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Acoustic characteristics of Punjabi retroflex and dental stops[a)]

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The phonological 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 2280 stop tokens produced by 30 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.
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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; however, Indo-Aryan languages make extensive use of these contrasts in their coronal-rich segmental inventories. Several studies have described aspects of retroflex production and perception in Indo-Aryan languages, but there is no consensus on the phonetic properties that characterize these consonants, and a lack of quantitative data to inform our understanding of how they differ from other coronals.

Punjabi is an Indo-Aryan language spoken in Pakistan and India, and in expatriate communities throughout the world. Despite the large number of speakers [$>100 \times 10^6$; 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 (using temporal and spectral analyses) because studies of other languages have shown that the contrast between retroflex and dental stops is difficult to perceive for both native (Wubuy listeners: Bundgaard-Nielsen *et al*., 2015a) and non-native listeners (perception of Hindi retroflex and dental stops by English and Japanese listeners: Pruitt *et al*., 2006; perception of Wubuy coronals by English and Bangla listeners: Bundgaard-Nielsen *et al*., 2015b). Palatal /ʧ/ is not included in this study, as it is acoustically and articulatorily quite different from retroflexes and dentals (cf. 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), and on coronal contrasts in particular. Within the class of coronals, lowering of $F3$ in preceding vowels has been argued to be the most important acoustic correlate of retroflexes (Hamann, 2003; Hamilton, 1996). By contrast, $F2$ may be raised or lowered before a retroflex, depending on vowel context. Retroflex articulations involve raising of the tongue tip towards the hard palate which can affect the trajectory of the third formant. $F3$ can be lowered in the transition from back vowels, raised in other vowel contexts, or remain stable in retroflex stops produced after /i e/ (Dave, 1977). The anteriority of coronal constriction also affects $F3$. Retroflexes with a more retracted constriction location have been found to have a significantly lower $F3$ than those produced further forward in the oral tract (Hamann, 2003; Ladefoged and Bhaskararao, 1983). In some Australian indigenous languages, $F2$ and $F3$ differentiate palatals from other coronals (Central Arrernte: Tabain, 2012; Pitjantjatjara: Tabain and Beare, 2011); however, dentals, alveolars, and retroflexes are not consistently differentiated by these formants. 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 these

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three places of articulation. 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, $F3$ onset transitions do not differentiate Wubuy dentals, alveolars, and retroflexes, suggesting that formant transitions might also be language-dependent (Bundgaard-Nielsen *et al.*, 2012).

In addition to their effect on individual formant trajectories, retroflexes can cause formant convergence in some vowel contexts. In a study of ten speakers of Hindi, Ohala and Ohala (2001) found retroflex stops to be characterized by $F3$–$F2$ convergence after vowels /i a u/. On the other hand, Dave (1977) found no $F3$–$F2$ convergence in a two-speaker study of Gujarati retroflex stops produced after /i/ and /e/. More data are required to understand in which languages and in which phonological environments $F3$–$F2$ convergence is a reliable acoustic correlate of retroflex articulations.

Voice onset time (VOT) is another acoustic cue that is widely used to distinguish among coronals produced at different places of articulation. In Tiwi, word-medial retroflexes/postalveolars are characterized by a shorter VOT compared to dentals (Anderson and Maddieson, 1994). In a cross-linguistic study of VOT, Lisker and Abramson (1964) compared coronal stops produced by single speakers of two Indo-Aryan languages: Hindi and Marathi. Mean VOTs of initial voiceless unaspirated retroflex and dental stops in both languages were 11 ms. 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). 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 between the voiceless unaspirated retroflex (22 ms) and dental (22 ms) stops, while another speaker had a longer VOT for retroflex (31 ms) than dental (26 ms) stops. Thus, comparisons of VOT between retroflexes and dentals do not consistently show that retroflexes have a longer VOT.

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. Sindhi voiceless unaspirated retroflex stops were also shorter in duration (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 the closure durations of retroflex and dental stops. Maxwell *et al.* (2015) investigated the closure duration and total stop duration (closure + VOT) of the Bengali word-medial aspirated retroflex and aspirated dental stops and also found no significant differences.

Apart from formant transitions, VOT/burst duration, closure duration, and total stop duration, spectral moments [spectral center of gravity (CoG), spectral standard deviation (SD), spectral skewness, spectral kurtosis] have also been widely used to classify different places of articulation (e.g., retroflex and dental fricatives: Gordon *et al.*, 2002; stops in general: Eshghi *et al.*, 2013; Nissen and Fox, 2009; Tabain, 2012). Spectral moments are correlated with different articulatory configurations of the vocal tract and therefore provide important information about the length of the oral cavity and tongue postures in the production of consonants (Forrest *et al.*, 1988; Jongman *et al.*, 2000; Li *et al.*, 2009).[1] The first spectral moment (or spectral CoG) indicates mean distribution (or concentration) of acoustic energy in the burst spectrum, and correlates with the length of the front cavity (Nittrouer, 1995). The second spectral moment (spectral SD) corresponds to the distribution of acoustic energy on both sides of the mean and differentiates the tongue posture of apical (alveolars and retroflexes) and laminal (dentals and palatals) articulations (Li *et al.*, 2009; Nittrouer, 1995). The third spectral moment (spectral skewness or tilt) indicates whether the acoustic energy in the burst spectrum is skewed toward higher (negative skewness) or lower (positive skewness) frequencies, and is correlated with the length of the front cavity (Jongman *et al.*, 2000; Li *et al.*, 2009). The fourth spectral moment (spectral kurtosis) is a measure of "peakiness" in the spectral envelope of the release burst, and differentiates the tongue posture of apical and laminal articulations (Li *et al.*, 2009; Tabain and Butcher, 2015). Within the class of coronals, laminals (dentals and palatals) show higher spectral CoG, spectral SD, and negative spectral skewness and spectral kurtosis, compared to apicals (retroflexes and alveolars) (Gordon *et al.*, 2002; Tabain, 2012; Tabain *et al.*, 2016). In retroflexes, raising the tongue tip towards a hard palate increases the length of the front cavity. As a result, the space underneath the tongue (sublingual cavity) also enlarges (see Hamann, 2003). Unlike some other coronals, there is typically no constriction separating postlabial and sub-lingual cavities in retroflex production; rather, the whole space anterior to the coronal constriction forms a single large front cavity. Increasing the length of the front cavity lowers the spectral CoG, spectral SD, but increases the spectral skewness and spectral kurtosis (Laaksonen *et al.*, 2011; Tabain *et al.*, 2014). Spectral moments of alveolars more closely match those of retroflexes than dentals in some coronal-rich languages (Tabain, 2012; Tabain *et al.*, 2016), but spectral CoG does not reliably differentiate retroflexes and dentals in word-medial (/aCa/) and word-initial (/a#Ca/) contexts in Wubuy, a language with a similar set of coronal contrasts (Bundgaard-Nielsen *et al.*, 2016).

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. Dentals are produced at a more anterior location with the tongue blade, and typically use a larger lingual contact area than retroflexes (see Kang, 2000; Keating, 1991). Retroflexes are articulated further back in the oral tract with the tip of the tongue, which typically results in faster release and more intense bursts than dentals

(Gordon and Maddieson, 1999; Kuehn and Moll, 1976; Ohala and Ohala, 1992; Tabain, 2012). The acoustic consequences of these differences in articulation are that retroflexes are often characterized by shorter closure and release burst durations, a more peaked spectrum (positive spectral kurtosis and skewness), and energy distribution at lower frequencies (lower spectral CoG and SD) compared to dentals (Anderson and Maddieson, 1994; Bundgaard-Nielsen *et al.*, 2016; Gordon and Maddieson, 1999; Stevens and Blumstein, 1975; Tabain, 2012).

The discriminability of some coronal contrasts may also depend on the type and direction of transition cues. Steriade's (2008) cross-linguistic survey of coronals in different word contexts concluded that retroflexes were better differentiated from other coronals in terms of VC (Vowel-Consonant) transitions compared to CV (Consonant-Vowel) transitions. This claim is based on data from Australian and other coronal-rich languages that neutralize contrasts—apical alveolar vs apical postalveolar or retroflex—in CV contexts, where there are no cues from a preceding vowel (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. Perception studies lend some support to Steriade's observations: a perceptual categorization study of the coronal contrasts of Western Arrernte found that in a VCV (Vowel-Consonant-Vowel) context, the correct identification rate of retroflexes by native Arrernte listeners was 74%. However, this identification rate dropped significantly in a CV context, where retroflexes were correctly identified as retroflexes in only 19% of the cases (Anderson, 1997). It should be noted that Western Arrernte does not contrast apicals (alveolars vs retroflexes) in word-initial context. Anderson (1997) used CV stimuli excised from VCV stimuli and then asked the Arrernte listeners to discriminate the alveolar vs retroflex contrast in CV context. This might be the reason why Arrernte listeners performed poorly in a CV context, compared to VCV context. Bundgaard-Nielsen *et al.* (2015b) also showed that Bangla speakers from Dhaka performed poorly on the word-initial alveolar vs retroflex contrast of Wubuy, while those from another region were better able to discriminate the same contrast. Their findings suggested that Bangla listeners use language/dialect-specific phonetic features to characterize the coronal contrasts of Wubuy. In another study, Bundgaard-Nielsen *et al.* (2015a) tested the perception of Wubuy coronals by native listeners of Wubuy and found similar differences in the perception of coronals according to syllable position: Wubuy native listeners discriminated retroflexes and dentals in intervocalic context with 83% correct discrimination rate, but dropping to 72% for word-initial context. The alveolar vs retroflex contrast had a much lower correct discriminability than the dental vs retroflex contrast in both contexts: 70% in intervocalic context and 63% in word-initial context.

The formant transitions, VOT/burst duration, closure duration, total stop duration, and spectral moments associated with a particular stop are also expected to differ across vowel contexts (Nissen, 2003). For instance, retroflexes show a 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 [see Hamann (2003) for a discussion]. The incompatibility of retroflexes adjacent to high front vowels has long been noted in Mandarin (Chao, 1968; Lee-Kim, 2014), and the phonological representation of syllables with retroflex initials and /i/ finals is a topic of ongoing debate (Lee and Zee 2003; Duanmu, 2006, 2007). Previous studies of Indo-Aryan coronal stops have only addressed temporal cues (Berkson, 2012; Benguerel and Bhatia, 1980) or formant transitions (Dave, 1977; Ohala and Ohala, 2001). However, we know very little about the influence of vowels and word contexts on the temporal and spectral properties of retroflex and dental stops in Indo-Aryan languages. Maxwell *et al.* (2015) investigated the acoustic characteristics of Bengali word-medial aspirated retroflex and dental stops and found that $F3$ was a reliable descriptor of the retroflex-dental contrast when preceded by the vowel /a/ in both nonsense and real words. When preceded by /i/, $F3$ did not distinguish the retroflex-dental contrast in real words but it did in nonsense words. There was no clear distinction between the two coronals in terms of closure duration and VOT.

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 retroflex-dental contrast. We focus 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.[2] We examine key temporal and spectral cues that have been widely used to classify coronals: formant trajectories, stop closure duration, release burst duration, total stop duration, 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 investigate formant transitions to see if $F3$ reliably differentiates coronal place, and whether Punjabi retroflexes are cued by $F3$–$F2$ convergence after high front vowels. The findings suggest that stop release duration and total stop duration reliably differentiate Punjabi retroflex and dental stops across all word contexts and vocalic environments. However, burst spectral measures and formant transitions do not consistently differentiate the two coronals.

