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Acoustic-phonetics of coronal stops: A cross-language study of Canadian English and Canadian French

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The study was conducted to provide an acoustic description of coronal stops in Canadian English (CE) and Canadian French (CF). CE and CF stops differ in VOT and place of articulation. CE has a two-way voicing distinction (in syllable initial position) between simultaneous and aspirated release; coronal stops are articulated at alveolar place. CF, on the other hand, has a two-way voicing distinction between prevoiced and simultaneous release; coronal stops are articulated at dental place. Acoustic analyses of stop consonants produced by monolingual speakers of CE and of CF, for both VOT and alveolar/dental place of articulation, are reported. Results from the analysis of VOT replicate and confirm differences in phonetic implementation of VOT across the two languages. Analysis of coronal stops with respect to place differences indicates systematic differences across the two languages in relative burst intensity and measures of burst spectral shape, specifically mean frequency, standard deviation, and kurtosis. The majority of CE and CF talkers reliably and consistently produced tokens differing in the SD of burst frequency, a measure of the diffuseness of the burst. Results from the study are interpreted in the context of acoustic and articulatory data on coronal stops from several other languages. © *2005 Acoustical Society of America.* [DOI: 10.1121/1.1953270]

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I. INTRODUCTION

Across the world's language inventories, coronal place is the most favored place for stops (Henton *et al.*, 1992). Both Canadian English (CE) and Canadian French (CF) phonemic inventories include /d/ and /t/. In both CE and CF, /d/ and /t/ are identified by "movement of the tongue from its neutral position," as defined by the feature [+ coronal], and by a constriction in front of the palato-alveolar region, as defined by the feature [+ anterior] (Chomsky and Halle, 1968). However, phonetic descriptions of /d/ and /t/ in CE and CF are different. Like American English (AE), CE coronal stops in initial position are phonetically transcribed as having an alveolar place of articulation; CF coronal stops are transcribed as having a dental place of articulation (Picard, 1987, 2001).

Although place differences across CE and CF have been described phonetically, their acoustic consequences have not been previously investigated for several reasons. Few languages use place of articulation differences within coronal stops to contrast meaning. Consequently, it is difficult to obtain reliable acoustic measures differentiating coronal stops across languages given differences in vowels and the implementation of voicing in the two languages of interest. Furthermore, several researchers (Jongman *et al.*, 1985; Stevens *et al.*, 1985) have suggested that a greater variability in production by talkers is likely to be a direct consequence of having one or the other (but not both) subgroup of coronal stops in the phonetic inventory. Dental allophones of /d/ and /t/ occur in English, specifically preceding interdental consonants; some researchers have also claimed that coronal consonants are dentalized in several dialects of English (Francis, 1958) or even that some English speakers do not distinguish between dental and alveolar stops, often interchanging them (Dixon, 1980). Thus, variability, in addition to that routinely expected across talkers of the same language, is likely to make generalizations regarding acoustic characteristics of coronal stops difficult.

Finally, at present there are no articulatory data for coronal stops in CE and CF. Besides place of articulation differences, researchers have also suggested that subgroups of coronal stops differ in the length of constriction (Chomsky and Halle, 1968) or the active articulator (Stevens *et al.*, 1985). Articulatory recordings of multi-syllabic utterances with coronal consonants in intervocalic position from 20 speakers of American English (AE) and European French (EF) presented by Dart (1991, 1998) illustrate the problem of identifying the articulatory differences between coronal stops in these two languages. Using data from palatograms and linguagrams, Dart investigated whether differences in place of articulation, constriction length, or active articulator underlie the differences between AE and EF coronal stops. She reports that whether coronal stops in AE and EF differ in the active articulator used to produce it, the place of articulation, or the constriction length, varies considerably across individuals. Thus, Dart's results attest to the variability in the articulation of coronal stops in languages that do not have both kinds of coronal stops.

For the reasons stated above, predicting the acoustic characteristics of coronal stops in CE and CF is not straight-

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forward. The present study was designed to address how (if at all) the acoustic characteristics of coronal stops, both voiced and voiceless, differ across CE and CF. Apart from providing an acoustic description of language-specific characteristics of coronal stops in CE and CF, results from this study will provide an essential baseline for investigations of monolingual and bilingual acquisition of coronal stops. Finally, the acoustic characteristics of coronal stops in each of the two languages will help predict the articulatory movements underlying coronal stop production in CE and CF.

