typically adapted as retroflexes when English words are borrowed into Indo-Aryan languages (Ghotra, 2006; Arsenault, 2008). Given that Indo-Aryan languages have retroflex, dental and palatal stops, it is not known why English alveolar stops are mapped to the category of retroflexes rather than dentals or palatals. Are there any acoustic similarities between English alveolar and retroflex stops? This paper investigates the acoustic characteristics of the word-final loanword /t/ and Australian English (AusE) /t/ and compares them with native Punjabi retroflex and dental stops produced after different vowels. The results indicate that loanword /t/ is acoustically more similar to the Punjabi retroflex than dental stops, especially with respect to closure duration, spectral variance and spectral skewness. However, a comparison of temporal and spectral characteristics of AusE /t/ and the Punjabi retroflex stops found only a few similar acoustic characteristics (e.g., spectral skewness).

1. Introduction

When speakers of a particular language borrow words from a foreign language, they make changes that are constrained by the phonological grammar of their native language (e.g., deletion of illicit consonants, simplification of clusters with vowel epenthesis). The term “loanword adaptation” refers to the process of borrowing the non-native words and then making them compatible with the native segmental inventory and phonotactic constraints (Kang, 2011). Several models of loanword adaptation have been proposed. Phonologically-motivated analyses propose that loanword adaptation is governed by the phonological constraints of the native language (Jacobs & Gussenhoven, 2000; LaCharité & Paradis, 2005; Paradis, 2006; Paradis & LaCharité, 1997, 2011). An example supporting the phonological view comes from Japanese, a language that does not allow complex consonant clusters (Vance, 2008). As a result, English loanwords with complex onset or coda clusters are simplified with vowel epenthesis ([desɯkɯ] ‘*desk*’) (see Paradis & LaCharité, 2011). However, other accounts suggest that loanword adaptation is primarily driven by perceptual factors (Peperkamp, 2005, 2015; Peperkamp & Dupoux, 2003; Peperkamp, Vendelin, & Nakamura, 2008). Some of the examples regarding the role of perceptual factors in loanword adaptations come from Japanese which does not allow complex clusters. Both psycholinguistic and electrophysiological studies have demonstrated that Japanese listeners hear epenthesis in a nonsense word [ebzo] and perceive it as [ebɯzo] (Dehaene-Lambertz, Dupoux, & Gout, 2000; Dupoux, Kakehi, Hirose, Pallier, & Mehler, 1999; Peperkamp, 2005). Other accounts emphasize the importance of both perceptual and phonological factors in the adaptation of loanwords (Silverman, 1992; Yip, 1993), some suggesting that the different methods used may contribute to different proposals of loanword adaptation (e.g., Rose & Demuth, 2006). In this paper, we explore the possible perceptual underpinnings of loanword adaptation by examining the adaptation of English alveolar stops in words such as *sheet*, into Punjabi.

Punjabi is an Indo-Aryan language that has been in contact with various languages, including British English, Persian, Arabic and Turkish. Among these, British English left a significant mark on the Punjabi lexicon with the introduction of new administrative, agricultural and architectural terms (Ghotra, 2006; Kachru, 2008). It should be noted that very few Punjabi speakers probably had direct contact with the British English. Rather, contact was via Indian English. Indian English (Sailaja, 2009) emerged when the British recruited administration staff who could work as interpreters between locals and the higher administrative government (e.g., law courts; Clark, 1956). Thus, these people might have started borrowing and adapting words from English into Punjabi and other Indo-Aryan languages.

Punjabi has a three way coronal contrast (e.g., /t̪ ʈ ʧ/) (Bhatia, 1993; see Appendix 1). Previous studies of Punjabi loanword phonology have reported that English alveolar /t/ is adapted as retroflex rather than as dental (e.g., /mɛʈ/ 'mat'; Ghotra, 2006; Pahari: Sharma, 1980), but there has been little investigation as to why. Arsenault (2006, 2008) hypothesized that English alveolar stops can either be adapted as retroflexes or dentals in Indo-Aryan languages because alveolars show acoustic similarities to both retroflexes and dentals. Alveolar stops share the characteristics of release bursts with retroflexes, but share preceding and following F2 formant transitions with dentals (Bundgaard-Nielsen, Baker, Kroos, Harvey, & Best, 2012; Hamilton, 1996). Interestingly, the phonological features associated with dentals, alveolars and retroflexes also overlap: dentals and alveolars are characterized as [+anterior] whereas retroflexes as [–anterior] (Arsenault, 2008; Kang, 2000). However, in terms of apicality, dentals are specified as [–apical] but alveolars and retroflexes as [+apical] (see Clements, 2001). This suggests that alveolars share the feature of anteriority with dentals, but share the feature of apicality with retroflexes. Perhaps, then, there are competing acoustic characteristics for Punjabi listeners that might contribute to the adaptation of English alveolar stops as retroflexes or dentals. It should be noted that Arsenault's (2008) observations are based on other sources

(Koshal, 1978; Ohala, 1978), and without any acoustic evidence. Moreover, previous studies on Punjabi (Ghotra, 2006) and Pahari (Sharma, 1980) also relied on perceptual judgements of phoneme mappings. Therefore, a detailed acoustic study is needed to investigate the potential similarities between English alveolar /t/ and Indo-Aryan retroflex and dental stops. This study will shed light on the phonetic realization of the English alveolar /t/ as adapted into Punjabi and the possible role of the temporal and spectral characteristics that listeners might use in adapting English alveolar stops.

In the current literature on coronal contrasts, temporal characteristics (VOT, closure and burst durations, total stop duration (closure + VOT): Benguerel & Bhatia, 1980; Berkson, 2012; Dutta, 2007; Hussain, Proctor, Harvey, & Demuth, in revision; Maxwell, Baker, Bundgaard-Nielsen, & Fletcher, 2015; Mikuteit, 2009; Mikuteit & Reetz, 2007), F3-F2 difference (Dave, 1977) and first four spectral moments (spectral CoG, spectral variance, spectral skewness and spectral kurtosis: Tabain, 2012) are widely used to compare retroflexes with dentals. In an earlier study, we investigated the temporal and spectral characteristics of the Punjabi retroflex /ʈ/ and dental /t̪/ stops in word-medial, word-initial and word-final positions (Hussain et al., in revision). The findings indicated that in word-medial position, VOT and total stop duration (closure + VOT) consistently distinguished Punjabi retroflex and dental stops across vowel contexts (smaller VOT and total stop duration in retroflexes than dentals). However, the F3-F2 difference was not significantly different for Punjabi coronals produced after /i/ nor before /i e/. Moreover, closure duration alone and the spectral moments (spectral CoG, spectral skewness, and spectral kurtosis) of stop release bursts did not consistently distinguish the two stops in all vocalic environments. In word-initial position, VOT consistently differentiated Punjabi retroflex and dental stops produced before all vowels /i e a o u/. In word-final position (where Punjabi retroflex and dental stops were examined across the three vowel contexts /i a u/), all temporal characteristics differed significantly between Punjabi retroflex and dental stops. However, among the four spectral characteristics of the word-final stop release bursts, only spectral variance consistently differentiated the retroflex and dental stops in all vocalic environments. Overall these findings indicate that temporal characteristics provide reliable acoustic information differentiating Punjabi retroflex and dental stops, across word-positons and vowel contexts. This raises the possibility that, if English alveolar /t/ was adapted as a retroflex, the temporal characteristics of English /t/ and Punjabi retroflex /ʈ/ might be more similar than those of English alveolar /t/ and Punjabi dental /t̪/. If this is found to be the case, this would suggest that Punjabi listeners might weigh temporal characteristics more heavily than spectral characteristics in the adaptation of English alveolars as retroflexes. Such a scenario would be consistent with literature on cue weighting suggesting the importance of temporal characteristics during the perception of non-native sounds (Kivistö-de Souza & Carlet, 2014).

In this paper, we examine the temporal and spectral characteristics of Punjabi native retroflex /ʈ/ and dental /t̪/, English source loanword /t/, and native English /t/ in the context of vowels /i a u/. To examine whether loanword /t/ and English alveolar /t/ share similar temporal and spectral characteristics with native Punjabi retroflex /ʈ/ and dental /t̪/, we conducted two experiments: one with Punjabi speakers producing a) native Punjabi word-final retroflex /ʈ/ and dental /t̪/ and b) loanwords from English containing a word-final /t/; and a second experiment with Australian English (AusE) speakers producing English word-final /t/. AusE (Cox, 2012) and Standard Southern British English (McMahon, 2002) are similar in terms of their consonantal systems, and should therefore approximate historical patterns of loanword adaptation. However, there are some important differences between the vowel systems of Punjabi and Australian English. In Australian English, /ʉː/ is fronted and therefore it does not resemble the Punjabi vowel /u/ (see Figure 1). Rather, the AusE vowel /oː/ shares similar F1, F2 and F3 formant values with Punjabi /u/.[21] Thus, instead of /ʉː/, English words with the vowel /oː/ were selected for this experiment. In this way, we were better able to assess possible similarities in the spectral characteristics of the Punjabi and English words across vowel contexts (see the section on speech material for more detail).

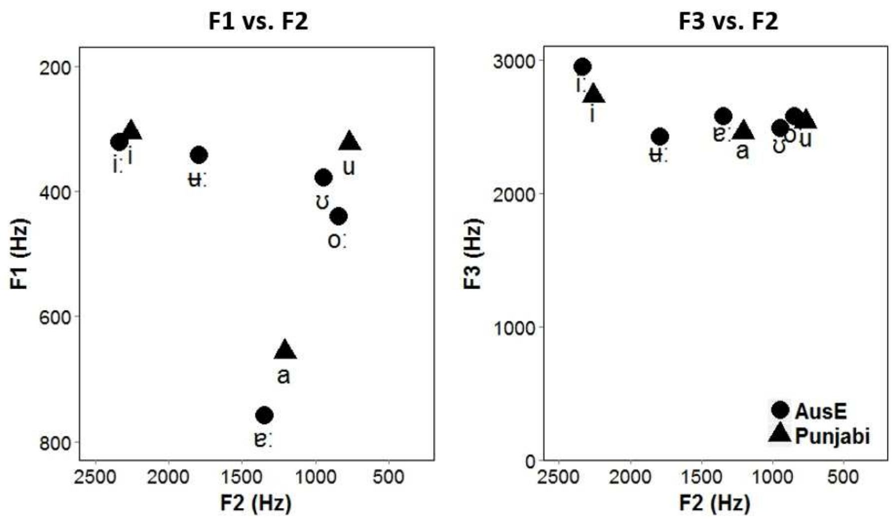

Figure 1. Mean F1, F2 and F3 of Punjabi (triangles) vowels /i a u/ (18 male Punjabi speakers) and Australian English (circles) vowels /iː ɐː oː ʊ ʉː/ (60 male Australian English speakers; Cox, 2006). The left panel shows F1 (y-axis) and F2 (x-axis). The right panel presents F3 (y-axis) and F2 (x-axis).

Several studies have also reported differences between monolinguals and bilinguals when producing English consonants. McCarthy, Evans, and Mahon (2013) tested monolingual and bilingual speakers in an immigrant community in the UK and found significant differences in the production of English stops. In their study, they focused on Sylheti, an indigenous language of Bangladesh that contrasts retroflexes and dentals (Gope & Mahanta, 2015). McCarthy et al. (2013) found that Sylheti speakers who had recently arrived in the UK used L1 phonetic characteristics in the production of L2 English labial /p b/, alveolar /t d/ and velar /k g/ stops.

[21] F3 and F2 vowel plot is also presented because our main focus is on the F3 and F2 formants (see the section on acoustic analysis).

However, those Sylheti speakers who were born in the UK, and had grown up there bilingually, had different realizations of the same consonants, producing English stops like native English speakers. This raises interesting questions about how loanwords are adapted in a non-immigrant situation. For example, in Pakistan, Punjabi speakers, whether they are monolinguals or trilinguals, predominantly speak Punjabi at home (Mansoor, 1993). Trilinguals may speak Urdu (and some English) at work and with friends, and are typically literate (Mansoor, 1993). Urdu has a similar set of coronal contrasts compared to that found in Punjabi (dental, retroflex and palatal). English, on the other hand, has only alveolar stops, and has a limited role in the day to day life of Punjabi speakers. Therefore, even multilingual Punjabi speakers in Pakistan are less likely to be influenced by English phonetics/phonology than bilingual speakers growing up in the UK. However, to fully assess the possibility that increased exposure to either written or spoken English might affect the acoustic characteristics of loanwords adapted from English in a non-immigrant situation, we also tested both trilingual and monolingual Punjabi speakers.