II. METHOD

A. Participants

Word-medial and word-initial coronal contrasts were examined in the speech of 12 male speakers of Punjabi (20 to 29 yrs of age, mean 22.6 yrs). All speakers were trilinguals with some knowledge of Urdu and English. Coronal contrasts were elicited in word-final context from another 18 male Punjabi speakers (ten trilinguals and eight monolinguals; 22 to 30 yrs old, mean 26.4 yrs). 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. None of the speakers had speech or hearing difficulties. All the speakers were recruited from Faisalabad, Pakistan, and spoke the Lyallpuri dialect of Punjabi (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 retroflex /ʈ/ or a dental /t̪/. V_1 and V_2 were selected from the five vowels /i e a o u/.[3] The word-final target words consisted of 12 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).[4] 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 because they show the widest phonotactic distribution and can occur in all word contexts (medial, initial, and final). Central vowels, on the other hand, can only occur word-initially or medially (Dulai and Koul, 1980).

Word-medial and word-initial coronals 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 × 5 repetitions × 12 speakers = 1200 tokens). The word-final coronals data were recorded using an elicited imitation task.[5] 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 Sec. IV.

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 (Zoom Corporation, Tokyo, Japan) 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 by averaging the two channels, using the default mono conversion algorithm in Praat (Boersma and Weenink, 2014).

D. Acoustic analyses

A total of 2280 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, five 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 Fig. 1). All landmarks

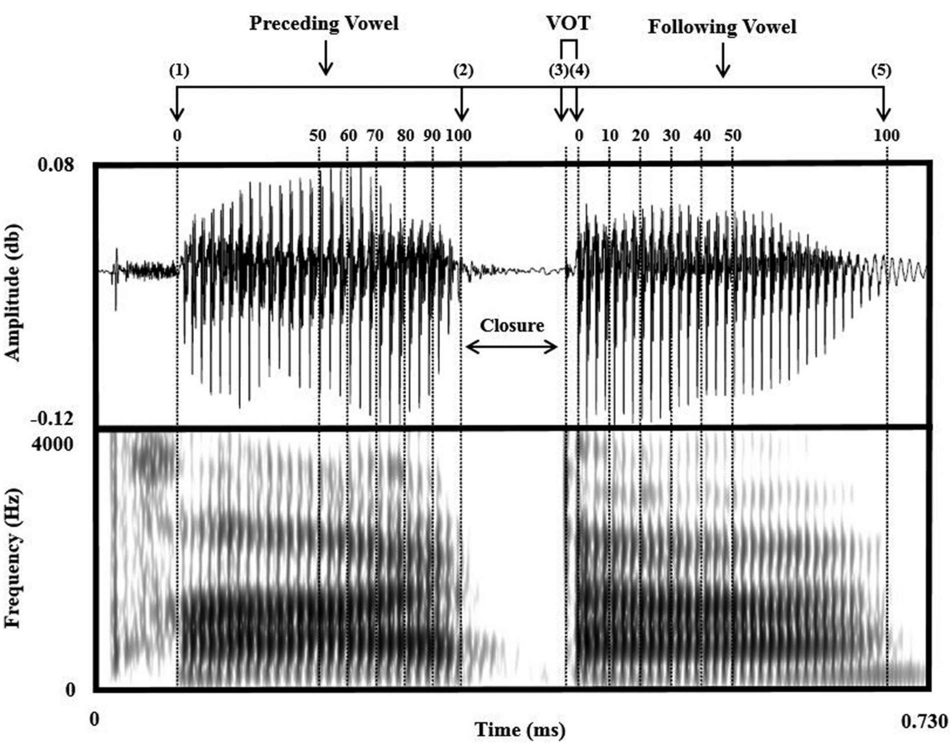


FIG. 1. Spectral and temporal analysis of Punjabi word-medial coronal stops: acoustic waveform and wideband spectrogram for the nonsense word /pʰaʈa/. Temporal landmarks indicated at (1) preceding vowel onset, (2) preceding vowel offset (stop closure onset), (3) release burst onset, (4) voice onset of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

were manually located by visual inspection of the waveform and spectrogram, making reference to periodicity and formant energy bands. Landmarks (2) and (3)—delimiting stop closure duration—were located at the points of maximum attenuation of $F2$ energy in the transition from adjacent vocalic intervals. 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 voice onset of following vowel (4). In word-final context, where VOT cannot be measured, we used burst release duration as an equivalent parameter. Total stop duration therefore provided a consistent measure of closure + release duration for stops produced in word-medial and word-final contexts, because all stops examined in this study were voiceless. As closure duration cannot be reliably measured word-initially, only VOT was reported for initial stops.

To validate the placement of temporal landmarks, a trained phonetician independently segmented 10% of the data containing medial stops (60 items). Mean VOTs and closure durations measured by this phonetician and the research team showed close agreement, suggesting that landmark placement was consistent and reproducible, and that the temporal measures derived from these landmarks were reliable.[6]

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 (TPs) 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 Fig. 1, Appendix D). Formants were extracted with LPC analysis over a sliding 25 ms analysis window with a 50 dB dynamic range. 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 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 (see Appendix E, Fig. 12). Final analyses were based on the corrected formant trajectories.

The first four spectral moments (spectral CoG, spectral SD, spectral skewness, and spectral kurtosis) of stop release bursts were also measured in Praat from fast Fourier transform (FFT) spectra generated over a single 5 ms Hamming analysis window centered at the beginning of the stop release burst, using the power value of $p = 2$ (Fig. 2). Because the duration of the shortest release burst was 3 ms, a narrow analysis window was used so that the spectral moments were never influenced by the formants of the following vowel. The same analysis window duration was used for both

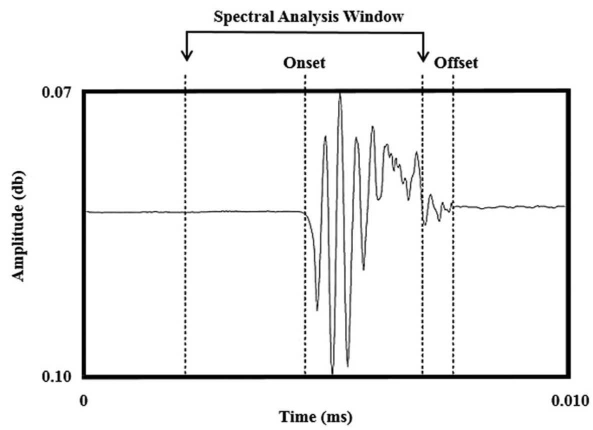


FIG. 2. Spectral moment analysis of Punjabi coronal stops: acoustic waveform showing the onset and offset of the release burst of the word-final retroflex stop in /kuʈ/ "mountain top." Four moments were calculated from a spectrum using FFT over a 5 ms Hamming windowed speech segment centered at the stop release burst onset.

retroflexes and dentals, so that spectral moments could be compared across all stops (cf. Gordon and Maddieson, 1999).

E. Statistical analyses

The data were analyzed in R (R Core Team, 2012). A series of Linear Mixed Effects (LMEs) models were conducted for each acoustic measure using the *lme4* (Bates *et al.*, 2015), *lmerTest* (Kuznetsova *et al.*, 2012), *pbkrtest* (Halekoh and Højsgaard, 2014) and *lsmeans* (Lenth, 2016) packages. For temporal and spectral moments analysis, Speaker was used as a random factor, consonant (retroflex vs dental) and vowel (/i e a o u/) were included as fixed factors (alpha value was set at $p = 0.05$). The LME models for formant transitions were conducted separately for each vowel context, with Speaker as a random factor, consonant (retroflex vs dental), and six sample TPs from the preceding (50% to 100%) and following (0% to 50%) vowels as fixed factors.[7]

III. RESULTS

A. Word-medial stop properties

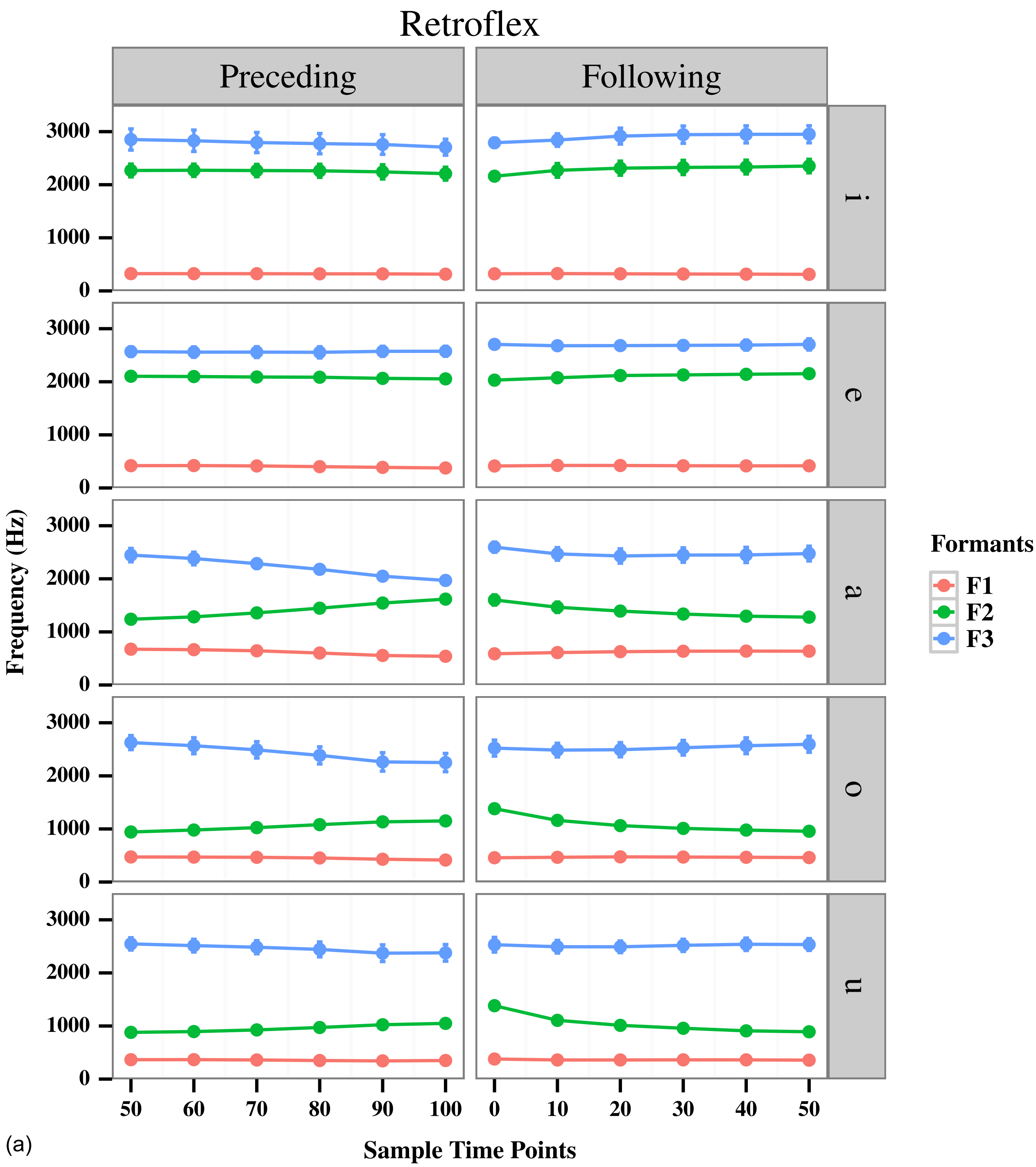
1. Formant measures of word-medial stops

We first describe the formant trajectories of the vowels /i e a o u/ preceding or following the Punjabi word-medial retroflex and dental stops. Figures 3(a) and 3(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.