To determine whether the acoustic characteristics of coronal stops in CE and CF are different, in this study, burst intensity and burst spectral measures were used. Burst intensity and burst spectral measures have been previously applied to identification of coronal stops thought to differ in place of articulation (Jongman *et al.*, 1985; Stoel-Gammon *et al.*, 1994). Jongman *et al.* (1985) first introduced a measure of the intensity of the burst with respect to the following vowel in order to distinguish place differences in voiceless coronal stops produced by three adult male talkers of Malayalam. Malayalam is one of the few languages thought to include both dental and alveolar stops in its phonetic inventory; specifically, in intervocalic position the dental-alveolar place difference for voiceless stops contrasts meaning. Jongman *et al.* predicted that differences in place of articulation alter the nature of turbulent noise generated around the constriction, as well as the direction of airflow as it hits the teeth; therefore, alveolar and dental stops should differ in burst amplitude. Because burst amplitude is likely to be modulated by overall loudness of productions, they measured root mean square (rms) amplitude of the burst relative to the amplitude of the following vowel ($\mathrm{Amp}_{\mathrm{vowel}}/\mathrm{Amp}_{\mathrm{burst}}$; a ratio without units).

Jongman *et al.* (1985) reported that alveolar stops are characterized by a louder burst and consequently relative burst amplitude ratios below 5 (a rms amplitude ratio of 5 corresponds to an intensity difference of about 14–15 dB). Dental stops are characterized by a softer burst and a relative burst amplitude above 5. Subsequently, using a ratio of 5 between vowel and burst rms amplitude as a metric, they successfully classified 95.8% of voiceless coronal stops produced by three new Malayalam speakers. However, when applied to distinguish /d/ and /t/ produced by three male native speakers of AE and Dutch, they had limited success. The dental-alveolar distinction does not contrast meaning in either of the two languages; in initial position AE coronal stops are described as alveolar whereas Dutch coronal stops have been described as dental. Although AE coronal stops were characterized by a louder burst, only about 68.2% of stops produced by AE speakers had relative burst amplitude below 5. Similarly, although Dutch coronal stops were characterized by a softer burst, only 63.2% of the tokens produced by Dutch speakers had relative burst amplitude above 5. Thus, Jongman *et al.* (1985) demonstrated that within as well as cross-language differences in place of articulation for coronal stops can be captured with a relative amplitude measure. However, they reported greater speaker-to-speaker variability in the number of tokens that can be correctly identified using the relative amplitude measure in AE and Dutch—languages with only one of the two coronal stops in their inventories—when compared to Malayalam, where both types of coronal stops are encountered.

More recently, Stoel-Gammon *et al.* (1994) have successfully applied an analogous relative intensity measure ($I_{\mathrm{vowel}}-I_{\mathrm{burst}}$; measured in dB) to distinguish between AE and Swedish coronal stops. Like CF and Dutch coronal stops, Swedish coronal stops are described as dental. Stoel-Gammon *et al.* contrasted /t/ productions in five vowel contexts (/i/, /ɪ/, /e/, /a/, and /u/) in real and nonsense /t/-initial words embedded in carrier phrases by ten female native speakers of AE and ten female native speakers of Swedish. AE alveolar stops had louder bursts and consequently lower relative burst intensity when compared to Swedish dental stops. They reported that relative intensity was significantly different for AE and Swedish stops, successfully demonstrating that this measure can be used to reliably distinguish between alveolar and dental stops even in a cross-language comparison where this distinction is not contrastive.

Stoel-Gammon *et al.* (1994) also measured burst spectra to distinguish alveolar and dental stops. Researchers have previously demonstrated consequences of place differences on the shape of burst spectra (Blumstein and Stevens, 1979). Forrest *et al.* (1988) describe numerical indices using spectral moments analysis to describe spectral shape differences. In this approach, the spectrum is treated like a probability distribution of energy over frequencies, which can then be used to calculate four spectral moments. The four spectral moments index four independent features of the energy distribution over frequency to derive average energy concentration (mean frequency), spectral shape as indexed by spread of frequency around the mean (standard deviation), the symmetry or tilt of the distribution (skewness), and the degree of its peakedness (kurtosis).