The monolingual participants in this study, however, were not literate, thereby restricting the speech materials to picturable nouns that could be used in an elicited production task. Most of the loanwords nouns with /t/ occurring in the context of the three point vowels /i a u/ contained /t/ in coda position. This study therefore focused on the acoustic characteristics of Punjabi native coronals, loanword /t/, and (Australian) English coda /t/.

2. Method

2.1 Participants

Three groups of male participants were recruited: ten Punjabi trilinguals (who spoke Punjabi, Urdu and English: 22 to 29 years old, mean 25.2 years), eight Punjabi monolinguals (26 to 30 years old, mean 28 years) and ten monolingual speakers of Australian English (AusE) (23 to 38 years old, mean 30.2 years). Two additional Punjabi monolingual participants were excluded from the analysis due to inappropriate production of the target words: one consistently resyllabified the target words with the carrier sentence, and the other produced atypical vowels. All Punjabi participants were recruited from the Government College University, Faisalabad and the University of Agriculture, Pakistan. All spoke the Lyallpuri dialect of Punjabi, which closely resembles the Majhi dialect of Punjabi spoken in Lahore (Gill & Gleason, 1962). The AusE speakers were recruited from Macquarie University, Sydney, Australia.

2.2 Speech material

Three types of speech material were used: a) Punjabi native words with word-final retroflex /ʈ/ and dental /t̪/, b) loanwords from English with word-final /t/, and c) English words with word-final alveolar /t/ (Table 1). All were elicited with a picture naming task. English loanwords were selected from a corpus of loanwords (Ghotra, 2006). Target consonants were elicited after three different vowels /i a u/. The /i/ vowel context was critical for our analysis because coronals are less contrastive in this context (see Hussain et al. (in revision) for further detail). Most of the high frequency picturable English loanwords found in the loanwords corpus with /t/ in the context of these three point vowels were monosyllabic nouns with a word-final /t/ (Ghotra, 2006). Thus, all speech materials used in this study were CVC monosyllables where the target coronal consonants appeared in word-final (coda) position. Six loanwords from English were selected from Ghotra (2006). These loanwords were elicited in an elicited production task using the Punjabi carrier phrase [kɛ___əʤ] (*'Say___today'*).

To compare loanwords with Punjabi native words, six Punjabi native words were selected, each with the target retroflex /ʈ/ and dental /t̪/ in the same word-final (coda) position, preceded by one of the three vowels /i a u/. Since it was not possible to find comparable minimal pairs for these items where the pictures were fully picturable nouns (see Table 1), the native Punjabi target words were pre-recorded by a native Punjabi speaker and played to participants, who then repeated them as part of the entire phrase. A female Punjabi speaker recorded the

Punjabi words using the same carrier phrase [kɛ___əʤ] (*'Say___today'*). The recordings were made using a Zoom H2 digital recorder with a built-in microphone at 44 KHz, and added to the pictures which were then shown on the computer screen. The Punjabi words (including the entire carrier phrase) were then used as auditory prompts presented to the Punjabi participants.

Table 1. Native Punjabi words with word-final retroflex /ʈ/ and dental /t̪/, loanwords with /t/, and Australian English words with alveolar /t/, after front, low and back vowels.

	Vowels					
	Front		**Low**		**Back**	
Punjabi /ʈ/	/pʰiːʈ/	*'village officer'*	/pʰaːʈ/	*'torn'*	/kuːʈ/	*'mountain top'*
	/ʧʰiːʈ/	*'type of cloth'*	/ʧaːʈ/	*'fruit dish'*	/ɡuːʈ/	*'short man'*
Punjabi /t̪/	/ɡiːt̪/	*'song'*	/baːt̪/	*'talk'*	/suːt̪/	*'thread'*
	/biːt̪/	*'passed'*	/ʧʰaːt̪/	*'roof'*	/ʧʰuːt̪/	*'impure'*
Loanword /t/	/siːt/	*'seat'*	/kaːt/	*'cut'*	/buːt/	*'boot'*
	/ʃiːt/	*'sheet'*	/paːt/	*'pot'*	/suːt/	*'suit'*
AusE /t/	/siːt/	*'seat'*	/hɐːt/	*'heart'*	/koːt/	*'court'*
	/ʃiːt/	*'sheet'*	/kɐːt/	*'cart'*	/foːt/	*'fort'*

Based on the spectral similarities of Punjabi vowels and AusE vowels (Figure 1), a set of six AusE CVC words were selected with the long vowels /iː ɐː oː/ and coda /t/. These most closely matched the Punjabi vowels /i a u/ in spectral characteristics. In a picture naming task, the target English words were elicited in a carrier phrase before an unstressed vowel: *'I say______ again'*. It should be noted that in English, flapping can occur when /t/ is preceded by a stressed vowel and followed by an unstressed vowel (de Jong, 1998). Flaps also have very short durations (10-

40 ms) and no release burst (Riehl, 2003; Zue & Laferriere, 1979). To minimize flapping, the participants were asked to speak slowly (see the next section on procedure for more details).

2.3 Procedure

The Punjabi participants were invited into a quiet room at the University of Agriculture, Faisalabad (Pakistan). Before the experiment, they were familiarized with the task. For the native Punjabi experiment, pseudo-randomized visual prompts (accompanied by auditory prompts) were presented on a computer screen in five different blocks (12 items × 5 repetitions × 18 participants (10 trilinguals and 8 monolinguals) = 1080 items). After seeing and hearing the prompts, participants were asked to produce the target word in the carrier phrase. After eliciting the Punjabi native words, the loanwords were then elicited using the same procedure (and participants), but without the auditory prompt. These again were pseudo-randomized and presented on a computer screen in five different blocks (6 items × 5 repetitions × 18 participants (10 trilinguals and 8 monolinguals) = 540 items). There was a small break between the two parts of the experiment. Speech recordings were made using a Zoom H2 digital voice recorder with built-in microphone, at a sampling rate of 44.1 KHz. At the end of the experiments, the participants completed a language background questionnaire.

The AusE participants were invited into a sound-attenuated room at Macquarie University. The procedure was similar to that used with the native Punjabi speakers for the loanword stimuli. The visual prompts used to elicit the target English words were pseudo-randomized and presented in five different blocks (6 items × 5 repetitions × 10 participants = 300 items). There was a small break halfway through the experiment to ensure that the participants did not ‘speed up’ and begin to produce the alveolar /t/ as a flap. All the target items produced by the participants had a release burst (confirmed by a strong vertical spike in the burst spectrum, see the next section 2.4 Acoustic analysis). Thus, all target items by the AusE speakers were included in the analysis. The presence of release bursts in all items also confirmed that there was no flapping. The recordings were made with AKG C 353 EB microphone at a sampling rate of 44.1 KHz and recorded on a Windows computer with Audacity software.

2.4 Acoustic analyses

A total of 1920 words were recorded (native Punjabi words (retroflex and dental stops): 1080; loanwords from English produced by Punjabi speakers: 540; English words produced by Australian English speakers: 300). For each word, 4 temporal landmarks were located: (1) vowel onset, (2) vowel offset (stop closure onset), (3) release burst onset and (4) release burst offset (see Figure 2). Landmarks (1) and (2) defining vowel interval were manually located by visual inspection of the waveform and spectrogram, making reference to periodicity and formant energy bands. Stop closure was located at the point of maximum attenuation of F2 energy in the transition from adjacent vocalic interval. The stop release burst was located at the onset of the first strong vertical spike in the waveform (landmarks (3) and (4); Song, Demuth, & Shattuck-Hufnagel, 2012). Total stop duration (closure + burst) was identified from the closure onset (2) to burst offset (4).

For validation of the temporal landmarks, another trained phonetician segmented 10% of the data from native Punjabi retroflex and dental stops (108 items). The average difference between two coders for closure duration was 0 ms (retroflex) and 3 ms (dental). For the burst duration, the average inter-coder difference was 3 ms for both stops.

Formant analyses for loanword /t/, AusE /t/, and Punjabi retroflex /ʈ/ and dental /t̪/ were conducted, focusing on the first three formant trajectories (F1, F2, F3) into each target stop. A Praat script was then used to identify F1, F2 and F3 values at six equidistant time points (50, 60, 70, 80, 90% and 100%) from the preceding vowels. Our main formants of interest are F2 and F3 (F3-F2 difference) because these two formants are widely used to investigate coronal places of articulation (Dave, 1977; Ohala & Ohala, 2001). Formants were estimated using LPC analysis over a sliding 25 ms analysis window with a 50 db dynamic range (Boersma & Weenink, 2014). The automatic formant tracker in Praat did not always correctly identify the formants near the offset of the preceding vowels. Therefore, to ensure that Praat's formant tracker extracted the correct formant trajectories, the extracted formants were validated at each time step by visually comparing with an additional set of formant estimates superimposed on the target spectrogram, using an algorithm in Matlab (14^{th} order LPC, 25 ms analysis window, max search frequency: 4000 Hz), and manually corrected where needed. The final analyses were based on the corrected formants.

The first four spectral moments (spectral CoG, spectral variance, spectral skewness, and spectral kurtosis) of stop release bursts were also measured in Praat from FFT spectra generated over single sliding 20 ms Hamming analysis windows centred at the beginning of the stop release bursts (landmark (3), Figure 2) (Forrest, Weismer, Milenkovic, & Dougall, 1988).

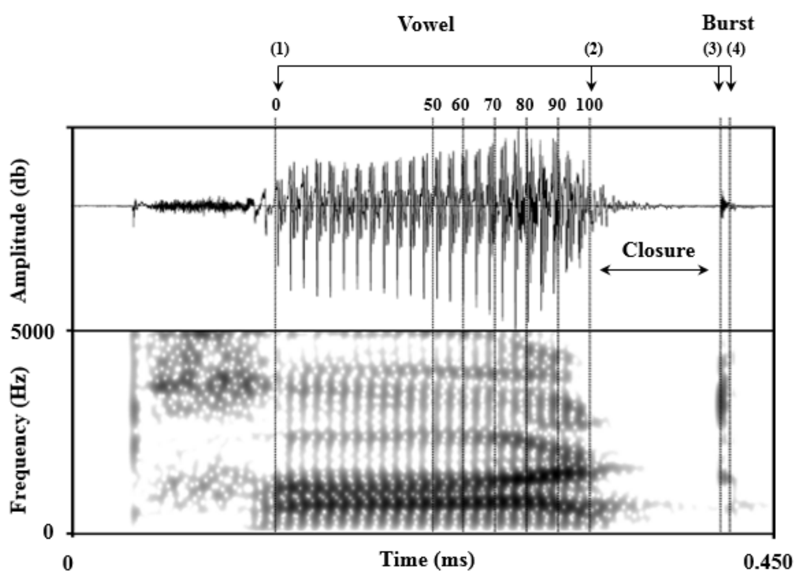

Figure 2. Temporal and spectral analysis of stops: acoustic waveform and wideband spectrogram for the word /pʰaʈ/ *'torn'*. Temporal landmarks indicated at: (1) vowel onset, (2) vowel offset (stop closure onset), (3) release burst onset and (4) release burst offset. Formants F1, F2 and F3 are measured at six equidistant sample time points (50, 60, 70, 80, 90, 100%) in the vowel before the coda stop.

2.5 Hypotheses

Based on the previous studies on Punjabi loanword phonology that reported the adaptation of English alveolar /t/ as retroflex /ʈ/ (Ghotra, 2006; Sharma, 1980), we hypothesized that loanword /t/ would share more temporal (closure duration, burst duration and total stop duration) and spectral characteristics (F3-F2 difference and spectral moments of stop release bursts (spectral CoG, spectral variance, spectral skewness and spectral kurtosis)) with Punjabi retroflex /ʈ/ than Punjabi dental /t̪/, across the vowel /i a u/ contexts. We also hypothesized that AusE /t/ would share more temporal and spectral characteristics with Punjabi retroflex /ʈ/ than with Punjabi dental /t̪/. Regarding the possible effects of multilingualism, we hypothesized that there would be no difference in acoustic characteristics between the monolingual and trilingual Punjabi speakers because the dominant local languages in Pakistan are Punjabi and Urdu (rather than English).