Overall, the 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 $F3$–$F2$

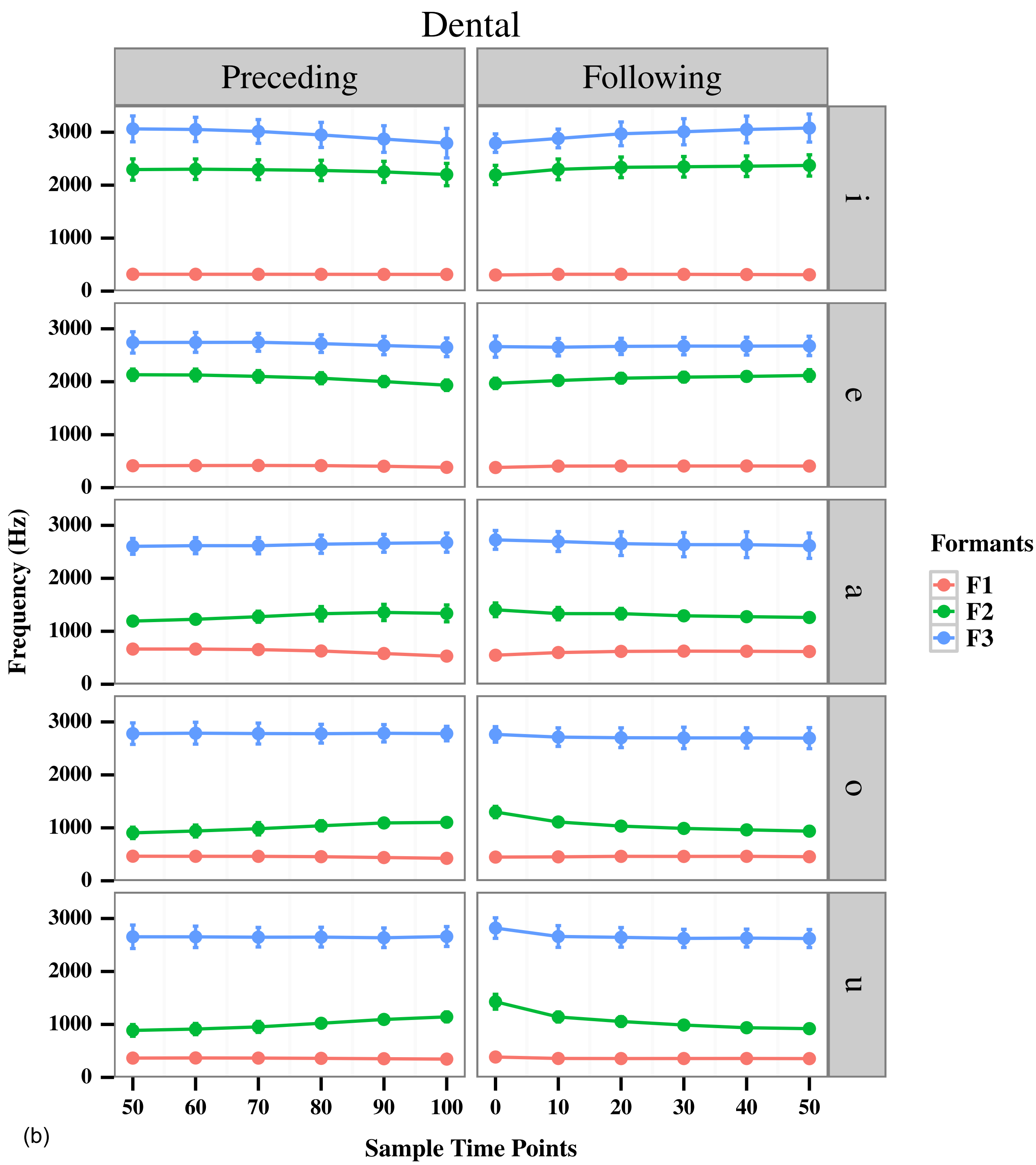
difference was found for the retroflex stop near the offset of the preceding vowel /a/. To examine the influence of Punjabi word-medial retroflex and dental stops on formant trajectories in context vowels, LME models were performed on the $F3$–$F2$ difference in each vowel context, with Speaker as a random factor and consonant (retroflex vs dental) and sample TPs (six levels corresponding to the six sample TPs) from preceding (50% to 100%) and following (0% to 50%) vowels as fixed factors. Statistical results are presented in Table I.

The LME results showed the significant effect of a consonant on $F3$–$F2$ difference across all preceding vowels /i e a o u/, suggesting that the $F3$–$F2$ difference of these vowels is significant for both coronals. However, the effect of TPs was only significant in the /a o u/ contexts but it was non-significant for the front vowels /i e/. This indicates that the



(a)

FIG. 3. (Color online) (a) Mean vowel trajectories (Hz) of /i e a o u/ preceding (left) and following (right) word-medial retroflex stops (all speakers, all items). Formants averaged at six sample TPs for each context vowel. Error bars show SD of mean frequencies (Hz). (b) Mean vowel trajectories (Hz) of /i e a o u/ preceding (left) and following (right) word-medial dental stops (all speakers, all items). Formants averaged at six sample TPs for each context vowel. Error bars show SD of mean frequencies (Hz).



(b)

FIG. 3. (Color online) (*Continued*)

*F*3–*F*2 difference does not differ across TPs in the preceding vowels /i e/. The interaction between consonant and sample TPs was significant for all preceding context vowels /i e a o u/, indicating that the relationship between the second and third formants varied systematically with place in the transition from preceding vowels /i e a o u/ into retroflex vs dental stops.

The mean *F*3–*F*2 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 the *F*3–*F*2 difference from the onset of a following vowel /i/ was slightly higher in retroflexes [630 Hz (98)] than in dental stops [601 Hz (75)]. The results of the LME models on following vowels showed that consonant had a significant effect on *F*3–*F*2 difference in following /a o u/ vowels, suggesting that the *F*3–*F*2 of the vowels following Punjabi retroflex and dental stops varied significantly for these vowels. However, no significant effect of consonant was found on the *F*3–*F*2 difference in following front vowels /i e/. The effect of TPs on the *F*3–*F*2 difference was significant for following /e o u/, but non-significant for following /i a/. The interaction between consonant and TPs was significant for vowels /i a o u/ but not for /e/. This indicates that the *F*3–*F*2 difference of vowels /i a

TABLE I. $F3$-$F2$ difference in word-medial stops: results of LME models with Speaker as a random factor, consonant (retroflex vs dental), and six sample TPs from preceding (50% to 100%) and following (0% to 50%) vowels as fixed factors. The LME models were run separately for each vowel context. The degrees of freedom, F values, and p values are provided. Shaded cells denote significant results with an alpha value of $p = 0.05$.

	$F3$-$F2$ difference (Hz)														
	/i/			/e/			/a/			/o/			/u/		
Factors	df	F	p	df	F	p	df	F	p	df	F	p	df	F	p
Preceding vowel															
Consonant (C)	1	4.66	=0.053	1	34.48	<0.001	1	181.32	<0.001	1	31.43	<0.001	1	5.13	=0.044
TPs	5	1.88	=0.216	5	1.32	=0.353	5	17.60	<0.001	5	17.78	<0.001	5	8.70	=0.006
C × TPs	5	8.13	<0.001	5	8.16	=0.055	5	379.81	<0.001	5	81.42	<0.001	5	5.61	<0.001
Following vowel															
Consonant (C)	1	1.21	=0.294	1	0.69	=0.422	1	22.41	<0.001	1	19.85	<0.001	1	8.64	=0.044
TPs	5	1.14	=0.418	5	3.99	=0.049	5	2.22	=0.163	5	9.61	=0.004	5	15.79	=0.001
C × TPs	5	9.81	<0.001	5	0.74	=0.590	5	17.19	<0.001	5	16.73	<0.001	5	16.44	<0.001

o u/ following Punjabi retroflex and dental stops varied across TPs and consonants.

In addition to the $F3$–$F2$ 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. LME models were performed on $F3$ of the preceding vowels using Speaker as a random factor, consonant (retroflex vs dental) and six sample TPs (50% to 100%) as fixed factors. The LME results showed that $F3$ transitions into retroflex and dental stops are significantly different in preceding /e a o u/ contexts (/e/: [df = 1, $F = 13.37$, $p = 0.003$]; /a/: [df = 1, $F = 106.71$, $p < 0.001$]; /o/: [df = 1, $F = 27.57$, $p < 0.001$]; /u/: [df = 1, $F = 23.18$, $p < 0.001$]); however, $F3$ transitions from preceding vowel /i/ did not differ significantly [df = 1, $F = 4.28$, $p = 0.062$]. These data suggest that $F3$ may only provide a robust cue to place for Punjabi coronal stops produced after non-high front vowels.

2. Temporal properties of word-medial stops

Figure 4 presents boxplots of closure duration, VOT, and total stop duration of the Punjabi word-medial retroflex and dental stops. Retroflex stops were characterized by shorter mean closure duration [collapsed across vowels: 101 ms (20)] and VOT [13 ms (4)]. In contrast, dental stops showed a longer mean closure duration [112 ms (18)] and VOT [19 ms (4)]. The total stop duration of the retroflex stops was also shorter [114 ms (19)] than that of the dental stops [131 ms (17)].

LME models were performed on closure duration, VOT, and total stop duration of Punjabi word-medial retroflex and dental stops. We compared both consonants in each vowel context using *lsmeans* package which gives an estimated mean (or β value), standard error (SE), t- and p-values. The results showed that closure duration differentiated the Punjabi retroflex and dental stops but only in the context of /i_i/, /e_e/, and /a_a/ (/i_i/: [$\beta = -17.96$, SE = 3.30, $t = -5.42$, $p < 0.001$]; /e_e/: [$\beta = -16.18$, SE = 3.30, $t = -4.89$, $p < 0.001$]; /a_a/: [$\beta = -10.86$, SE = 3.30, $t = -3.28$, $p = 0.002$]). However, in the context of back vowels /o u/, closure duration did not differentiate the Punjabi word-medial retroflex and dental stops (/o_o/: [$\beta = -5.73$, SE = 3.30, $t = -1.73$, $p = 0.091$]; /u_u/: [$\beta = -6.25$, SE = 3.30, $t = -1.88$, $p = 0.067$]). VOT reliably differentiated the Punjabi word-medial retroflex and dental stops in all vowel contexts (/i_i/: [$\beta = -8.26$, SE = 1.35, $t = -6.10$, $p < 0.001$]; /e_e/: [$\beta = -7.03$, SE = 1.35, $t = -5.19$, $p < 0.001$]; /a_a/: [$\beta = -4.11$, SE = 1.35, $t = -3.04$, $p = 0.006$]; /o_o/: [$\beta = -5.83$, SE = 1.35, $t = -4.31$, $p < 0.001$]; /u_u/: [$\beta = -5.31$, SE = 1.35, $t = -3.92$, $p < 0.001$]). Similarly, total stop duration also differentiated the word-medial retroflex and dental stops in all vowel contexts (/i_i/: [$\beta = -26.01$, SE = 3.58, $t = -7.25$, $p < 0.001$]; /e_e/: [$\beta = -23.16$, SE = 3.58, $t = -6.45$, $p < 0.001$]; /a_a/: [$\beta = -15.06$, SE = 3.58, $t = -4.20$, $p < 0.001$]; /o_o/: [$\beta = -11.63$, SE = 3.58, $t = -3.24$, $p = 0.003$]; /u_u/: [$\beta = -11.65$, SE = 3.58, $t = -3.24$, $p = 0.003$]). 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 5 depicts boxplots of the first four spectral moments (spectral CoG, spectral SD, spectral skewness, and spectral kurtosis) of stop release bursts of Punjabi word-medial retroflex and dental stops produced in all five vowel contexts. 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/: 831 Hz (199); /u_u/: 685 Hz (209)] consistently showed smaller spectral CoG values compared to dental stops [/o_o/: 1396 Hz (453); /u_u/: 1506 Hz (561)]. Mean spectral CoG collapsed across all vowel contexts was 1216 Hz (363) for retroflex stops and 1485 Hz (544) for dental stops, suggesting that the concentration of acoustic energy in the burst spectrum is characteristically lower for retroflexes than dentals. The results of the LME models showed that spectral CoG differentiated the Punjabi word-medial retroflex and dental stops only in the context of back vowels (/o_o/: [$\beta = -564.90$, SE = 152.46, $t = -3.70$, $p < 0.001$]; /u_u/: [$\beta = -821.03$, SE = 152.46, $t = -5.38$, $p < 0.001$]). However, spectral CoG did not differentiate the Punjabi word-medial retroflex and dental stops in the context