Stoel-Gammon *et al.* (1994) used the indices described by Forrest *et al.* (1988) to characterize differences between AE and Swedish bursts. They reported that among the spectral measures, AE and Swedish /t/ differed significantly on standard deviation and kurtosis of burst frequency. AE stops had more compact and more peaked burst spectra as indicated by a smaller standard deviation and higher kurtosis when compared to Swedish stops.

However, as the AE and Swedish corpora were recorded in different physical locations with different equipment, the differences in spectral shape reported by Stoel-Gammon *et al.* need to be interpreted with caution. In a subsequent investigation, Buder *et al.* (1995) documented the effects of recording condition differences on the burst spectra of a calibration signal. They reported small but systematic differences in spectral mean and standard deviation and large differences in the skewness and kurtosis measures in a calibration signal played in the two conditions. Buder *et al.* (1995) then reanalyzed just the spectral mean and standard deviation data from Stoel-Gammon *et al.* (1994) with corrections made for differences in recording condition. Although spectral standard deviation remained significantly different, mean frequency was now also found to be significantly different across the two languages. When compared to Swedish stops, AE stops had a higher spectral mean frequency. Buder *et al.* (1995) do not report results for skewness or kurtosis measures.

In the present study, the relative intensity and spectral moments measures used by Stoel-Gammon *et al.* (1994) were used to determine the acoustic characteristics of coronal stops, /d/ and /t/, in CE and CF. Given that the vowels in CE and CF are likely to differ in their formant (F1 and F2) structure, and as these differences are also likely to influence burst characteristics, specifically, the mean burst frequency, only vowels that are similar in CE and CF were selected.

However, not only do CE and CF differ in their vowel inventories but they also differ in how voicing is realized. Caramazza *et al.* (1973) have previously demonstrated that CE and CF differ in the voice onset time (VOT) patterns underlying the two-way voicing contrast in each of the two languages. Caramazza *et al.* report that CE talkers, like AE talkers, produce nonoverlapping VOT distributions for voiced and voiceless stops at each place of articulation. Voiced stops in CE are produced typically with short-lag VOT and voiceless stops are produced with long-lag VOT (mean VOT=70 ms). Caramazza *et al.* do not report mean values of VOT for voiced stops. In contrast, CF talkers produce overlapping VOT distributions for voiced and voiceless stops at each place of articulation. Voiced stops in CF are produced with either lead VOT or short-lag VOT and voiceless stops are produced with short-lag VOT (mean VOT =23 ms). Thus, unlike in CE, in CF voiced-voiceless distinctions cannot be uniquely identified by VOT values alone.

Crucial to the present study, VOT values can be expected to influence the burst intensity (Pickett, 1999). Burst intensity differences relating to VOT may be related to the aerodynamic consequences of duration of oral closure. Typically, stops with greater VOT values can be expected to have longer closure durations (Chen, 1970) and, consequently, a greater build-up of oral pressure resulting in louder bursts. Thus, VOT values for /d/ and /t/ in CE and CF are also reported. As VOT alone is not sufficient to signal voicing in CF, in the present study the spectral moments were also analyzed for voicing effects.

Unlike Stoel-Gammon *et al.* and Jongman *et al.*'s investigations, male and female subjects were recorded in this study to provide a comprehensive description of the coronal stops in CE and CF. Furthermore, in view of predictions of greater variability for acoustic measures for noncontrastive segments, in addition to analyzing group differences, individual talker data are also reported. Neither Stoel-Gammon *et al.* (1994) nor Buder *et al.* (1995) report how well (if at all) data from individual subjects conform to group patterns. Finally, burst intensity and spectral measures of coronal stops in CE and CF from this study are related to possible underlying articulatory movements.