3. Results

To test our hypotheses, we conducted a range of repeated-measure ANOVAs. Separate repeated-measure ANOVAs were first used to compare the different group of speakers (Punjabi monolinguals and trilinguals). The second set of analyses compared the temporal and spectral characteristics of the following consonants: (a) loanword /t/ vs. Punjabi retroflex /ʈ/; (b) loanword /t/ vs. Punjabi dental /t̪/; (c) AusE /t/ vs. Punjabi retroflex /ʈ/ and (d) AusE /t/ vs. Punjabi dental /t̪/. Several repeated-measure ANOVAs and one-way ANOVAs were run to compare the acoustic characteristics of these consonants and to determine whether the temporal and spectral characteristics of loanword /t/ and AusE /t/ were more similar to Punjabi retroflex /ʈ/ or dental /t̪/.

The temporal and spectral characteristics of loanword /t/ were first compared with Punjabi retroflex /ʈ/ and dental /t̪/. The possible effect of group (Punjabi monolinguals and trilinguals) on the acoustic characteristics of loanword /t/, and Punjabi retroflex /ʈ/ and dental /t̪/ was also investigated. Finally, the spectral and temporal characteristics of AusE /t/ were compared with Punjabi retroflex /ʈ/ and dental /t̪/.

3.1 Phonetic characteristics of loanword /t/, Punjabi retroflex and dental stops

3.1.1 F3-F2 difference

Figure 3 illustrates the mean formant transitions of the vowels /i a u/ produced before loanword /t/, Punjabi retroflex /ʈ/ and dental /t̪/ (mean values are presented in Appendix 2). It can be observed that the formant transitions of the loanword /t/ are closer to Punjabi retroflex /ʈ/ than dental /t̪/. Punjabi retroflex /ʈ/ showed F3-F2 convergence before vowels /a u/, but not before /i/. Similarly, loanword /t/ was also characterized by F3-F2 convergence for /a/ and /u/ but not for /i/. Punjabi dental /t̪/, on the other hand, showed flat F3 and raised F2 in the contexts of /a/ and /u/.

To investigate the effect of various factors on the F3-F2 difference of the vowels /i a u/ produced before loanword /t/, Punjabi retroflex /ʈ/ and dental /t̪/, a repeated-measures ANOVA was conducted, with group (Punjabi monolinguals vs. trilinguals) as a between-subjects factor, consonant type (loanword /t/, Punjabi retroflex /ʈ/ and Punjabi dental /t̪/), vowels (/i a u/) and six equidistant sample time points (50% to 100%) in preceding vowels as within-subject factors; and F3-F2 difference as a dependent variable. The results indicated that there was no significant effect of group [F (1, 16) = .059, p=0.811], suggesting that Punjabi monolinguals and trilinguals did not differ significantly in terms of F3-F2 difference. Subsequent repeated-measure ANOVAs for each vowel context and consonant type were conducted to compare loanword /t/, Punjabi retroflex /ʈ/ and dental /t̪/. As there were no significant differences between monolinguals and trilinguals, the factor of group was no longer included in the subsequent-models of repeated-measure ANOVAs.

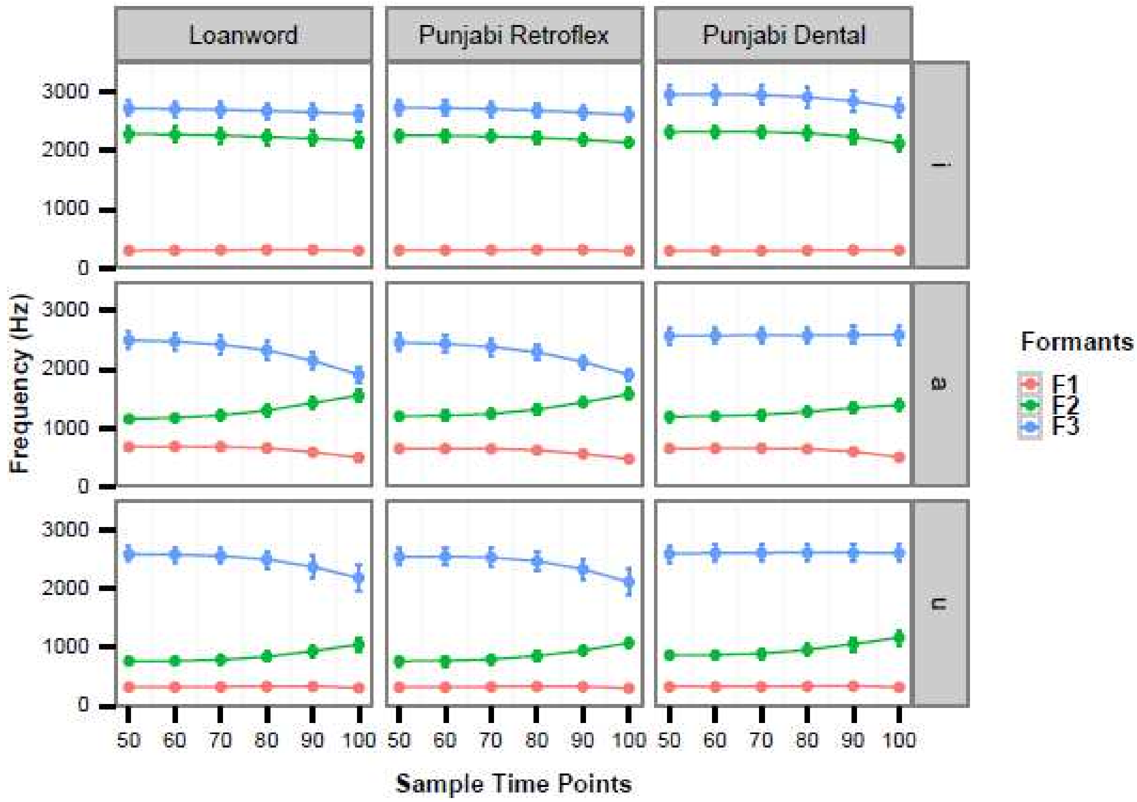

Figure 3. Mean formant trajectories in vowels /i a u/ produced before loanword /t/ (left), Punjabi retroflex /ʈ/ (middle) and Punjabi dental /t̪/ (right) (all speakers, all items), at six equidistant sample time points. Error bars show standard deviation of mean frequencies (Hz).

The comparisons of F3-F2 difference of the vowels /i a u/ produced before loanword /t/ and Punjabi retroflex /ʈ/ showed that in the context of /i/, there were no significant differences [F (1, 17) = 2.167, p=0.159]. However, the F3-F2 difference varied significantly in the context of /a/ [F (1, 17) = 10.180, p=0.005] and /u/ [F (1, 17) = 4.719, p=0.044]. On the other hand, the F3-F2 difference of the vowels produced before loanword /t/ and Punjabi dental /t̪/ was significant in the context of /i/ [F (1, 17) = 36.765, p<0.001] and /a/ [F (1, 17) = 91.625, p<0.001], but not /u/ [F (1, 17) = .848, p=0.370]. This indicated that the F3-F2 difference of the vowels produced before loanword /t/ and Punjabi retroflex /ʈ/ were similar in terms of F3-F2 difference, but only in the context of /i/, not /a u/. However, formant transitions into loanword

/t/ and Punjabi dental /t̪/ were significantly different in terms of F3-F2 difference in the contexts of /i/ and /a/.

3.1.2 Temporal properties of word-final stops

Figure 4 presents the boxplots of closure duration, burst duration and total stop duration of the word-final loanword /t/, Punjabi retroflex /ʈ/ and dental /t̪/, produced after /i a u/ (mean values are presented in Appendix 3). To investigate the effect of various factors on closure duration, burst duration and total stop duration of the loanword /t/, Punjabi retroflex /ʈ/ and dental /t̪/, a repeated-measures ANOVA was first conducted with group (monolinguals vs. trilinguals) as a between-subjects factor, consonant type (loanword /t/, Punjabi retroflex /ʈ/ and Punjabi dental /t̪/) and vowels (/i a u/) as within-subject factors; closure duration, burst duration and total stop duration as dependent variables.

The results of repeated-measures ANOVA showed no significant effect of group on closure duration [F (1, 16) = .482, p=0.497], burst duration [F (1, 16) = .220, p=0.645] and total stop duration [F (1, 16) = .418, p=0.527]. This indicates that there were no significant differences in Punjabi monolinguals and trilinguals across temporal characteristics. Subsequent repeated-measure ANOVAs for all speakers and each vowel context showed that in the context of /i/ [F (1, 17) = 3.967, p=0.063] and /u/ [F (1, 17) = 3.361, p=0.084] there was no difference in closure duration of the loanword /t/ and Punjabi retroflex /ʈ/. However, in the context of /a/ there were significant differences [F (1, 17) = 4.984, p=0.039]. The comparison of loanword /t/ and Punjabi dental /t̪/ indicated that there was a significant difference in closure duration between two stop types across all vowels (/i/: [F (1, 17) = 42.181, p<0.001]; /a/: [F (1, 17) = 50.858, p<0.001]; /u/: [F (1, 17) = 25.010, p<0.001]. This suggests that closure duration of loanword /t/ was similar to Punjabi retroflex /ʈ/ (in the context of /i/ and /u/), but was quite different from that of the Punjabi dental /t̪/.

A comparison of burst duration of loanword /t/ and Punjabi retroflex /ʈ/ showed that these were significantly different across vowels (/i/: [F (1, 17) = 13.791, p=0.002]; /a/: [F (1, 17) = 15.741, p=0.001]: /u/ [F (1, 17) = 6.746, p=0.019]). The burst duration of loanword /t/ and Punjabi dental /t̪/ also showed significant differences across vowels (/i/: [F (1, 17) = 56.445, p<0.001]; /a/: [F (1, 17) = 37.216, p<0.001]; /u/: [F (1, 17) = 37.056, p<0.001]). These results indicate that loanword /t/ is significantly different from both Punjabi retroflex /ʈ/ and dental /t̪/. However, the burst duration of loanword /t/ is closer to Punjabi retroflex /ʈ/ than to dental /t̪/ (Figure 4).

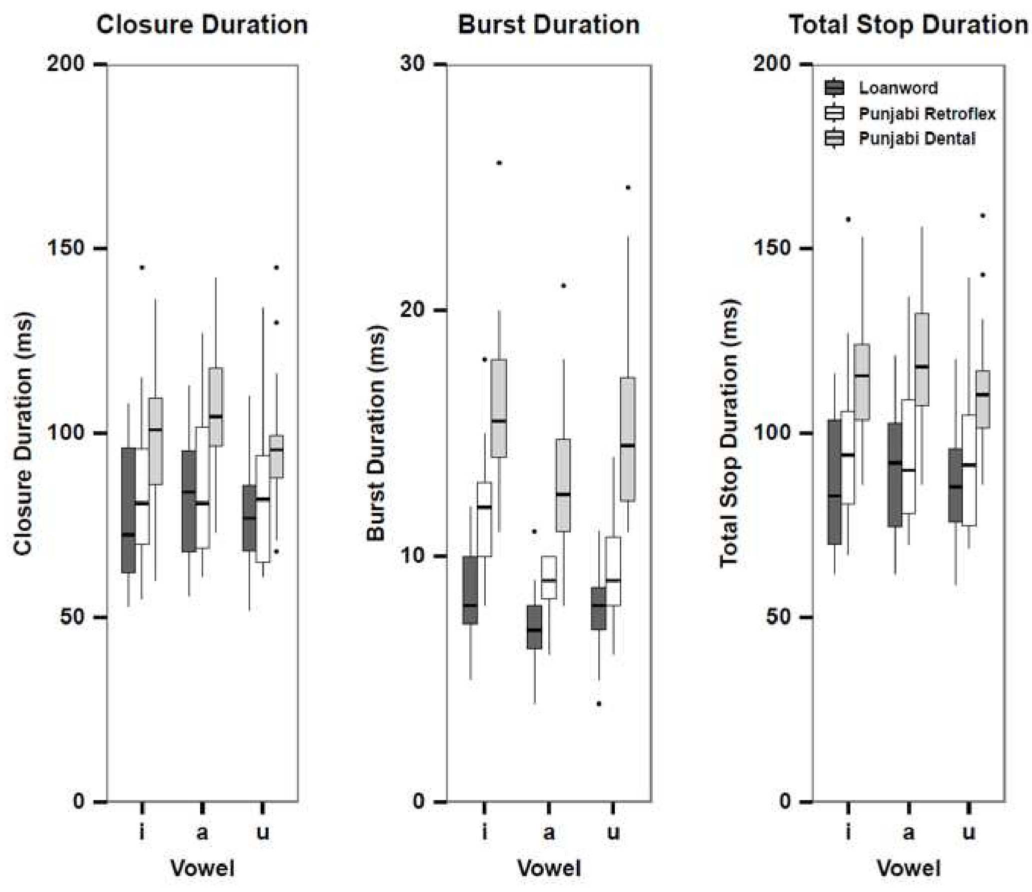

Figure 4. Boxplots of closure duration (ms), burst duration (ms), and total stop duration (closure + burst (ms)) of loanword /t/ (dark grey boxes), Punjabi retroflex /ʈ/ (white boxes) and dental /t̪/ (light grey boxes), produced after vowels /i a u/ (all speakers, all items).