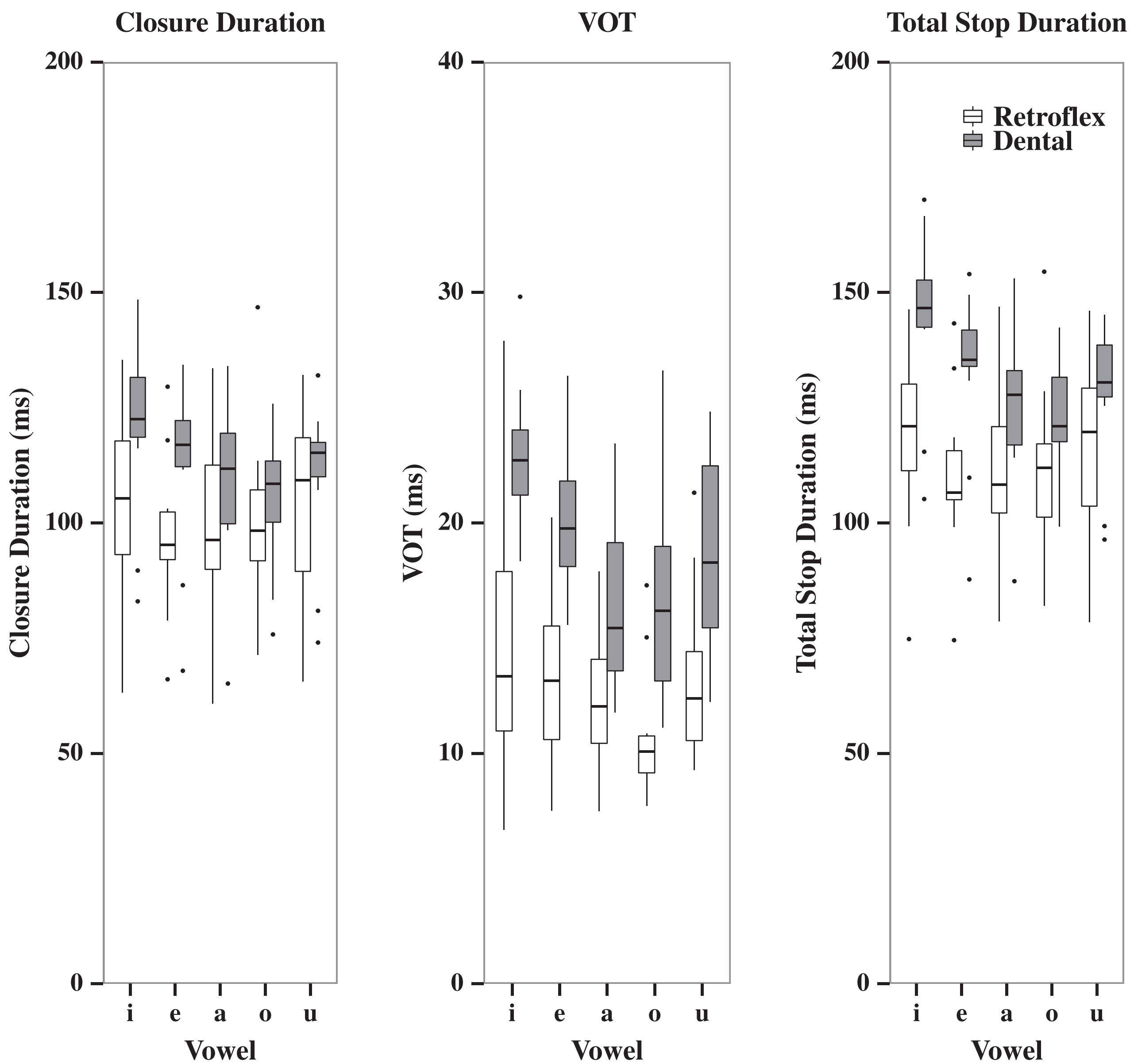


FIG. 4. Boxplots of closure duration (ms), VOT (ms), and total stop duration (ms) of the Punjabi word-medial retroflex and dental stops produced in /i_i/, /e_e/, /a_a/, /o_o/, and /u_u/ contexts (all speakers, all items).

of /i_i/ [$\beta = 88.86$, SE = 152.46, $t = 0.58$, $p = 0.563$], /e_e/ [$\beta = 98.80$, SE = 152.46, $t = 0.64$, $p = 0.520$], and /a_a/ [$\beta = -143.63$, SE = 152.46, $t = -0.94$, $p = 0.351$].

Spectral SD was lowest for the word-medial retroflex stops [/i_i/: 1546 Hz (345); /e_e/: 1300 Hz (323); /a_a/: 1017 Hz (245); /o_o/: 758 Hz (247); /u_u/: 686 Hz (208)], compared to dental stops [/i_i/: 1824 Hz (559); /e_e/: 1315 Hz (479); /a_a/: 1337 Hz (352); /o_o/: 1163 Hz (256); /u_u/: 1063 Hz (287)]. Averaged across all vowels, overall spectral SD was 1062 Hz (274) for retroflex stops and 1360 Hz (387) for dental stops. Spectral SD reliably distinguished the Punjabi word-medial retroflex and dental stops in the context of /i_i/ [$\beta = -277.91$, SE = 82.89, $t = -3.35$, $p = 0.001$], /a_a/ [$\beta = -319.50$, SE = 82.89, $t = 3.85$, $p < 0.001$], /o_o/ [$\beta = -404.56$, SE = 82.89, $t = -4.88$, $p < 0.001$], and /u_u/ [$\beta = -377.01$, SE = 82.89, $t = -4.54$, $p < 0.001$]. However, the coronals were not differentiated in the context of /e_e/ [$\beta = -114.73$, SE = 82.89, $t = -1.38$, $p = 0.172$]. Three speakers produced dental stops with very low spectral SD (SP9: 680 Hz; SP10: 737 Hz; SP11: 767 Hz) in the /e_e/ context, even lower than retroflex stops (SP9: 749 Hz; SP10: 809 Hz; SP11: 971 Hz). This is probably why spectral SD did not reach statistical significance.

In /i_i/, /e_e/, and /a_a/ contexts, retroflex stops showed much smaller spectral skewness [/i_i/: 1.24 (0.64)]; /e_e/: [1.98 (0.73); /a_a/: (2.90 (1.18)], compared to dental stops [/i_i/: 2.33 (1.30)]; /e_e/: [3.27 (1.35); /a_a/: (3.17 (0.88)]. In back vowel contexts, retroflex stops were characterized by higher spectral skewness [/o_o/: 3.59 (1.54); /u_u/: 4.50 (1.54)] than dental stops [/o_o/: 2.29 (1.49); /u_u/: 2.06 (1.80)]. Overall spectral skewness collapsed across all vowels was 2.84 (1.12) for retroflex stops and 2.62 (1.37) for dental stops. Spectral skewness differentiated the Punjabi word-medial retroflex and dental stops across all vowel contexts, except /a_a/ (/i_i/: [$\beta = -1.08$, SE = 0.42, $t = -2.54$, $p = 0.013$]; /e_e/: [$\beta = -1.28$, SE = 0.42, $t = -3.00$,

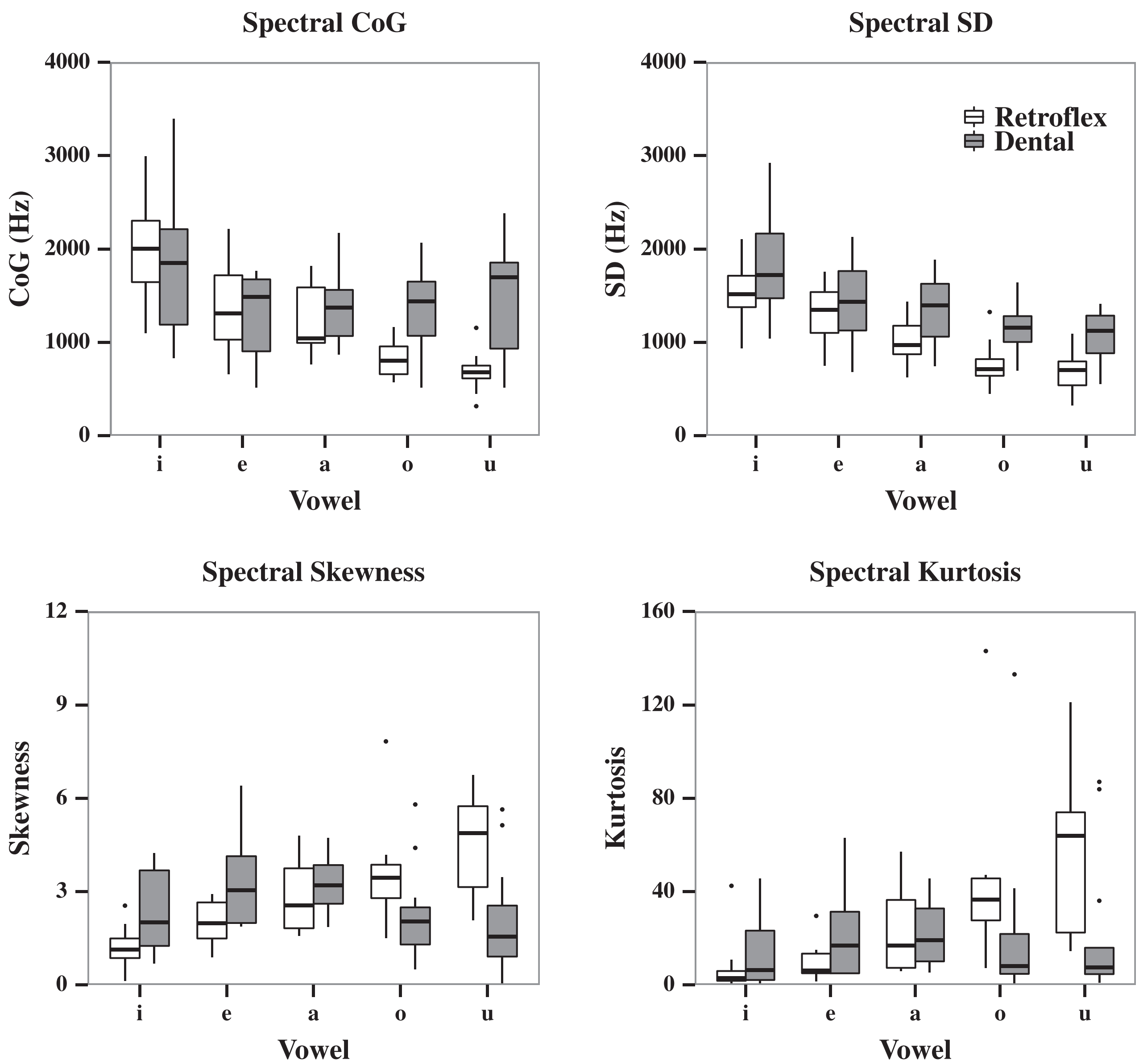


FIG. 5. Boxplots of spectral CoG (Hz), spectral SD (Hz), spectral skewness, and spectral kurtosis of stop release bursts of the Punjabi word-medial retroflex and dental stops produced in /i_i/, /e_e/, /a_a/, /o_o/, and /u_u/ contexts (all speakers, all items).