II. METHOD

A. Subjects

Six adult monolingual (3 M and 3 F) speakers of CE and six speakers of CF were recorded for analyses (mean age =24; range=22 to 35). Subjects had no history of speech, language, or hearing impairment. Their language background was assessed using a detailed language questionnaire including a self-rating of language ability in both CE and CF on a scale from 1 to 7, where 7 represents nativelike ability whereas 1 represents no ability. Subject-selection criteria were kept stringent because most people educated in Canada receive formal instruction in both languages at school. However, this instruction is mainly in reading and writing with minimal emphasis on speaking or listening skills. Thus, steps were taken to ensure that subject's competence in the non-native language was minimal. For this purpose, a proficient bilingual research assistant interviewed each subject in both languages. Subsequently, a 3-min speech sample describing a picture story [*Frog, where are you?* by Mayer (1969)] was collected from each subject in his or her native language. These samples were presented to three native listeners of CE (or CF). They were asked to rate the sample on a scale from 1 to 7, where 7 represents nativelike ability and 1 represents no ability. Strict criteria were also necessary to make the present study comparable to a parallel investigation of production by bilingual adults.

To be included in the native CE (or CF) group, subjects had to meet the following five criteria. First, subject's parents were monolingual speakers of CE (or CF). Second, subjects were schooled in CE (or CF). Third, they rated their ability in their native language with a minimum of 6 on a scale of 1 to 7. If they had any knowledge of the non-native language, they rated it below 3 on the same scale. The bilingual interviewer confirmed their lack of proficiency in the non-native language. Fourth, they had spent no time in a country where a language other than their native language was spoken. Fifth, native CE (or CF) listeners rated their speech sample describing the picture story with a minimum of 6 on a scale from 1 to 7. Six additional monolingual subjects (two CE male and one CE female; two CF female and one CF male) were recorded but excluded from the analyses because native listeners rated their speech sample lower than 6.

TABLE I. Canadian English and Canadian French stimuli are listed in the columns. Only initial voiced and voiceless coronal stops (/d/ and /t/) were analyzed.

C English		C French	
docile	toffee	docile	toffee
doctor	topic	docteur	topique
dopey	total	doper	total
dodo	topaz	dodo	topaz
deadly	textile	detter	textile
despot	texture	despote	texture
dagger	tablet	dadais	tablette
dapper	taxi	datcha	taxi

B. Stimuli

Subjects were recorded producing bisyllabic real words with coronal stops in word-initial position in a soundproof booth using an AKG C1000S microphone and a Tascam DA-30 digital audio recorder. Subjects read target words (Table I), twice embedded in sentences, followed by twice in

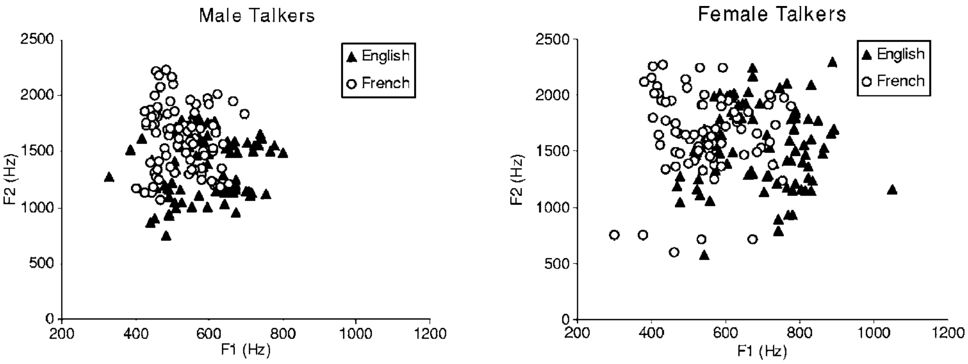

FIG. 1. F1-F2 data from male and female CE and CF talkers.

isolation. On a trial the subject produced the following utterance "Now I say doctor again. Now I say doctor again. Doctor. Doctor." The French words were embedded in the carrier phrase "Maintenant je dis__encore." To avoid list effects, each subject read the sentences in a different order and the sentences of interest were interspersed with 30 other sentences that were not analyzed. Subjects were asked to read at a comfortable rate of speech monitored by the experimenter. In the present study, analyses of isolated tokens—that is, tokens not embedded in sentences—are presented.