Total stop duration of loanword /t/, Punjabi /ʈ/ and dental /t̪/ was also compared. The results of repeated-measure ANOVAs showed that loanword /t/ and Punjabi retroflex /ʈ/ were significantly different across vowels (/i/: [F (1, 17) = 7.111, p=0.016]; /a/: [F (1, 17) = 7.594, p=0.014]; /u/: [F (1, 17) = 4.823, p=0.042]). Total stop duration of loanword /t/ and Punjabi dental /t̪/ also indicated significant differences across vowels (/i/: [F (1, 17) = 69.914, p<0.001]; /a/: [F (1, 17) = 67.117, p<0.001]; /u/: [F (1, 17) = 39.831, p<0.001]). This indicates that the total stop duration of loanword /t/ is significantly different from both Punjabi retroflex /ʈ/ and dental /t̪/. Again, however, it can be observed in Figure 4 that loanword /t/ more closely resembles Punjabi retroflex /ʈ/ in terms of total stop duration, across all vowels. This may be why loanword /t/ is reported to be adapted in Punjabi as retroflex /ʈ/. It also raises interesting questions about the temporal properties of English /t/, and how these will be similar or different to loanword /t/.

3.1.3 Spectral properties of word-final stop releases

Figure 5 shows the boxplots of spectral moments (spectral CoG, variance, skewness and kurtosis) of stop release bursts of loanword /t/, Punjabi retroflex /ʈ/ and dental /t̪/ (mean values are presented in Appendix 3). To investigate the effect of various factors on the spectral moments of stop release bursts, a repeated-measures ANOVA was conducted with group (monolinguals vs. trilinguals) as a between-subjects factor, consonant type (loanword /t/, Punjabi retroflex /ʈ/ and Punjabi dental /t̪/) and vowels (/i a u/) as within-subject factors; spectral CoG, spectral variance, spectral skewness, and spectral kurtosis as dependent variables. The results showed that there was no effect of group on spectral CoG [F (1, 16) = .322, p=0.578], spectral variance [F (1, 16) = .503, p=0.489, spectral skewness [F (1, 16) = .120, p=0.734] and spectral kurtosis [F (1, 16) = .052, p=0.823]. This suggests that spectral moments of stop release bursts were not different for Punjabi monolinguals and trilinguals.

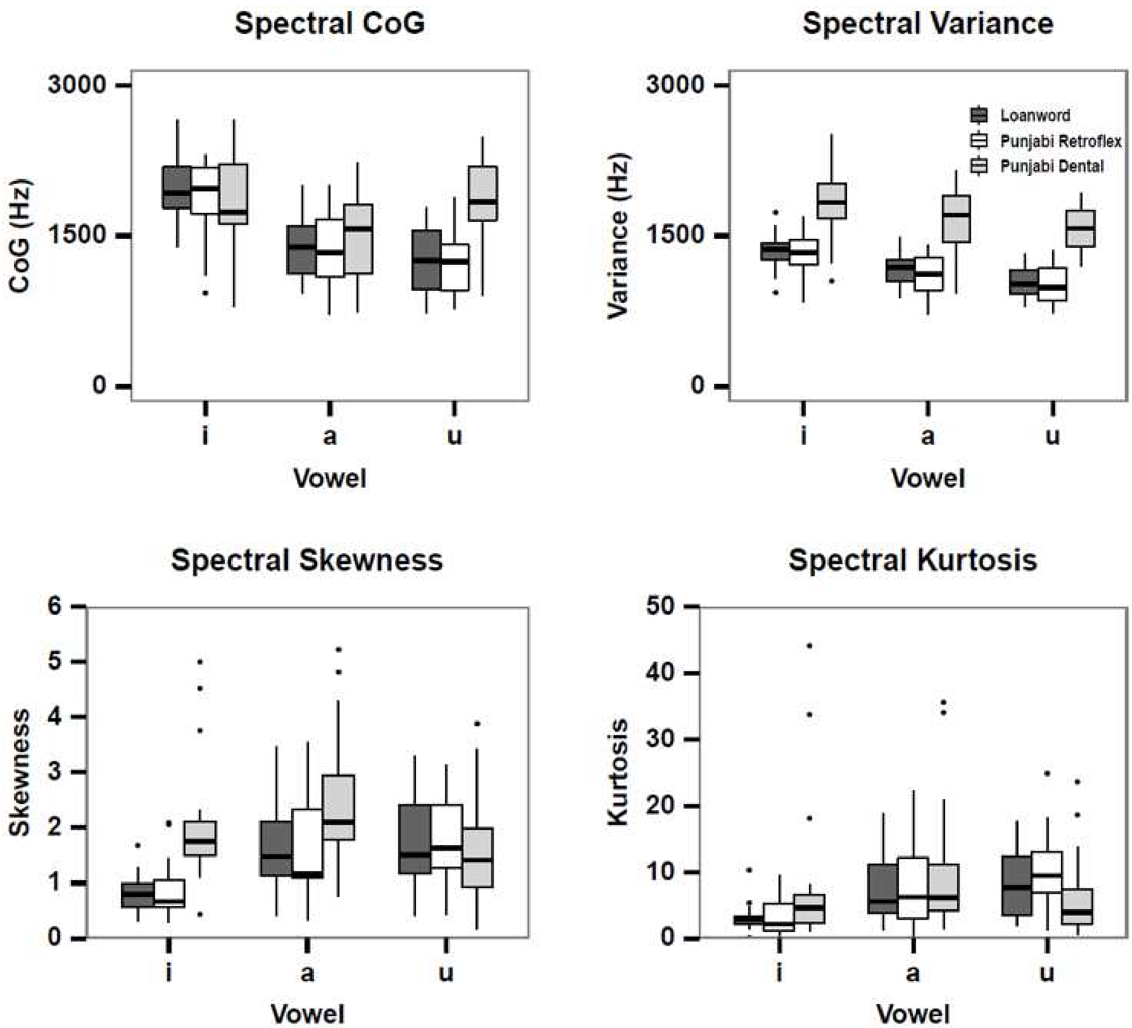

Figure 5. Boxplots of spectral moments of stop release bursts for loanword /t/ (dark grey boxes), Punjabi retroflex /ʈ/ (white boxes) and dental /t̪/ (light grey boxes) produced after vowels /i a u/ (all speakers, all items).

Subsequent repeated-measure ANOVAs were conducted for the different vowel contexts using all participants, comparing the spectral moments of stop release bursts of loanword /t/, Punjabi retroflex /ʈ/ and dental /t̪/. The comparisons of spectral CoG of loanword /t/ and Punjabi retroflex /ʈ/ in the different vowel contexts indicated that there were no significant differences (/i/: [F (1, 17) = 1.198, p=0.289]; /a/: [F (1, 17) = .088, p=0.771]; /u/: [F (1, 17) = .793, p=0.386]). Similarly, spectral CoG of loanword /t/ and Punjabi dental /t̪/ indicated no significant differences in the context of /i/ [F (1, 17) = 1.513, p=0.235] and /a/ [F (1, 17) = .641, p=0.434]. However, in the context of /u/, loanword /t/ and Punjabi dental /t̪/ were significantly different [F (1, 17) = 18.965, p<0.001]. These results reveal that loanword /t/, Punjabi retroflex /ʈ/ and Punjabi dental /t̪/ had similar spectral CoG across vowels, except for Punjabi dental /t̪/ in the context of /u/.

Measures of spectral variance of loanword /t/ and Punjabi retroflex /ʈ/ in different vowel contexts indicated that there were no significant differences in the context of /i/ [F (1, 17) = .274, p=0.607], /a/ [F (1, 17) = 2.024, p=0.173] and /u/ [F (1, 17) = .443, p=0.515]. However, the comparisons of loanword /t/ and Punjabi dental /t̪/ in different vowel contexts showed significant differences across vowels (/i/: [F (1, 17) = 28.037, p<0.001]; /a/: [F (1, 17) = 34.426, p<0.001]; /u/: [F (1, 17) = 57.907, p<0.001]). This indicates that loanword /t/ and Punjabi retroflex /ʈ/ share similar properties of spectral variance, but that Punjabi dental /t̪/ is quite different.

Spectral skewness of loanword /t/ and Punjabi retroflex /ʈ/ showed no significant differences across vowels (/i/: [F (1, 17) = .239, p=0.631]; /a/: [F (1, 17) = .007, p=0.935]; /u/: [F (1, 17) = .722, p=0.407]). On the other hand, the spectral skewness of loanword /t/ and Punjabi dental /t̪/ showed significant differences between the two stop types in the context of /i/ [F (1, 17) = 19.096, p<0.001] and /a/ [F (1, 17) = 7.077, p=0.016], though not for /u/ [F (1, 17) = .095, p=0.762]. This suggests that spectral skewness for loanword /t/ was similar to Punjabi retroflex /ʈ/ but different from Punjabi dental /t̪/.

Spectral kurtosis of loanword /t/ and Punjabi retroflex /ʈ/ showed no significant differences for any vowel (/i/: [F (1, 17) = .000, p=0.983]; /a/: [F (1, 17) = .171, p=0.684]; /u/: [F (1, 17) = 2.714, p=0.118]). A comparison with loanword /t/ and Punjabi dental /t̪/ in the different vowel contexts also showed no significant differences (/i/: [F (1, 17) = 3.365, p=0.084]; /a/: [F (1, 17) = .955, p=0.342]; /u/: [F (1, 17) = 1.613, p=0.221]). This indicates that loanword /t/, Punjabi retroflex /ʈ/ and Punjabi dental /t̪/ all share similar values in spectral kurtosis.

Overall, these findings show that loanword /t/ is acoustically similar to the Punjabi retroflex /ʈ/ in terms of many of the temporal (closure duration) and spectral (spectral variance and skewness) characteristics investigated. Punjabi dental /t̪/, on the other hand, differs from loanword /t/ in both temporal and spectral characteristics. This suggests that loanword /t/ is produced as retroflex /ʈ/ by Punjabi speakers, rather than as dental /t̪/.

In the next section, we compare the acoustic characteristics of AusE /t/ with Punjabi retroflex /ʈ/ and dental /t̪/. This might shed light on why Punjabi speakers adapt English alveolar stops as retroflexes, rather than as dentals. As there were no acoustic differences found between the Punjabi monolinguals and trilinguals in the above analysis, their data are treated together as one group in the analysis below.

3.2 Phonetic characteristics of AusE /t/, Punjabi retroflex and dental stops

3.2.1 F3-F2 difference

In this section we compare the F3-F2 difference of Australian English (AusE) vowels /iː ɐː oː/ and Punjabi vowels /i a u/ produced before AusE /t/, Punjabi retroflex /ʈ/ or dental /t̪/.[22] Figure 6 illustrates the mean formant transitions of the vowels produced before AusE /t/, Punjabi retroflex /ʈ/ and dental /t̪/ (mean values are presented in Appendix 2). It can be observed in Figure 6 that the formant transitions of the AusE /t/ in the context of /i/ are closer to Punjabi retroflex /ʈ/ than dental /t̪/. However, in the context of /a u/, AusE /t/ does not show F3-F2 convergence and looks more similar to Punjabi dental /t̪/ than retroflex /ʈ/.

[22] For the figures and reporting of stats, we will use the vowels /i a u/, representing both AusE /iː ɐː oː/ and Punjabi /i a u/.