$p = 0.003$]; /a_a/: [$\beta = -0.27$, SE $= 0.42$, $t = -0.63$, $p = 0.529$]; /o_o/: [$\beta = -1.30$, SE $= 0.42$, $t = 3.05$, $p = 0.003$]; /u_u/: [$\beta = 2.44$, SE $= 0.42$, $t = 5.72$, $p < 0.001$]).

The highest spectral kurtosis values were observed for the retroflex stops produced in back vowel contexts [/o_o/: 41.75 (34.18); /u_u/: 58.86 (34.30)]. In contrast, dental stops showed the lowest spectral kurtosis values in /o_o/ and /u_u/ contexts [/o_o/: 23.02 (37.11); /u_u/: 21.41 (31.25)]. The spectral kurtosis collapsed across all vowels was 28.08 (21.16) for retroflex stops and 20.22 (23.29) for dental stops. Spectral kurtosis distinguished the Punjabi word-medial retroflex and dental stops in the context of /o_o/ and /u_u/, but not in the context of /i_i/, /e_e/, and /a_a/ (/i_i/: [$\beta = -5.79$, SE $= 8.48$, $t = -0.68$, $p = 0.495$]; /e_e/: [$\beta = -12.74$, SE $= 8.48$, $t = -1.50$, $p = 0.135$]; /a_a/: [$\beta = 1.64$, SE $= 8.48$, $t = 0.19$, $p = 0.846$]; /o_o/: [$\beta = 18.73$, SE $= 8.48$, $t = 2.20$, $p = 0.028$]; /u_u/: [$\beta = 37.44$, SE $= 8.48$, $t = 4.41$, $p < 0.001$]).

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 Fig. 6. 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 vowel /i/ was larger in retroflex [672 Hz (149)] than dental stops [543 Hz (123)].

To examine the influence of Punjabi word-initial retroflex and dental stops on formant trajectories in context vowels, LME models were performed on the $F3$–$F2$ difference in each vowel context, with Speaker as a random factor and consonant (retroflex vs dental) and six sample TPs (0% to

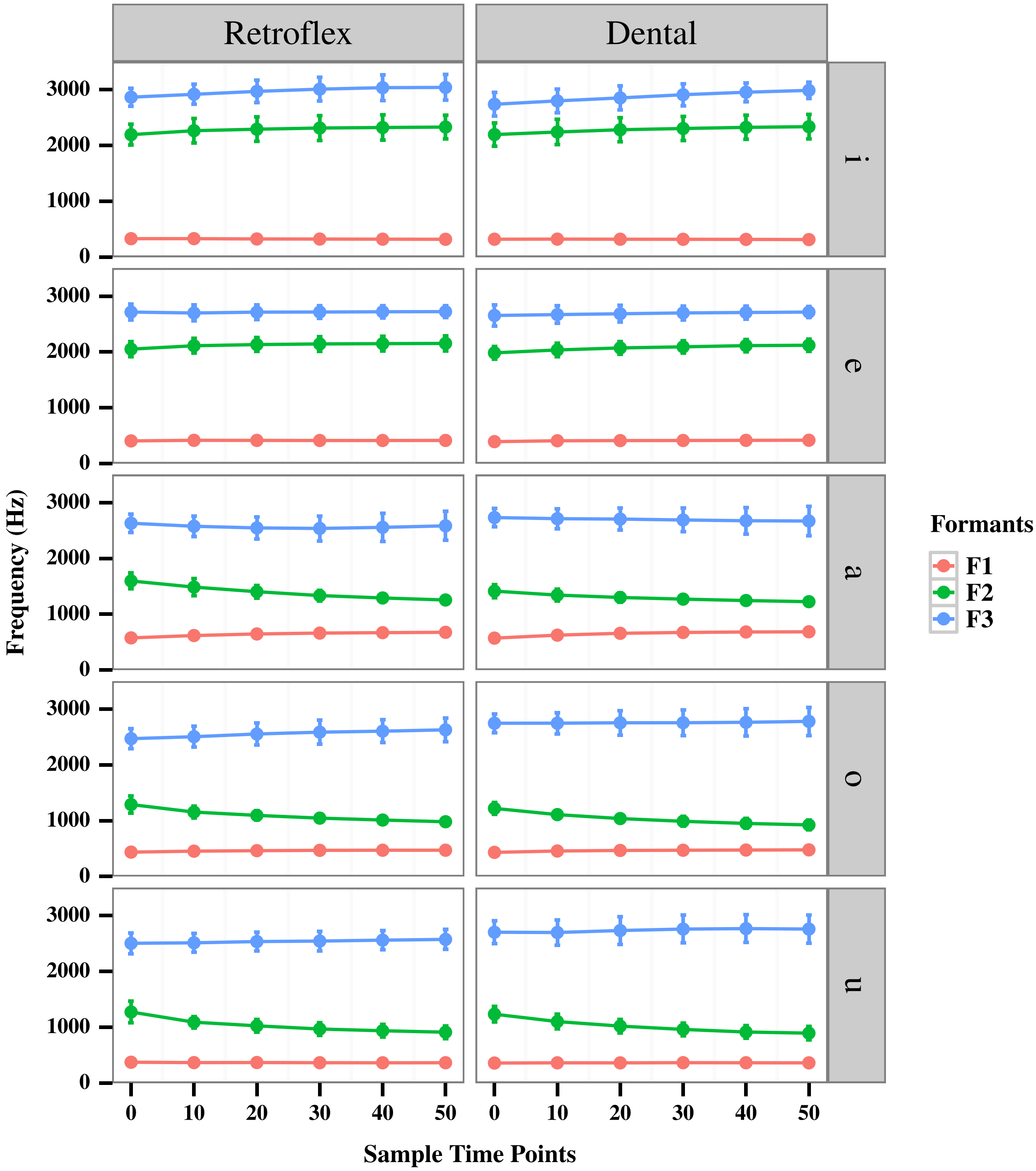


FIG. 6. (Color online) Mean vowel trajectories (Hz) of /i e a o u/ produced after word-initial retroflex (left) and dental (right) stops (all speakers, all items). Formants averaged at six sample TPs for each context vowel. Error bars show SD of mean frequencies (Hz).

50%) from following vowels as fixed factors. Statistical results are presented in Table II. The LME results showed that there was a significant effect of a consonant on the $F3$–$F2$ difference of following vowels /a o u/ and there were significant effects of TPs and significant interactions between consonant and TPs. The results indicate that the $F3$–$F2$ difference of following /a o u/ vowels varied across consonant and TPs. However, no significant effect of consonant on the $F3$–$F2$ difference of the following vowels /i e/ was observed, neither TPs nor the interaction between consonant and TPs achieved statistical significance for these two vowels. This suggests that the place contrast of Punjabi retroflex and dental stops is cued by the $F3$–$F2$ difference but only in the context of following vowels /a o u/, but not for following front vowels /i e/.

2. Temporal properties of word-initial stops

Figure 7 presents boxplots of VOT for the Punjabi word-initial retroflex and dental stops. Longer VOTs can be

TABLE II. $F3$-$F2$ difference in word-initial stops: results of LME models with Speaker as a random factor, consonant (retroflex vs dental), and six sample TPs (0% to 50%) from following vowels as fixed factors. The LME models were run separately for each vowel context. The degrees of freedom, F values, and p values are provided. Shaded cells denote significant results with an alpha value of $p = 0.05$.

	$F3$-$F2$ difference (Hz) of following vowels														
	/i/			/e/			/a/			/o/			/u/		
Factors	df	F	p	df	F	p	df	F	p	df	F	p	df	F	p
Consonant (C)	1	3.94	=0.072	1	1.87	=0.198	1	10.12	<0.001	1	28.97	<0.001	1	24.50	<0.001
TPs	5	0.57	=0.719	5	2.90	=0.098	5	3.96	=0.050	5	26.27	=0.001	5	15.04	=0.001
C × TPs	5	1.59	=0.159	5	1.50	=0.186	5	19.59	<0.001	5	11.83	<0.001	5	2.45	=0.032

observed for dentals produced in all vowel contexts, compared to the shorter VOTs that characterize retroflex stops. Mean VOT for retroflexes collapsed across all vowels was shorter [15 ms (3)] than the grand mean VOT for dentals [21 ms (4)].

The LME results showed that VOT reliably differentiated the Punjabi word-initial retroflex and dental stops in all vowel contexts (/i/: [$\beta = -9.70$, SE = 0.95, $t = -10.17$, $p < 0.001$]; /e/: [$\beta = -7.73$, SE = 0.95, $t = -8.11$, $p < 0.001$]; /a/: [$\beta = -3.10$, SE = 0.95, $t = -3.25$, $p = 0.002$]; /o/: [$\beta = -3.45$, SE = 0.95, $t = -3.62$, $p < 0.001$]; /u/: [$\beta = -6.25$, SE = 0.95, $t = -6.55$, $p < 0.001$]). This suggests that VOT is a robust acoustic correlate of place for Punjabi word-initial retroflex and dental stops.

3. Spectral properties of word-initial stop releases

Boxplots of the first four spectral moments (spectral CoG, spectral SD, spectral skewness, and spectral kurtosis) characterizing stop release bursts of the Punjabi word-initial retroflex and dental stops are compared in Fig. 8. In the context of back vowels, retroflex stops showed much smaller spectral CoG [/o/: 988 Hz (215); /u/: 851 Hz (167)] compared to dental stops [/o/: 1912 Hz (555); /u/: 1708 Hz (415)]. When collapsed across all vowels, the mean spectral CoG of the word-initial retroflex and dental stops was 1431 Hz (326) and 1801 Hz (515), respectively. The results of the LME models 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/: [$\beta = -71.78$, SE = 377.42, $t = -0.19$, $p = 0.852$]; /e/: [$\beta = 13.78$, SE = 377.42, $t = 0.03$, $p = 0.971$]; /a/: [$\beta = -11.96$, SE = 377.42, $t = -0.03$, $p = 0.975$]; /o/: [$\beta = -923.23$, SE = 377.42, $t = -2.44$, $p = 0.029$]; /u/: [$\beta = -865.90$, SE = 377.42, $t = -2.27$, $p = 0.040$]).

The word-initial retroflex stops showed the lowest spectral SD across all vowels than dental stops. The overall spectral SD collapsed across all vowels was 1254 Hz (245) for retroflex stops and 1567 Hz (328) for dental stops. Spectral SD distinguished the Punjabi word-initial retroflex and dental stop bursts before all vowels except /e/ (/i/: [$\beta = -255.38$, SE = 81.18, $t = -3.14$, $p = 0.002$]; /e/: [$\beta = -65.95$, SE = 81.18, $t = -0.81$, $p = 0.420$]; /a/: [$\beta = -352.63$, SE = 81.18, $t = -4.34$, $p < 0.001$]; /o/: [$\beta = -560.03$, SE = 81.18, $t = -6.89$, $p < 0.001$]; /u/: [$\beta = -331.80$, SE = 81.18, $t = -4.08$, $p < 0.001$]).

Spectral skewness of the Punjabi word-initial retroflex stop releases was higher in the context of back vowels /o u/, compared to the dental stops in the same vocalic contexts (Fig. 8). Spectral skewness collapsed across all vowels was 2.35 (0.88) for the retroflex stops and 1.74 (0.62) for the dental stops. Word-initial retroflex and dental stop release bursts were differentiated by spectral skewness but only before /e o u/ (/e/: [$\beta = -0.66$, SE = 0.27, $t = -2.39$, $p = 0.019$]; /o/: [$\beta = -2.13$, SE = 0.27, $t = 7.73$, $p < 0.001$]; /u/: [$\beta = 2.37$, SE = 0.27, $t = 8.60$, $p < 0.001$]). Spectral skewness did not differentiate the Punjabi word-initial retroflex and dental stops before high front vowel /i/ [$\beta = -0.51$, SE = 0.27, $t = -1.87$, $p = 0.064$] and low vowel /a/ [$\beta = -0.27$, SE = 0.27, $t = -0.98$, $p = 0.326$].

Spectral kurtosis of the word-initial retroflex stops produced before back vowels /o u/ was higher than dental stops produced in the same contexts. Mean spectral kurtosis collapsed across all vowel contexts was 16.23 (10.86) for retroflex stops and 7.23 (5.85) for dental stops. Release burst spectral kurtosis distinguished the word-initial retroflex and dental stops but only before /o u/ (/o/: [$\beta = 25.99$, SE = 4.15, $t = 6.26$, $p < 0.001$]; /u/: [$\beta = 25.47$, SE = 4.15, $t = 6.13$, $p < 0.001$]). Spectral kurtosis did not differentiate the Punjabi word-initial retroflex and dental stops before front vowels /i e/ and low vowel /a/ (/i/: [$\beta = -1.00$, SE = 4.15, $t = -0.24$,

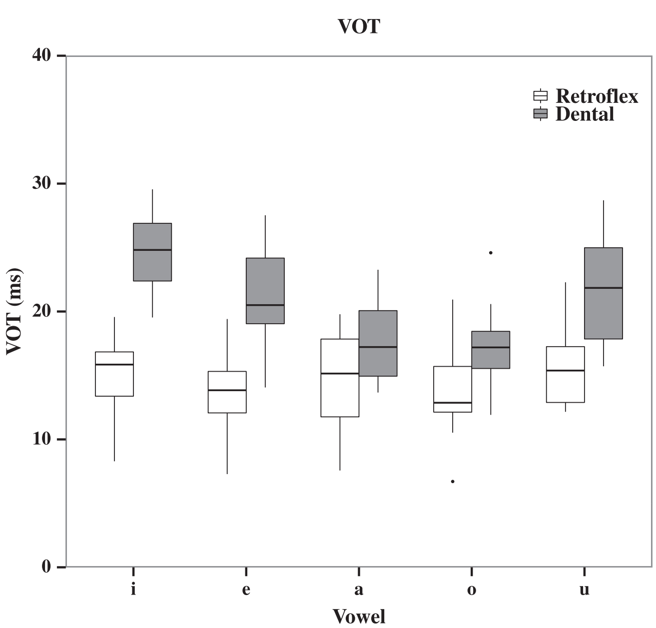


FIG. 7. Boxplot of VOT (ms) of the Punjabi word-initial retroflex and dental stops produced before vowels /i e a o u/ (all speakers, all items).

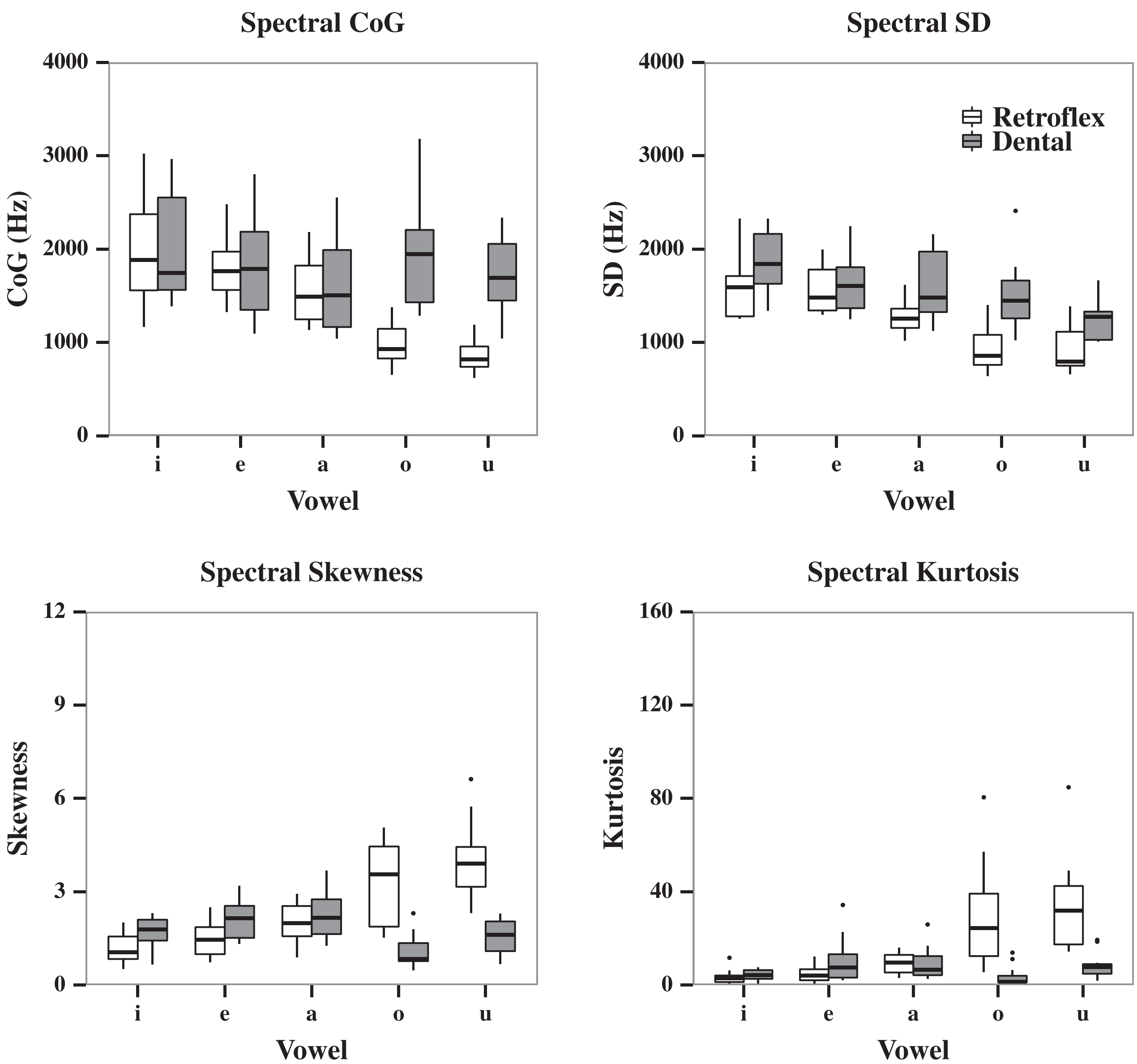


FIG. 8. Boxplots of spectral CoG (Hz), spectral SD (Hz), spectral skewness, and spectral kurtosis of stop release bursts of the Punjabi word-initial retroflex and dental stops produced before /i/, /e/, /a/, /o/, and /u/ contexts (all speakers, all items).

$p = 0.810$]; /e/: ([$\beta = -5.65$, SE $= 4.15$, $t = -1.36$, $p = 0.176$]; /a/ ([$\beta = -0.15$, SE $= 4.15$, $t = 0.03$, $p = 0.970$]).

C. Word-final stop properties

1. Formant measures of word-final stops

Figure 9 presents the mean formant trajectories of the vowels /i a u/ produced before the Punjabi word-final retroflex and dental stops. 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)].

LME models were run using Speaker, speaker group (trilinguals and monolinguals), and repetition as random factors, consonant (retroflex vs dental), and six sample TPs (50% to 100%) from the preceding vowels as fixed factors. There were no differences in the models with speaker group and repetition as random factors and the models without these two random factors. Therefore, we excluded these two factors from the subsequent LME models.

The LME results (Table III) indicated a significant effect of consonant on the $F3$–$F2$ difference of all preceding vowels /i a u/, suggesting that the $F3$–$F2$ difference of /i a u/ was significantly different for retroflex and dental stops. However, TPs reached statistical significance only in the preceding vowels /a u/ but not in the preceding /i/. This indicates that the $F3$–$F2$ difference varied across TPs for vowels /a u/ but not for /i/. This is reflected in Fig. 9 as well, where $F3$ and $F2$ show convergence in the context of preceding /a u/ but no notable change in $F3$ and $F2$ in the context of /i/.

In addition to the $F3$–$F2$ difference, separate analyses were also run to investigate if third formant trajectories in vowels produced before Punjabi word-final retroflex and

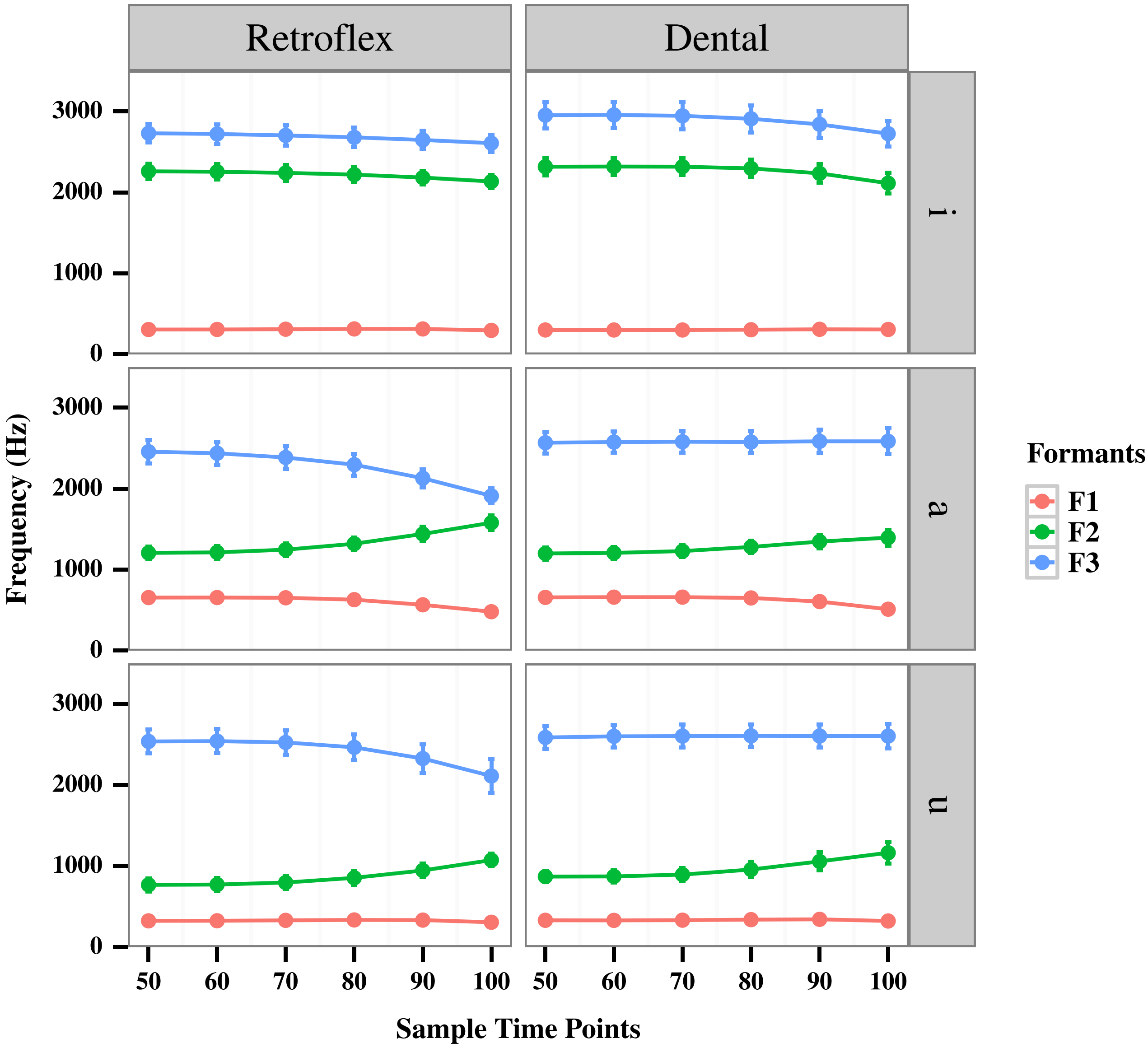


FIG. 9. (Color online) Mean vowel trajectories (Hz) of /i a u/ produced before Punjabi word-final retroflex (left) and dental (right) stops (all speakers, all items). Formants averaged at six sample TPs for each vowel. Error bars show SD of mean frequencies (Hz).

dental stops reliably differentiated the two coronals. The LME results showed that $F3$ transitions into retroflex and dental stops were significantly different in all preceding vowels /i a u/ (/i/: [df = 1, $F = 22.72$, $p < 0.001$]; /a/: [df = 1, $F = 94.66$, $p < 0.001$]; /u/: (df = 1, $F = 63.47$, $p < 0.001$]).