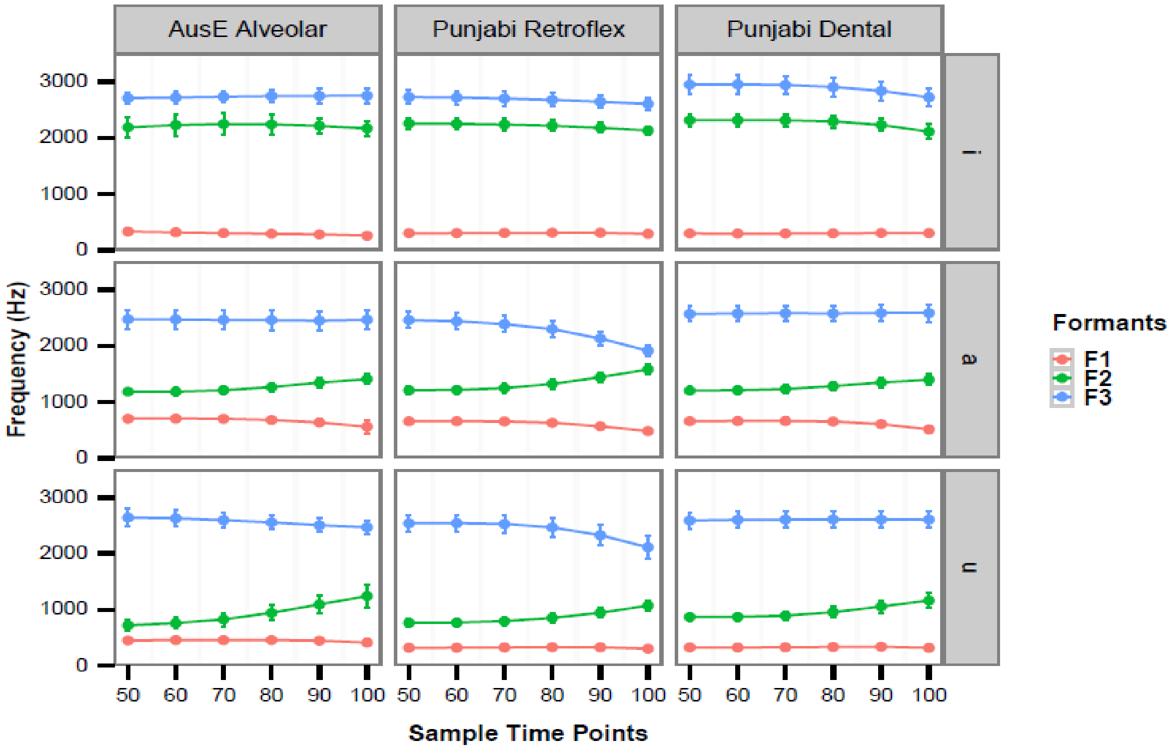

Figure 6. Mean formant trajectories of vowels produced before AusE /t/ (left), Punjabi retroflex /ʈ/ (middle) and Punjabi dental /t̪/ (right) (all speakers, all items), at six equidistant sample time points. Error bars show standard deviation of mean frequencies (Hz).

To investigate whether F3-F2 difference of the AusE /t/ is similar to either the Punjabi retroflex /ʈ/ or dental /t̪/, separate repeated-measure ANOVAs were conducted using consonant (AusE /t/, Punjabi retroflex /ʈ/ or dental /t̪/) as a between-subjects factor, vowels (/i a u/) and six equidistant sample time points within the vowels (50% to 100%) as within-subject factor; the F3-F2 difference as a dependent variable.

The comparisons of F3-F2 difference of the AusE /t/ and Punjabi retroflex /ʈ/ showed that there were no significant differences in the context of /i/ [F (1, 26) = 1.222, p=0.279] and /u/ [F (1, 26) = 2.266, p=0.144], suggesting that AusE /t/ and Punjabi retroflex /ʈ/ had similar F3-F2 difference. However, the F3-F2 difference varied significantly in the context of /a/ [F (1, 26) = 29.822, p<0.001]. The F3-F2 difference of the AusE /t/ and Punjabi dental /t̪/ showed no significant difference across vowels /i a u/ (/i/: [F (1, 26) = 2.966, p=0.097]; /a/: [F (1, 26) = 3.840, p=0.061]; /u/: [F (1, 26) = .000, p=0.992]). Overall, the results of F3-F2 difference suggest that AusE /t/ is similar to both Punjabi retroflex /ʈ/ and dental /t̪/.

3.2.2 Temporal properties of word-final stops

Figure 7 presents the boxplots of closure duration, burst duration and total stop duration (closure + burst) of the word-final AusE /t/, Punjabi retroflex /ʈ/ and dental /t̪/, produced after /i a u/ (mean values are presented in Appendix 2). Separate one-way ANOVAs were conducted in each vowel context, using consonant (AusE /t/, Punjabi retroflex /ʈ/ or dental /t̪/) and vowels (/i a u/) as independent variables, closure duration, burst duration and total stop duration as dependent variables. The results showed that closure duration of the AusE /t/ is different from Punjabi retroflex /ʈ/ across vowels (/i/: [F (1, 26) = 9.819, p=0.004]; /a/: [F (1, 26) = 6.872, p=0.014]; /u/: [F (1, 26) = 8.501, p=0.007]). The comparison of AusE /t/ and Punjabi dental /t̪/ also indicated that there was a significant difference in closure duration between two stop types across vowels (/i/: [F (1, 26) = 30.164, p<0.001]; /a/: [F (1, 26) = 28.894, p<0.001]; /u/: [F (1, 26) = 26.449, p<0.001]). It can be observed in Figure 7 that AusE /t/ has smaller closure duration than Punjabi retroflex /ʈ/ and dental /t̪/. However, the closure duration of the AusE /t/ was closer to Punjabi retroflex /ʈ/ than dental /t̪/. It is possible that small closure duration of the AusE /t/ leads to the adaptation of /t/ as retroflex in Punjabi.

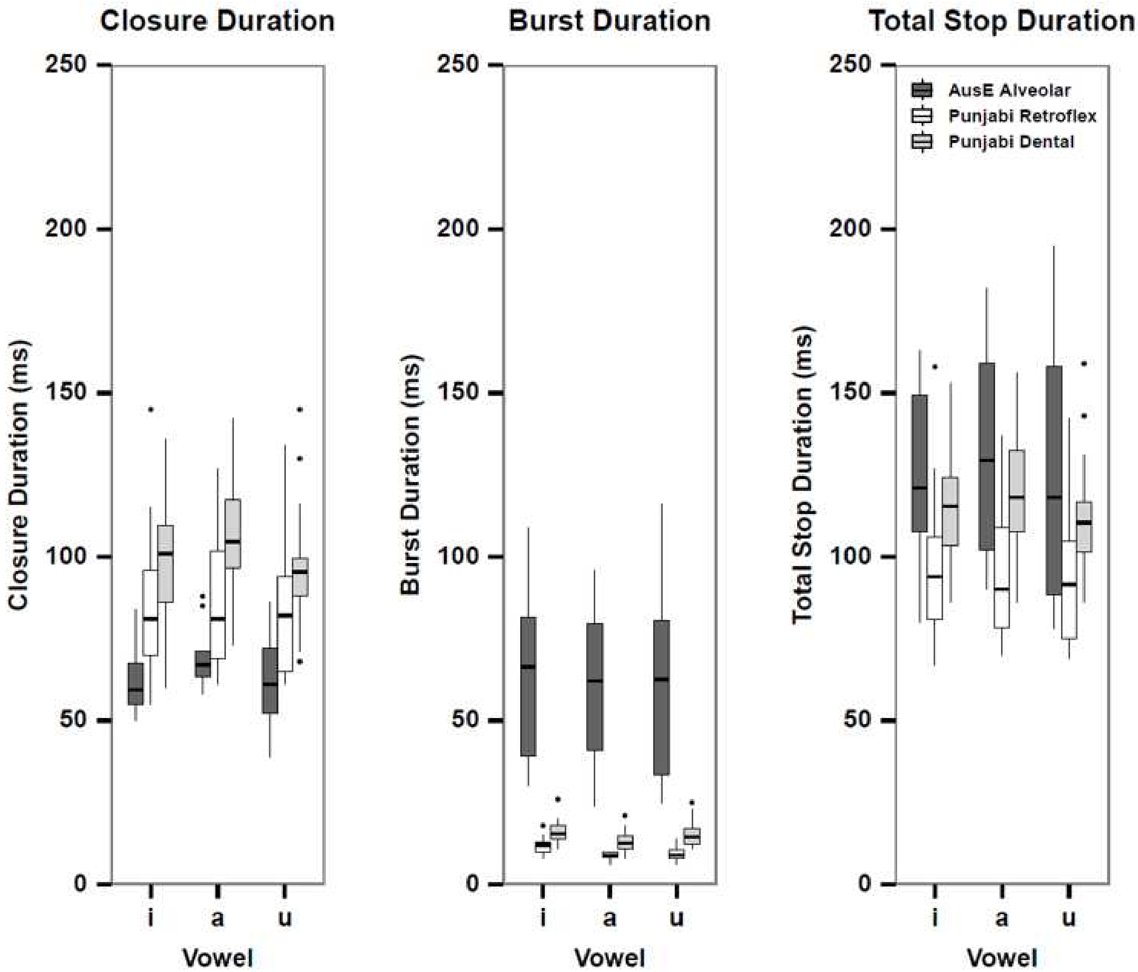

Figure 7. Boxplots of closure duration (ms), burst duration (ms), and total stop duration (closure + burst (ms)) of the AusE /t/ (dark grey boxes), Punjabi retroflex /ʈ/ (white boxes) and dental /t̪/ (light grey boxes), produced after vowels /i a u/ (all speakers, all items).

A comparison of burst duration of the AusE /t/ and Punjabi retroflex /ʈ/ showed that these were significantly different across vowels (/i/: [F (1, 26) = 69.234, p<0.001]; /a/: [F (1, 26) = 77.089, p<0.001]; /u/: [F (1, 26) = 52.298, p<0.001]). The burst duration of the AusE /t/ and Punjabi dental /t̪/ also showed significant differences across vowels (/i/: [F (1, 26) = 57.413, p<0.001]; /a/: [F (1, 26) = 63.005, p<0.001]; /u/: [F (1, 26) = 40.498, p<0.001]). As shown in Figure 7, significant differences in bust duration between AusE /t/ and Punjabi retroflex /ʈ/ and dental /t̪/ were due to the much longer burst duration of the AusE /t/.

Total stop duration of the AusE /t/, Punjabi /ʈ/ and dental /t̪/ was then also compared. The results of one-way ANOVA showed that AusE /t/ and Punjabi retroflex /ʈ/ were significantly different across vowels (/i/: [F (1, 26) = 9.353, p=0.005]; /a/: [F (1, 26) = 10.465, p=0.003]; /u/: [F (1, 26) = 6.982, p=0.014]). However, the total stop duration of the AusE /t/ and Punjabi dental /t̪/ showed no significant differences across vowels (/i/: [F (1, 26) = 1.368, p=0.253]; /a/: [F (1, 26) = 1.097, p=0.305]; /u/: [F (1, 26) = 1.118, p=0.300]). This suggests that the total stop duration of the AusE /t/ is significantly different from Punjabi retroflex /ʈ/ but it is similar to Punjabi dental /t̪/.

3.2.3 Spectral properties of word-final stop releases

Figure 8 shows the boxplots of spectral properties of stop release bursts for the AusE /t/, Punjabi retroflex /ʈ/ and dental /t̪/ produced after vowels /i a u/ (mean values are presented in Appendix 3). Separate one-way ANOVAs were conducted in each vowel context, using consonant (AusE /t/, Punjabi retroflex /ʈ/ or dental /t̪/) and vowels (/i a u/) as independent variables, spectral CoG, spectral variance, spectral skewness and spectral kurtosis as dependent variables. The ANOVA results showed that AusE /t/ and Punjabi retroflex /ʈ/ had different spectral CoG across vowels (/i/: [F (1, 26) = 31.047, $p<0.001$]; /a/: [F (1, 26) = 43.066, $p<0.001$]; /u/: [F (1, 26) = 57.451, $p<0.001$]). Similarly, the comparison of AusE /t/ and Punjabi dental /t̪/ showed significant differences in spectral CoG in the context of all vowels (/i/: [F (1, 26) = 27.102, $p<0.001$]; /a/: [F (1, 26) = 34.002, $p<0.001$]; /u/: [F (1, 26) = 18.685, $p<0.001$]).

Spectral variance of the AusE /t/ and Punjabi retroflex /ʈ/ were significantly different across vowels (/i/: [F (1, 26) = 64.041, $p<0.001$]; /a/: [F (1, 26) = 117.942, $p<0.001$]; /u/: [F (1, 26) = 48.075, $p<0.001$]). The comparison of AusE /t/ and Punjabi dental /t̪/ also showed significant differences in spectral variance in the context of all vowels (/i/: [F (1, 26) = 14.308, p=0.001]; /a/: [F (1, 26) = 27.992, $p<0.001$]; /u/: [F (1, 26) = 4.768, $p<0.001$]). As AusE /t/

were produced with extensive release, this might have affected the characteristics of spectral CoG and spectral variance which are higher than both Punjabi retroflex /ʈ/ and dental /t̪/.