TABLE III. $F3$-$F2$ difference in word-final stops: results of LME models with Speaker as a random factor, consonant (retroflex vs dental), and six sample TPs (50% to 100%) from preceding vowels as fixed factors. The LME models were run separately for each vowel context. The degrees of freedom, F values, and p values are provided. Shaded cells denote significant results with an alpha value of $p = 0.05$.

	$F3$-$F2$ difference (Hz) of preceding vowels								
	/i/			/a/			/u/		
Factors	df	F	p	df	F	p	df	F	p
Consonant (C)	1	11.22	=0.003	1	204.48	<0.001	1	12.45	=0.002
TPs	5	1.41	=0.284	5	66.65	<0.001	5	27.47	=0.006
C × TPs	5	2.52	=0.027	5	731.01	<0.001	5	270.01	<0.001

$F3$ also achieved statistical significance in the context of the front vowel /i/, where the third formant was consistently higher before dentals, compared to /i/ produced before retroflex stops (see Fig. 9).

2. Temporal properties of word-final stops

Figure 10 shows boxplots of closure duration, burst duration, and total stop duration of the Punjabi word-final retroflex and dental stops. The retroflex stops were consistently produced with smaller closure and burst durations [closure duration: 85 ms (21); burst duration: 10 ms (2)], 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 [95 ms (22)] and dental [116 ms (19)] stops.

The LME results showed that there was a closure duration difference between the Punjabi word-final retroflex and dental stops produced after all three vowels (/i/: [$\beta = -16.23$, SE = 2.40, $t = -6.75$, $p < 0.001$]; /a/: [$\beta = -18.16$, SE = 2.40,

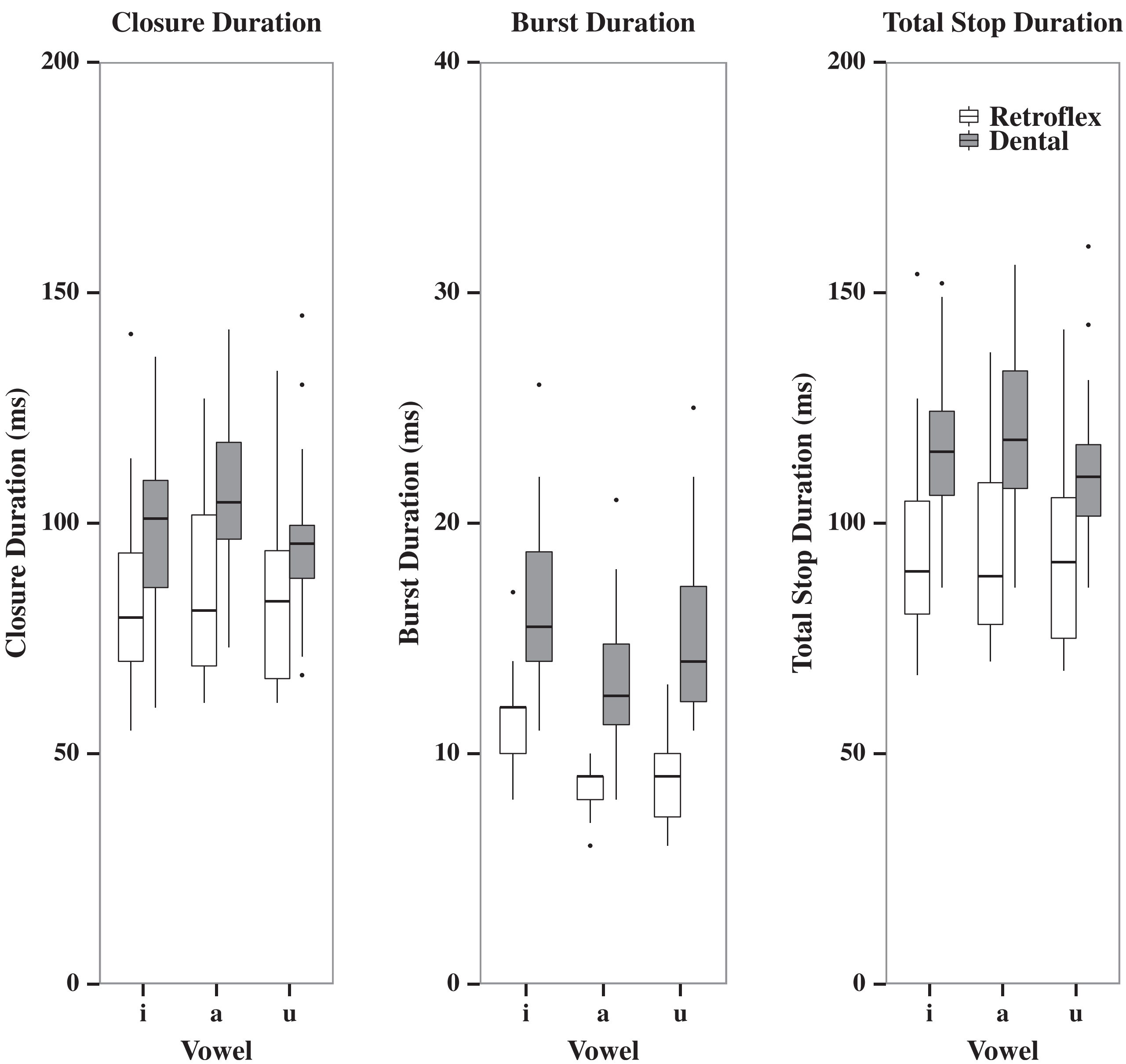


FIG. 10. Boxplots of closure duration (ms), burst duration (ms), and total stop duration (ms) of the Punjabi word-final retroflex and dental stops produced after /i a u/ (all speakers, all items).

$t=-7.54$, $p<0.001$]; /u/: [$\beta=-13.22$, SE = 2.40, $t=-5.49$, $p<0.001$]). The burst duration of the word-final retroflex and dental stops was also significant for each vowel context (/i/: [$\beta=-4.83$, SE = 1.21, $t=-3.97$, $p<0.001$]; /a/: [$\beta=-4.55$, SE = 1.21, $t=-3.74$, $p=0.001$]; /u/: [$\beta=-6.19$, SE = 1.21, $t=-5.09$, $p<0.001$]). Significant contrasts were also found for total stop durations (/i/: [$\beta=-21.01$, SE = 2.44, $t=-8.58$, $p<0.001$]; /a/: [$\beta=-22.69$, SE = 2.44, $t=-9.27$, $p<0.001$]; /u/: [$\beta=-19.37$, SE = 2.44, $t=-7.91$, $p<0.001$]). The findings suggest that in word-final context, all temporal cues consistently differentiated Punjabi retroflex and dental stops produced after all vowels.

3. Spectral properties of word-final stop releases

Figure 11 presents boxplots illustrating the first four spectral moments (spectral CoG, spectral SD, spectral skewness, and spectral kurtosis) of stop release bursts of the Punjabi word-final retroflex and dental stops produced after the vowels /i a u/. Overall, retroflex stops showed smaller spectral CoG [1665 Hz (310), collapsed across vowels], spectral SD [1201 Hz (189)], spectral skewness [1.24 (0.56)], and spectral kurtosis [6.21 (3.66)]. Dental stops, on the other hand, were characterized by higher spectral CoG [1992 Hz (587)], spectral SD [1706 Hz (333)], spectral skewness [1.74 (1.03)], and spectral kurtosis [8.81 (12.15)]. In the context of /i/, retroflex stops showed highest spectral CoG [1934 Hz (316)] and spectral SD [1286 Hz (215)]. However, lowest spectral CoG [1417 Hz (262)] and spectral SD [1083 Hz (164)] were observed in the context of back vowel /u/. This suggests that the place of articulation of the retroflex stop is fronted after /i/ but is retracted after /u/. These results are consistent with coarticulatory factors, if the retroflex stop was produced with a more anterior posture in the context of front /i/ compared to

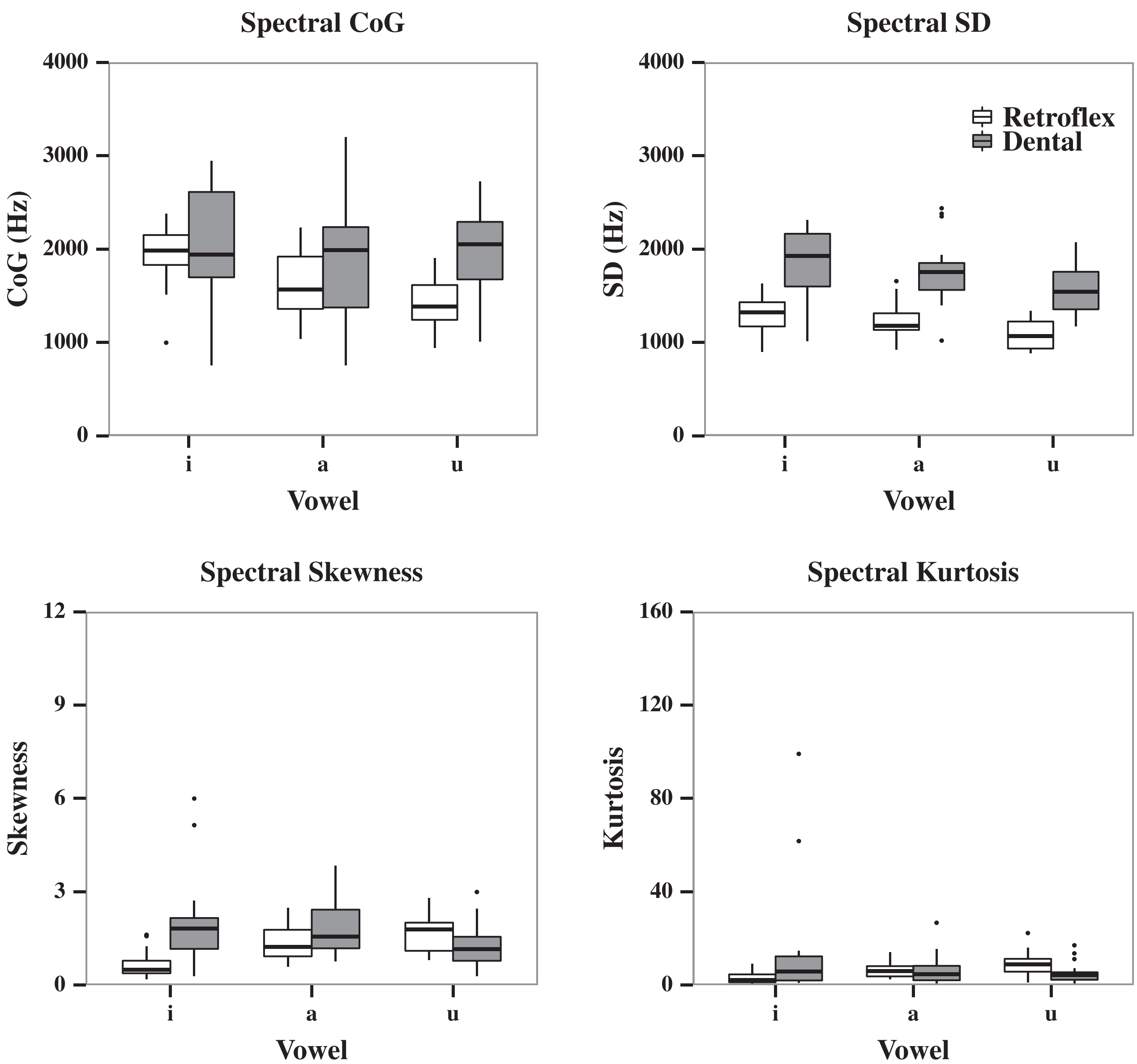


FIG. 11. Boxplots of spectral CoG (Hz), spectral SD (Hz), spectral skewness, and spectral kurtosis of stop release bursts of the Punjabi word-final retroflex and dental stops produced after /i a u/ contexts (all speakers, all items).

back /u/. Dental stops also showed a slight decrease in the spectral CoG of their release bursts from /i/ [2076 Hz (652)] to /u/ [1986 Hz (465)], but the lowest spectral CoG was observed in the context of /a/ [1914 Hz (644)].

The results of LME models showed that spectral CoG differentiated the Punjabi word-final retroflex and dental stops in the context of preceding /a u/, but not in the context of preceding /i/ (/i/: [$\beta = -141.81$, SE = 124.07, $t = -1.14$, $p = 0.262$]; /a/: [$\beta = -269.44$, SE = 124.07, $t = -2.17$, $p = 0.038$]; /u/: [$\beta = -568.36$, SE = 124.07, $t = -4.58$, $p < 0.001$]). Spectral SD reliably differentiated the retroflex and dental stops in all three vocalic environments (/i/: [$\beta = -515.95$, SE = 73.35, $t = -7.03$, $p < 0.001$]; /a/: [$\beta = -531.57$, SE = 73.35, $t = -7.24$, $p < 0.001$]; /u/: [$\beta = -468.20$, SE = 73.35, $t = -6.38$, $p < 0.001$]). Spectral skewness distinguished the two stops after /i/ and /a/, but not /u/ (/i/: [$\beta = -1.34$, SE = 0.25, $t = -5.38$, $p < 0.001$]; /a/: [$\beta = -0.49$, SE = 0.25, $t = -1.97$, $p = 0.058$]; /u/: [$\beta = 0.36$, SE = 0.25, $t = 1.44$, $p = 0.161$]). Spectral kurtosis only distinguished the word-final retroflex and dental stops produced after /i/, but not in /a/ and /u/ contexts (/i/: [$\beta = -11.21$, SE = 3.48, $t = -3.21$, $p = 0.002$]; /a/: [$\beta = -0.66$, SE = 3.48, $t = -0.19$, $p = 0.849$]; /u/: [$\beta = 4.08$, SE = 3.48, $t = 1.17$, $p = 0.249$]).

IV. DISCUSSION

In this study, we investigated the acoustic phonetic properties of the 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 SD was also significant for all speakers in all vocalic environments, except /e_e/. Three speakers (SP9, SP10, and SP11) had very low spectral SD for dental stops in /e_e/ context (lower than retroflex stops), which affected the overall spectral SD. Spectral skewness in /a_a/ and spectral kurtosis in /i_i/, /e_e/, 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/ and /e/ did not vary across TPs (suggesting no $F3$–$F2$ convergence), which is consistent with the findings of Gujarati retroflexes (Dave, 1977). However, the $F3$–$F2$ 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. Spectral CoG of the word-initial stop bursts was significant only in back vowel /o u/ contexts; spectral skewness distinguished the word-initial retroflex and dental contrast in vowels /e o u/ but not for /i a/. Spectral kurtosis differentiated both coronal stops but only in the contexts of /o u/. All acoustic properties distinguished the Punjabi 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 front vowels /i 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, the $F3$–$F2$ difference across TPs 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 SD 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 the 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 stimuli and elicitation methods. The word-final stops were based on real Punjabi words and were elicited in a carrier sentence. The participants might have produced word-final words faster (hypo-articulated) which resulted in smaller closure duration. Similarly, carrier sentence might also have compressed the overall closure duration. On the other hand, the word-medial stops consisted of nonsense words and were elicited in citation form which might have lengthened the closure duration (hyper-articulation). There were minor differences in VOT (or burst duration) of the Punjabi retroflex stops across word contexts, longest VOT in word-medial position (nonsense words) but smallest in word-final (real words) position [word-medial: 13 ms (4); word-initial: 15 ms (3), and word-final: 10 ms (2)]. Maxwell *et al.* (2015) found similar patterns in closure duration and VOT of Bengali aspirated retroflex and dental stops produced in real and nonsense words. The closure duration and VOT of Bengali coronals were longer in nonsense than real words.

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 high front vowel /i/. 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 a lingual posture that is convex between the blade and dorsum (Jackson and McGowan, 2012; Takemoto *et al.*, 2006), but retroflex consonant production involves tongue-retraction and raising of the tongue tip, prototypically realized with a concave tongue shape in the blade region (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 vowel /i/ 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 for retroflexes but higher for dentals. This is consistent with previous studies showing that retroflexes have a 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/ (in word-medial and word-initial positions), which is considered to be a neutral and optimal vowel for studying the coronal contrasts of a language (Kochetov *et al.*, 2014). Spectral SD, like spectral CoG, was also lower for retroflexes than dentals. Spectral SD has been associated with the degree of laminality in coronal articulations: sibilants produced by Japanese children were characterized by a more diffused spectrum with a higher spectral SD, which was interpreted as an acoustic signature of more laminal articulation. In contrast, /s/ productions by English children in the same study showed lower spectral SD, argued to result from their more apical articulation (Li *et al.*, 2009). This interpretation is consistent with the findings of this study, in which the more apical stops (retroflexes) were characterized by lower spectral SD than the more laminal stops (dentals).

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		

i				u
	ɪ		ʊ	
e				o
ɛ		ə		ɔ
		a		

APPENDIX B

Punjabi nonsense target words contrasting /ʈ/-/t̪/ in word-medial and word-initial contexts, preceded/followed by each of the five peripheral 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 peripheral 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"*	/guʈ/	*"short man"*
Dental	/git̪/	*"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)	162 (59)	193 (46)	183 (45)	186 (42)	182 (41)
	Dental	113 (41)	125 (38)	127 (36)	124 (40)	119 (40)	174 (41)	181 (35)	181 (40)	190 (40)	178 (36)
Initial	Retroflex	—	—	—	—	—	121 (35)	129 (33)	130 (31)	129 (35)	127 (35)
	Dental	—	—	—	—	—	117 (34)	118 (30)	132 (27)	127 (35)	123 (36)
Final	Retroflex	192 (16)	—	221 (15)	—	213 (21)	—	—	—	—	—
	Dental	199 (18)	—	215 (16)	—	190 (15)	—	—	—	—	—

APPENDIX E

Figure 12 presents an illustration of two-stage formant estimation method.

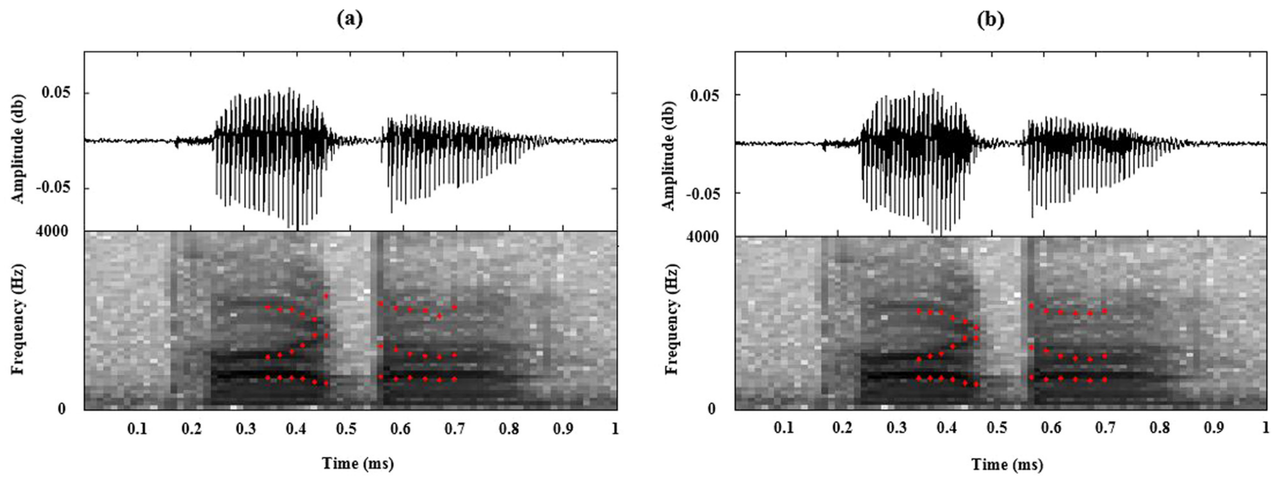

FIG. 12. (Color online) Illustration of two-stage formant estimation method: (a) initial estimates of formants $F1$ to $F3$ at each analysis time step, obtained from Praat formant tracking algorithm; (b) manually-corrected formants, modified with reference to underlying spectrogram (observe $F3$ transition into medial stop). Figures were generated from custom MATLAB formant analysis tool.

[1]Spectral CoG and spectral SD are measured in Hz, spectral skewness and spectral kurtosis are unitless.

[2]Punjabi has a 3-way voicing distinction (see Appendix A). It is beyond the scope of this study to examine coronal place contrast realization in the full system of stops; we have deliberately focused on the voiceless unaspirated series, to control aspiration and VOT as factors in stop realization.

[3]The vowel inventory of Punjabi contains centralized /ɪ ə ʊ/ and peripheral /i e ɛ u o ɔ a/ vowels (Appendix A). The central vowels are also referred to as "short" vowels and peripheral vowels as "long" (Gill and Gleason, 1962).

[4]All word-final stops have clear release in Punjabi (Arun, 1961).

[5]These data were acquired as part of a broader project comparing trilingual and monolingual Punjabi speakers. Because the monolingual speakers were unable to read Punjabi, we used real words and an elicited imitation task to target word-final consonants.

[6]Mean (SD) VOTs measured by the two analysts were 12 ms (4) vs 15 ms (4) for retroflex stops, and 17 ms (4) vs 18 ms (6) for dental stops. Mean closure durations measured by the two analysts were 105 ms (20) vs 97 ms for retroflex stops, and 122 ms (17) vs 123 ms (15) for dental stops.

[7]These models were compared with other models where we included speaker group (trilinguals and monolinguals for word-final context) and repetition (for all word contexts) as random factors. For all the acoustic measures examined here, there were no significant differences between the models that contained group and repetition as random factors and the models which did not contain these two random factors ($p > 0.05$). To keep the models parsimonious, we did not include group and repetition as random factors in the subsequent LME models.

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