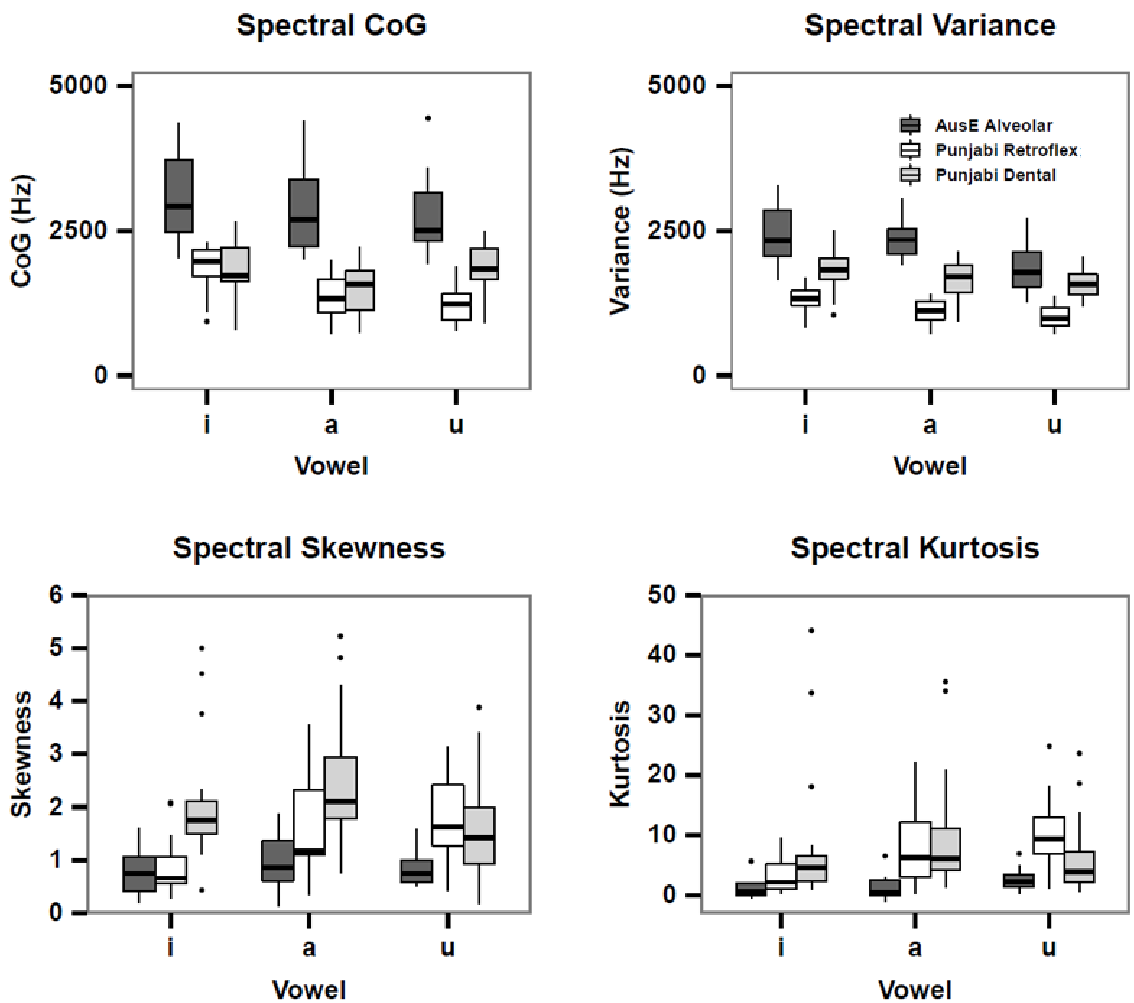

Figure 8. Boxplots of spectral properties of stop release bursts for the AusE /t/ (dark grey boxes), Punjabi retroflex /ʈ/ (white boxes) and dental /t̪/ (light grey boxes) produced after vowels /i a u/ (all speakers, all items).

Spectral skewness of the AusE /t/ and Punjabi retroflex /ʈ/ were not significantly different in /i/ [F (1, 26) = .070, p=0.793] and /a/ [F (1, 26) = 3.507, p=0.072] contexts. However, they differed significantly in the context of /u/ [F (1, 26) = 12.629, p<0.001]. Spectral skewness of the AusE /t/ and Punjabi dental /t̪/ showed significant differences across all vowels (/i/: [F (1, 26) =

10.438, p=0.003]; /a/: [F (1, 26) = 14.446, p=0.001]; /u/: [F (1, 26) = 5.190, p=0.031]). Thus, in terms of spectral skewness, AusE /t/ is similar to Punjabi retroflex /ʈ/ (in /i a/ contexts) but systematically different from Punjabi dental /t̪/. This also indicates that spectral skewness might contribute to the adaptation of English alveolar stops as retroflexes.

Spectral kurtosis of the AusE /t/ and Punjabi retroflex /ʈ/ showed no significant differences for /i/ [F (1, 26) = 2.677, p=0.114] but there were significant differences for /a/ [F (1, 26) = 8.996, p=0.006] and /u/ [F (1, 26) = 14.173, p=0.001]. A comparison of the AusE /t/ and Punjabi dental /t̪/ in the different vowel contexts showed no significant differences for /i/ [F (1, 26) = 3.412, p=0.076] and /u/ [F (1, 26) = 2.864, p=0.103]. However, there were significant differences in the context of /a/ [F (1, 26) = 7.267, p=0.012].

4. Discussion

In this paper, similarities and differences among the acoustic characteristics of the loanword /t/, AusE /t/ and Punjabi retroflex /ʈ/ and dental /t̪/ were investigated. Based on previous studies of Punjabi (Ghotra, 2006; Sharma, 1980), we hypothesized that loanword /t/ would share more temporal and spectral characteristics with Punjabi retroflex /ʈ/ than Punjabi dental /t̪/. We also hypothesized that AusE /t/ would be acoustically more similar to Punjabi retroflex /ʈ/ than to Punjabi dental /t̪/. Regarding the role of bilingualism, we expected that there would be no significant differences between Punjabi monolinguals and trilinguals in the production of loanword /t/.

Our first hypothesis was supported by the data. The results showed that the F3-F2 difference of the vowels produced before loanword /t/ and Punjabi retroflex /ʈ/ was similar in the contexts of /a/ and /u/ and there were more similarities in the temporal and spectral (moments) properties of loanword /t/ and Punjabi retroflex /ʈ/. Burst duration of loanword /t/ and Punjabi retroflex /ʈ/ was statistically significant but as can be observed in Figure 3, burst duration of loanword /t/ was closer to the Punjabi retroflex /ʈ/ than Punjabi dental /t̪/. There were some spectral similarities between the loanword /t/ and Punjabi dental /t̪/ as well. For instance, spectral CoG in the context of /i/ and /a/, spectral skewness in the context of /u/ and spectral kurtosis across /i a u/ showed similarities between the loanword /t/ and Punjabi dental /t̪/. This was due to the fact that, even in Punjabi native phonology, spectral CoG, spectral skewness and spectral kurtosis failed to characterize Punjabi retroflex and dental stops across vowel contexts (Hussain et al., in revision). These results suggest that the temporal aspects (e.g., small closure and burst durations) of loanword /t/ might have contributed to its incorporation into Punjabi as retroflex /ʈ/.

Our second hypothesis regarding the similarities between AusE /t/ and Punjabi retroflex /ʈ/ was not supported by the data and there were no consistent similarities between AusE /t/ and Punjabi retroflex /ʈ/. The F3-F2 difference of the vowels produced before AusE /t/ was similar to Punjabi retroflex /ʈ/ in the context of /i a/, but also similar to Punjabi dental /t̪/ across all three vowels /i a u/. Closure duration of the AusE /t/ was shorter than that of Punjabi retroflex /ʈ/, but more similar to it than to the longer duration of Punjabi dental /t̪/. However, the burst duration of the AusE /t/ was significantly longer than both Punjabi retroflex /ʈ/ and dental /t̪/. Taken together as total stop duration (closure + burst duration), the AusE /t/ was more similar to Punjabi dental /t̪/ than retroflex /ʈ/. It should be noted that we had two different elicitation methods: elicited imitation task to elicit the Punjabi native words, (b) picture identification task for the AusE experiment. In the first task, the target Punjabi words were recorded by a female speaker and presented to the participants as auditory prompts. In the second AusE experiment, the participants were only presented the pictures, without any auditory prompts. It is possible that due to different elicitation methods of native Punjabi and AusE words, our second hypothesis was not confirmed.

Note that Punjabi has separate phonemic categories for aspirated and unaspirated dental and retroflex stops. However, English alveolar stops are not reported to be adapted as aspirated retroflex stops, and showed no such tendency in our data. Chang (2012) reported similar results from Burmese that has a three-way laryngeal contrast (e.g., /p pʰ b/). In Burmese, English aspirated stops are adapted as unaspirated stops. Perhaps, then, when adapting English alveolar /t/ in loanwords, Punjabi speakers rely primarily on closure duration, incorporating it as retroflex /ʈ/. Or perhaps the AusE speakers in our study produced exaggerated release bursts as a function of the task. Both would be interesting issues to follow up on in further research, with a cue weighting task in case of the former, and exploring other contexts and elicitation methods for the latter.

The spectral characteristics of stop release bursts of AusE /t/ showed higher spectral CoG and spectral variance than Punjabi retroflex /ʈ/ and dental /t̪/. Again, this might be due to the heavily released AusE /t/. Spectral skewness of AusE /t/ was similar to Punjabi retroflex /ʈ/ (in /i a/ contexts). This suggests that Punjabi speakers might also use spectral skewness as a cue to adapt English alveolar /t/ as a retroflex /ʈ/. AusE /t/ and Punjabi dental /t̪/, on the other hand, were significantly different in terms of spectral skewness. Spectral kurtosis was similar in AusE /t/ and Punjabi retroflex /ʈ/ but only in the context of /i/.

Unlike other studies that found significant differences in the production of English consonants between monolingual and bilingual speakers living in the UK (McCarthy et al., 2013), this study did not find any significant differences between Punjabi monolingual and trilingual speakers (in line with our prediction). There are two main dominant languages in Pakistan: Punjabi and Urdu. Both languages have a similar set of coronals (e.g., dental, retroflex and palatal). In contrast, English plays a limited role in the day to day life of the Punjabi speakers, so having knowledge of Urdu and English had little effect on the acoustic characteristics of loanword /t/. The data presented in this study were collected in a non-immigrant situation and in a Punjabi dominant environment. This might further explain the lack of multilingual effects on the production of loanwords.

In conclusion, the current paper investigated the temporal and spectral similarities of loanword /t/ and AusE /t/ and compared them with Punjabi native retroflex /ʈ/ and dental /t̪/. The overall findings suggested that the acoustic characteristics of loanword /t/ are closer to Punjabi retroflex than dental stop. The AusE /t/ also showed some acoustic similarities with Punjabi retroflex but it was not consistent. In this paper, we only examined the adaptation of loanword /t/ in word-final position. Future research looking at other word-positions might shed light on the similarities and differences between English alveolar /t/ and Punjabi retroflex /ʈ/ and dental /t̪/.

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Appendix 1. Phonemic inventory of Punjabi (adapted from Bhatia, 1993).

	Labial	Dental	Alveolar	Retroflex	Palatal	Velar	Glottal
Plosive	p pʰ b	t̪ t̪ʰ d̪		ʈ ʈʰ ɖ	ʧ ʧʰ ʤ	k kʰ g	
Fricative	(f) (v)		s (z)		ʃ	(x) (ɣ)	h
Nasal	m		n	ɳ			
Lateral			l	ɭ			
Tap			r				
Flap				ɽ			
Approximant	ʋ				j		

Appendix 2. Mean (SD) F3-F2 difference (Hz) of vowels produced before Punjabi word-final retroflex /ʈ/, dental /t̪/, loanword /t/ and AusE /t/. Formant differences calculated at six equidistant sample time points (50% to 100%) from the preceding Punjabi /i a u/ and AusE /iː ɐː oː/ vowels.

		Sample Time Points from Preceding Vowel					
	Vowel	**50%**	**60%**	**70%**	**80%**	**90%**	**100%**
	/i/	470 (81)	467 (77)	463 (76)	460 (70)	465 (73)	473 (84)
Punjabi /ʈ/	**/a/**	1250 (147)	1224 (143)	1139 (143)	976 (124)	689 (108)	331 (88)
	/u/	1771 (122)	1771 (124)	1730 (135)	1611 (156)	1382 (177)	1039 (238)
	/i/	637 (150)	638 (156)	628 (156)	613 (148)	606 (131)	612 (102)
Punjabi /t̪/	**/a/**	1368 (125)	1368 (126)	1351 (127)	1296 (130)	1238 (134)	1190 (171)
	/u/	1718 (130)	1730 (131)	1711 (135)	1652 (140)	1549 (142)	1441 (158)
	/i/	434 (50)	432 (53)	434 (51)	443 (50)	449 (44)	451 (48)
Loanword /t/	**/a/**	1337 (164)	1296 (173)	1203 (189)	1027 (192)	717 (163)	353 (121)
	/u/	1814 (120)	1810 (121)	1762 (129)	1654 (163)	1431 (231)	1138 (279)
	/iː/	521 (203)	490 (218)	486 (200)	504 (188)	533 (170)	584 (171)
AusE /t/	**/ɐː/**	1292 (166)	1287 (172)	1253 (161)	1194 (146)	1105 (135)	1057 (133)
	/oː/	1919 (172)	1867 (157)	1768 (157)	1610 (150)	1410 (165)	1224 (217)

Appendix 3. Mean (SD) temporal (closure duration, burst duration, and total stop duration (closure + burst)) and spectral characteristics of Punjabi word-final retroflex /ʈ/, dental /t̪/, loanword /t/ and AusE /t/, across preceding Punjabi /i a u/ and AusE /iː ɐː oː/ vowels.

	Vowel	Closure	Burst	Clo+Bur	CoG	Variance	Skewness	Kurtosis
	/i/	85 (22)	12 (2)	97 (22)	1863 (398)	1332 (205)	.86 (.54)	3.24 (2)
Punjabi /ʈ/	**/a/**	88 (21)	9 (1)	97 (21)	1372 (395)	1115 (197)	1.57 (.96)	7.91 (6)
	/u/	84 (21)	9 (2)	93 (21)	1218 (323)	1014 (190)	1.79 (.80)	10.04 (5)
	Mean	**86 (21)**	**10 (2)**	**96 (22)**	**1484 (372)**	**1154 (198)**	**1.41 (.77)**	**7.06 (5.13)**
	/i/	100 (20)	16 (3)	145 (19)	1791 (542)	1809 (354)	2.08 (1)	8.58 (11)
Punjabi /t̪/	**/a/**	106 (20)	13 (3)	133 (18)	1479 (460)	1640 (334)	2.49 (1)	10.14 (10)
	/u/	98 (19)	15 (4)	126 (17)	1797 (449)	1580 (238)	1.60 (1)	6.19 (6)
	Mean	**101 (20)**	**15 (4)**	**116 (20)**	**1689 (484)**	**1677 (309)**	**2.06 (1.14)**	**8.30 (9.43)**
	/i/	78 (18)	9 (2)	86 (18)	1949 (344)	1353 (196)	0.81 (0.36)	3.22 (2.14)
Loanword /t/	**/a/**	83 (17)	7 (2)	90 (17)	1394 (325)	1162 (168)	1.59 (0.79)	7.38 (5.19)
	/u/	78 (15)	8 (2)	85 (16)	1266 (345)	1036 (157)	1.69 (0.81)	8.60 (5.46)
	Mean	**79 (17)**	**8 (2)**	**87 (17)**	**1536 (338)**	**1184 (174)**	**1.36 (0.65)**	**6.40 (4.26)**
	/iː/	62 (11)	65 (27)	127 (28)	3095 (781)	2437 (523)	0.80 (0.47)	1.54 (2.31)
AusE /t/	**/ɐː/**	69 (10)	61 (26)	130 (33)	2937 (872)	2422 (442)	0.94 (0.57)	1.35 (2.28)
	/oː/	62 (15)	62 (31)	125 (41)	2787 (773)	1866 (461)	0.83 (0.33)	2.65 (2.03)
	Mean	**65 (12)**	**62 (28)**	**127 (41)**	**2940 (809)**	**2242 (475)**	**0.86 (0.46)**	**1.85 (2.21)**

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Chapter 6: General Discussion

One of the fundamental issues in the current phonetic literature is how to characterize various types of coronals (Hall, 2011; Paradis & Prunet, 1991). The aim of this dissertation was to investigate the phonetic properties of the Punjabi retroflex and dental stops across word-positions and before/after vowels /i e a o u/, using temporal and spectral measures. Temporal characteristics of the Punjabi word-medial singleton and geminate stops were also investigated, showing that durational contrasts are important to understand stop oppositions in Punjabi. At the end, we then applied these insights to better understand the nature of loanword adaptation, showing the similarities and differences between (Australian) English alveolar /t/, source loanword /t/ and native Punjabi retroflex and dental categories. This dissertation addressed the following research questions:

a. What is the phonology of coronals and other features of the Punjabi language (Chapter 2)?
b. What are the temporal characteristics of Punjabi word-medial singleton and geminate stops (Chapter 3)?
c. Which acoustic cues differentiate the contrast between Punjabi retroflex and dental stops in word-medial, word-initial and word-final positions, across all vowel contexts /i e a o u/ (Chapter 4)?
d. How do the temporal and spectral differences between Punjabi retroflex and dental stops help explain the adaptation of (Australian) English alveolar /t/ as a retroflex rather than a dental in Punjabi (Chapter 5)?

In Chapter 2, a brief introduction to the phonology of coronals and other aspects of Punjabi were presented. Chapter 3 then investigated the temporal characteristics of Punjabi singletons and geminates in a $C_1V_1C_2V_2$ template and showed that consonant duration of C_2 and vowel duration of V_2 are the primary acoustic correlates of Punjabi singletons and geminates. These findings are in line with Hindi (Ohala, 2007). However, no differences in C_1 duration were found when the C_2 was either a singleton or geminate. These results differ from Italian (Turco & Braun, 2014) and Japanese (Han, 1994) where C_1 duration is longer for geminates than singletons. V_1 duration was also not significant in singletons and geminates, similar to the findings of Turkish but different from Bengali (Lahiri & Hankamer, 1988). The results of Chapter 3 suggest that Punjabi speakers use C_2 and V_2 durations as a cue to length distinction in Punjabi consonants.

A detailed investigation of the Punjabi retroflex and dental stops in word-medial, word-initial and word-final positions was then conducted in Chapter 4. Summaries of the overall results are presented in Tables 1-2. The findings suggest that there is considerable variation in the acoustic properties of Punjabi retroflex and dental stops across word-positions. The results of formant transitions indicate that there is no F3-F2 convergence in retroflex stops produced after the front vowels /i e/. These results are in line with Gujarati (Dave, 1977) and Tamil (Ramasubramanian & Thosar, 1971) but differ from Hindi where F3-F2 convergence is reported to occur in all vowels /i a u/ (Ohala & Ohala, 2001).

The results of formant transitions can be interpreted in terms of articulatory-acoustic mapping. Coronals generally have higher F2 compared to labials and velars.[23] Flemming (2003) argued that during the production of anterior coronals (dentals and alveolars), the tongue tip and blade move close to the teeth. This type of movement requires the tongue body to move forward, which results in a high F2. Pennington (2011) notes that the fronting of tongue body is reflected in F2. However, F2 is vowel or language dependent (Hamann, 2003). The lowering of F3, on the other hand, is associated with larger front cavity (Anderson & Maddieson, 1994; Narayanan, Byrd, & Kaun, 1999). F3-F2 convergence occurs when both front and back of the tongue are raised (Dart & Nihalani, 1999). In Punjabi, F3-F2 convergence in vowels /a o u/

[23] Stevens and Blumstein (1975) noted that F2 transitions in retroflex and non-retroflex consonants are similar.

indicates that both front and back parts of the tongue are raised. However, this is not true for the front vowels /i e/, where no F3-F2 convergence was observed (Figure 1a-b in Chapter 4).

Table 1. Summary of the results of F3-F2 difference of vowels /i e a o u/ produced before/after Punjabi word-medial, word-initial and word-final retroflex /ʈ/ and dental /t̪/ (✓ = statistically significant; Χ = no statistically significant).

	Preceding Vowel					Following Vowel				
Word-position	**/i/**	**/e/**	**/a/**	**/o/**	**/u/**	**/i/**	**/e/**	**/a/**	**/o/**	**/u/**
Word-medial	Χ	✓	✓	✓	✓	Χ	Χ	✓	✓	✓
Word-initial	-	-	-	-	-	✓	Χ	✓	✓	✓
Word-final	✓	-	✓	-	✓	-	-	-	-	-

Table 2. Summary of temporal cues and spectral moments of stop release bursts of Punjabi word-medial, word-initial and word-final retroflex /ʈ/ and dental /t̪/ across preceding/following /i e a o u/ vowels (✓ = statistically significant; ☓ = no statistically significant).

Word-position	Vowel	Closure	VOT/Bur	Closure+VOT/Bur	CoG	Variance	Skewness	Kurtosis
Word-medial	**/i_i/**	✓	✓	✓	☓	✓	☓	☓
	/e_e/	✓	✓	✓	☓	✓	✓	✓
	/a_a/	✓	✓	✓	☓	✓	✓	☓
	/o_o/	☓	✓	✓	✓	✓	✓	✓
	/u_u/	☓	✓	✓	✓	✓	✓	✓
Word-initial	**/i/**	-	✓	-	☓	✓	☓	☓
	/e/	-	✓	-	☓	✓	✓	✓
	/a/	-	✓	-	☓	✓	☓	☓
	/o/	-	✓	-	✓	✓	✓	✓
	/u/	-	✓	-	✓	✓	✓	✓
Word-final	**/i/**	✓	✓	✓	☓	✓	✓	☓
	/a/	✓	✓	✓	☓	✓	✓	☓
	/u/	✓	✓	✓	✓	✓	☓	✓

In Punjabi, temporal characteristics of the retroflex and dental stops appear to be the most reliable cues, specifically VOT and total stop duration, but not closure duration (see Table 2). Mean VOT values of the voiceless unaspirated retroflex and dental stops across languages and the current dissertation are presented in Tables 3-5 (Punjabi values are collapsed across vowels).

Table 3. VOTs (ms) of the *word-medial* retroflex and dental stops in Bengali (Mikuteit, 2009), Sindhi (Keerio, 2010) and Punjabi (Hussain et al., in revision). All values in ms.

	Bengali	**Sindhi**	**Punjabi**
Retroflex /ʈ/	11	14	13
Dental /t̪/	15	25	19

Table 4. VOTs (ms) of the *word-initial* retroflex and dental stops in Hindi (Yegnanarayana, Murty, & Rajendran, 2008), Kurtöp (Hyslop, 2009), and Punjabi (Hussain et al., in revision).

	Hindi	**Kurtöp**	**Punjabi**
Retroflex /ʈ/	16	22	15
Dental /t̪/	23	22	21

Table 5. Burst duration (ms) of the *word-final* retroflex and dental stops in Hindi (Ahmad, Miete, & Gupta, 1985), Toda (Shalev, Ladefoged, & Bhaskararao, 1993) and Punjabi (Hussain et al., in revision).

	Hindi	**Toda**	**Punjabi**
Retroflex /ʈ/	25	12	10
Dental /t̪/	35	22	15

Punjabi retroflex stops were characterized by short VOT/burst release in all word-positions. This is consistent with Indo-Aryan (Hindi: Ahmad et al., 1985; Yegnanarayana et al., 2008; Sindhi, spoken in Sindh: Keerio, 2010; Bengali: Mikuteit, 2009) and Dravidian languages (Toda: Shalev et al., 1993). Kurtöp, a Tibeto-Burman language spoken in Bhutan, is the only language that showed no difference in both coronal stops (Hyslop, 2009; see Table 4). It can be noted that the burst duration of the Hindi word-final retroflex and dental stops (Table 5) is longer than Punjabi retroflex and dental stops. This might be due to the differences in elicitation methods. Hindi burst durations are based on single word productions. However, burst durations of the Punjabi retroflex and dental stops are produced in a carrier phrase. Given that duration is not a reliable cue to the retroflex and dental contrast in all languages, this suggests that there is cross-linguistic variation in at least the phonetics of coronal place oppositions. The dental vs. retroflex opposition in Punjabi might not be same as in Kurtöp. The relation between this phonetic variation and potential phonological analyses needs to be investigated.

In Table 6, closure durations of the Punjabi word-medial retroflex and dental stops (Hussain et al., in revision) are compared with Bengali (Mikuteit, 2009) and Hindi (Benguerel & Bhatia, 1980). In word-medial position, closure duration did not differentiate the Punjabi retroflex and dental stops in back vowels /o u/ (see Table 2 above). In order to compare with other languages, here we collapsed the closure duration of Punjabi word-medial retroflex and dental stops across vowels. It can be observed in Table 6 that Punjabi word-medial retroflex and dental stops differed from Bengali and Hindi where no differences were found in closure duration of the word-medial retroflex and dental stops. This suggests that there are also cross-linguistic differences in the reliability of closure duration as a cue to coronal contrasts. Even languages belonging to the same language family can differ in the temporal characteristics of coronals.

Table 6. Closure duration (ms) of word-medial retroflex and dental stops in Bengali (Mikuteit, 2009), Hindi (Benguerel & Bhatia, 1980) and Punjabi (Hussain et al., in revision).

	Bengali	**Hindi**	**Punjabi**
Retroflex /ʈ/	122	145	101
Dental /t̪/	125	145	112

Moving towards the spectral moments of stop release bursts, spectral variance differentiated the Punjabi word-medial retroflex and dental stops in all vowel contexts except /e_e/. However, after excluding two speakers, spectral variance achieved statistical significance in the context of /e_e/. Spectral CoG did not differentiate the Punjabi word-medial retroflex and dental stops in the context of /i e a/. In the context of back vowels /o u/, however, spectral CoG reliably differentiated two stop types. Spectral skewness differentiated the Punjabi word-medial retroflex and dental stops in /e_e/, /a_a/, /o_o/ and /u_u/ contexts but not /i_i/. Spectral kurtosis distinguished Punjabi word-medial retroflex and dental stops in the context of /e_e/, /o_o/ and /u_u/ but not for /i_i/ and /a_a/. It can be noted that all spectral moments differentiated the Punjabi word-medial retroflex and dental stops in the context of back vowels (/o_o/ and u_u/). This suggests that robust spectral cues of release bursts of Punjabi word-medial coronals are found in the context of back vowels.

In word-initial position, spectral variance differentiated Punjabi retroflex and dental stops in the context of following vowels /i a o u/. Spectral variance was significant for /e/ as well but after excluding the two speakers that had unusual spectral variance. Spectral CoG differentiated Punjabi retroflex and dental stops only in the context of back vowels /o u/. Spectral skewness and spectral kurtosis of the word-initial retroflex and dental stops were significant only in the context of /e o u/.

In word-final position, spectral variance reliably differentiated the retroflex and dental stops in all three vocalic environments. Spectral CoG did not differentiate Punjabi retroflex and dental stops produced after /i/ and /a/, but it was significant for back /u/. Spectral skewness distinguished both coronal stops after /i/ and /a/, but not after /u/. Spectral kurtosis only distinguished word-final retroflex and dental stops produced after /u/.

Overall, the results of spectral moments indicated lower spectral CoG and spectral variance for retroflexes but higher for dentals. This is consistent with previous studies showing that retroflexes have concentration of acoustic energy in the lower regions of burst spectrum, compared to dentals (Tabain, 2012; Stevens & Blumstein, 1975). The results also showed that spectral CoG of stop release bursts did not characterize the Punjabi retroflex and dental stops in the context of front vowels /i e/. Spectral CoG is correlated with the length of front cavity. This indicates that the length of front cavity in Punjabi retroflex and dental stops is not different for front vowels /i e/. Surprisingly, spectral CoG also failed to distinguish the Punjabi retroflex and dental stops in the context of low vowel /a/ which is considered to be a neutral and optimal vowel for studying the coronal contrasts of a language (Kochetov, Sreedevi, Kasim, & Manjula, 2014).

These acoustic results can also be interpreted in light of previous articulatory studies. There are several articulatory studies confirming that high front vowels constrain the articulation of retroflexes (see Hamann, 2003 for discussion). This is due to the fact that high front vowels are typically produced with bunched lingual posture (Jackson & McGowan, 2012; Takemoto, Honda, Masaki, Shimada, & Fujimoto, 2006), but retroflex consonant production involves tongue-retraction and raising of the tongue tip (Bhat, 1973; Narayanan et al., 1999; Smith, Proctor, Iskarous, Goldstein, & Narayanan, 2013). Many of the goals of production of the high-front vowels therefore appear to be articulatorily incompatible with those of retroflex production. Moreover, the length of front cavity is smallest in the front vowel /i/ (Sundberg &

Lindblom, 1990) but the articulation of retroflexes involve larger front cavity. Several articulatory studies have confirmed that retroflexes are fronted in the context of front vowels. Khatiwada (2007) showed that Nepali retroflex stops are produced in the alveolar region when surrounded by the front vowels /i_i/. In Tamil, retroflex stops and rhotics are produced with an apical-postalveolar constriction in vowels /a_a/ and /u_u/. However, in the context of /i_i/, retroflexes are produced with tongue bunching and a laminal post-alveolar constriction (Smith et al., 2013). Kannada retroflex stops are also produced with a fronted tongue body in vowel /i_i/ (Irfana & Sreedevi, 2016; see also Kochetov & Sreedevi, 2014). Tabain and Butcher (2015) found similar effects in Pitjantjatjara, where retroflex stop release before /i/ vowel was more anterior than alveolar stop release. They proposed that these findings may account for the cross-linguistic scarcity of retroflexes in the context of high front vowel /i/.

In the loanword study (Chapter 5), it was observed that loanword /t/ is acoustically closer to Punjabi retroflex than dental stops, both in terms of temporal (closure duration) and spectral (spectral variance and spectral skewness) properties. However, the results indicated that the temporal and spectral characteristics of the AusE /t/ and Punjabi retroflex stops did not show robust patterns of similarities. The F3-F2 difference of the vowels produced before AusE /t/ and Punjabi retroflex was similar in the context of /a/ and /u/. Closure duration of the AusE /t/ was shorter than both Punjabi retroflex and dental stops, though more similar to that of the retroflex. The AusE /t/ was produced with very long burst duration. Therefore, burst duration of the AusE /t/ was much longer than either the Punjabi retroflex and dental stops. This also affected on the spectral moments of stop release burst of AusE /t/. Spectral CoG and spectral variance of the AusE /t/ were higher than both Punjabi retroflex and dental stops.

Another finding was that there were no significant differences in Punjabi monolinguals and trilinguals across acoustic measures (Chapter 5). The Punjabi speakers recruited for the experiments were residing in Pakistan and the data were collected in a Punjabi dominant environment. All of the speakers had exposure to English and Urdu but this did not affect on the phonetic characterization of the native as well as non-native coronal contrasts. Urdu also has a contrastive retroflex and dental series (Kelkar, 1968). In terms of non-native speakers, it is the second most dominant language in Pakistan (see Rahman, 2006 for discussion). Punjabi has also been in contact with other languages (Hindi, Bengali, Persian, Urdu, Portuguese and Dutch) and has borrowed English loanwords via several sources (e.g., Hindustani, Bengali and Persian: see Clark, 1956). The role of different routes of borrowing during the adaptation of English loanwords is still unclear and needs further investigation. Another important point to be noted here is that Punjabi has contrastive aspiration in voiceless stops (see the discussion section in Chapter 5). However, English word-final alveolar stops have never been reported to be adapted as aspirated stops. Languages like Mandarin Chinese have also contrastive aspiration (Duanmu, 2007). Paradis and Tremblay (2009) demonstrated that a large number of English loanwords with voiceless aspirated or unaspirated stops were adapted as aspirated in Mandarin Chinese. In contrast, English aspirated stops are adapted as unaspirated in Burmese, which also has contrastive aspiration in stops (Chang, 2012).

Study limitations and future directions

This dissertation has some limitations as well. For instance, the spectral properties of Punjabi coronals can be further investigated using DCT (Discreet Cosine Transformation; Harrington, 2010). DCT analysis can provide important information about F3-F2 convergence in Punjabi coronals across word-positions and vowels /i e a o u/ (see Karjigi & Rao, 2012). Moreover, it can also show the extent of F3 lowering in the context of front vowels. We anticipate that DCT analysis would show similar results as that found here for the F3-F2 difference.

Linear Mixed Effects (LME) Models have been recently used in the phonetic literature because they provide more powerful and sophisticated statistical results than GLM repeated-measure ANOVAs. For instance, the interactions between various factors can be explored using a number of random vs. fixed effects. This dissertation used repeated-measure ANOVAs that have already been employed in the phonetic studies. This made possible to compare our data with a wide range of literature on coronals.

This dissertation only looked at voiceless unaspirated coronals. A more complete study could be conducted including voiceless aspirated and voiced coronals of Punjabi. This would make possible comparisons of our data to wider literature on both voiceless and voiced coronals. The loanword study only looked at word-final English alveolar /t/ produced by native Australian English speakers and native Punjabi speakers. It would be good to extend these results to other word-positions (e.g., word-medial and word-final) and voicing contrasts.

In this dissertation we only looked at the phonetic properties of coronals using acoustic measures. Follow up articulatory studies using EMA and Ultrasound imaging could also provide insights into the tongue kinematics of the Punjabi retroflex and dental stops in the context of different preceding/following vowels. EMA has a good spatial and temporal resolution for tracking the articulation of speech sounds (Gick, Wilson, & Derrick, 2013). It can provide data from tongue, jaw and lips. Hence, the role of these articulators during the production of Punjabi coronals can be explored. Ultrasound, on the other hand, would be helpful in examining the shape of tongue during retroflex productions and how this shape varies across vowels (Kochetov et al., 2014). Another possible articulatory method that could be used to study Punjabi coronals is MRI which also provides good spatial and temporal resolution (Smith et al., 2013).

It would also be worthwhile to explore the perception of Punjabi coronals using synthetic and natural speech stimuli to test whether VOT (or total stop duration) or other acoustic cues provide the most reliable categorization of Punjabi coronals. For instance, a perception experiment could be run using an English alveolar /t/ with varying closure duration and VOT which correspond to the lowest Punjabi retroflex measurements at one end and to the highest dental measurements at the other. Punjabi speakers could be asked to identify whether they perceive retroflex or dental stop. By using this kind of perception experiment, we could better understand the acoustic cues that Punjabi listeners might use to perceive Punjabi coronal contrasts. Furthermore, perception experiments could also help tease apart the role of temporal and spectral cues in distinguishing Punjabi coronals. The perception of English alveolar stops could also be tested in different vowel contexts, using nonsense or real words and coronals from various languages (e.g., Persian and Arabic).

This dissertation also presented a brief phonological structure of Punjabi. Further analysis of the vowel inventory and other areas of the Punjabi phonological system is greatly to be desired and could have implications for the hypotheses presented here.

Implications

The class of coronals consists of a wide range of speech sounds, produced with very subtle differences in acoustics and articulation (Paradis & Prunet, 1991). This dissertation provided a detailed phonetic analysis of the complex coronal system of Punjabi (both singletons and geminates). These findings will help inform various phonetic processes underlying rich coronal contrasts of Indo-Aryan languages. Moreover, detailed phonetic analyses of Punjabi coronals across word-positions and vocalic contexts will help to address some of the inconsistencies in the current literature on the phonetics of coronals. This dissertation will also provide a baseline for other phonetic studies on the typology of coronal contrasts in Australian, Indo-Aryan and Dravidian languages. Phoneticians and phonologists can therefore use the data presented here for conducting phonetic studies on the acquisition of coronals. It also opens a window for future research on the phonetics and phonology of coronals.

This dissertation also raised questions about loanword adaptation in Indo-Aryan languages, particularly Punjabi, showing why English alveolar stops are adapted as retroflexes, rather than as dentals. The study presented on loanword adaptation has implications for the models of loanword phonology (perceptual and phonological), and also for phonological theory in general. For instance, whether adaptation of English alveolar stops is phonologically motivated or based on the perceptual grounds. As mentioned in Chapter 5, loanword /t/ was closer to Punjabi retroflex than dental stop, in terms of temporal and spectral characteristics. However, some acoustic characteristics (spectral CoG, spectral skewness and spectral kurtosis) of loanword /t/ were similar to Punjabi dental stop. There were no clear patterns of acoustic similarities between AusE /t/ and Punjabi retroflex stops. Given that English alveolar stops are reported to be consistently adapted as retroflexes, this suggests that other factors may be relevant. This dissertation provided a test case by investigating the adaptation of English alveolar stops into Punjabi and raised further interesting questions about the adaptation of coronals from Persian and Arabic into Punjabi and other Indo-Aryan languages.

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Appendix (Ethics approval) of this thesis has been removed as it may contain sensitive/confidential content