Thirty-two target words (16 English and 16 French) were selected to meet three criteria. First, articulatory descriptions and phonetic symbols of the vowels following coronal stops in the target words were identical across the two languages (Picard, 1987, 2001). As a result, target words with the four mid-vowels (/ɛ/, /æ/, /o/ and /ɔ/) in the first syllable were selected. These vowels include vowel height contrasts and front-back distinctions. Vowel formants were measured to confirm overlap in acoustic space for CE and CF tokens. Second, the consonant following the target syllable was a fricative, affricate, or stop. This helped to ensure that syllable boundary could be easily identified on the spectrographic and waveform display. Third, because initial syllables of words are likely to manifest coarticulatory influences of successive segments, segments (consonants and vowels) that are unique to either language were excluded to ensure that differences between contrasting syllables were restricted to those based on place or VOT only. Thus, whenever possible, cognates, defined as words with both identical orthographies and largely overlapping semantics, were selected to minimize differences in the target coronal stop due to differences in the phonetic context in which it was produced in the two languages.

Because few monosyllabic words met all the above-mentioned criteria, bisyllabic words were used despite differences in stress allocation in CE and CF. Although there is little research on the effect of stress on burst intensity and spectral measures, a recent study (Cole *et al.* 2003) indicates that at least within English, burst amplitude in stressed and unstressed syllables was not significantly different. The tokens were digitized at 22 050 Hz and 16-bit quantization. Subsequently, the first syllable was excised from target words. Acoustic analyses are reported for these syllables.

C. Acoustic analyses

Analyses of VOT, burst intensity, and burst spectral properties were conducted excluding tokens without clear bursts. A visual inspection of the waveform and spectrograph revealed that all CF talkers, except one, produced some prevoiced /d/ tokens without clearly delineated bursts. These included 8% of /d/ tokens (3 tokens) produced by male talkers and 41.6% of tokens (15 tokens) produced by female talkers. It is possible that with a long prevoicing duration, clear bursts may not be produced due to insufficient build-up of intraoral pressure. To see if the lack of a clear burst was related to the duration of glottal vibration preceding the vowel, correlations were calculated between the relative intensity of the burst and prevoicing duration. There was no significant correlation between the two. Further, these bursts had spectral mean frequency values less than mean +2 SD for the rest of the distribution. Tokens without clear bursts were removed from analysis, as were unclear tokens.

A total of 318 tokens, 179 CE and 139 CF tokens, were analyzed. All analyses were carried out in PRAAT (Boersma and Weenink, 1992). The focus of investigation in the present study was initial /d/ and /t/. Five cursor positions were identified using a waveform display supplemented by a wideband spectrographic display; first periodic pattern before the burst (if any), onset of the burst, offset of burst, first periodic pattern after the burst signaling vowel onset, and vowel offset.

Vowel formants were measured at mid-point between vowel onset and offset to confirm that the vowels in CE and CF overlapped acoustically. Formant frequencies were derived from LPC analysis with a 15-ms hamming window centered at vowel steady state. None of these speakers produced the vowel in the first syllable as a diphthong. Figure 1 plots F_1 vs. F_2 for /ɛ/, /æ/, /o/, and /ɔ/ produced in the context of the syllables analyzed for this manuscript. Although far from identical, there is considerable overlap in the vowel space of CE and CF. The vowel space for CF is shifted upward in F_2 and downward in F_1 for both male and female talkers. The formant data suggest a tongue position that is more posterior and lower for CE and more forward and higher for CF; this difference may be related to articulatory set differences, coronal place differences, or some combination of the two (see Sec. IV for details).

VOT was measured as the time between the onset of the first clearly periodic pattern and the onset of the burst (Lieberman and Blumstein, 1988). Burst intensity and shape of the burst spectrum were calculated over the entire burst duration beginning at consonantal release. The size of the analysis window thus varied from token to token; it was determined by the duration of burst. When calculating burst intensity measures for voiceless aspirated stops in CE, aspiration was not included in the analysis window. Visual inspection of the spectrograph and waveform was used to distinguish the burst duration from subsequent aspiration. Aspiration was characterized by a sudden drop in intensity and reduced energy at lower frequencies.

Relative burst intensity was calculated relative to the intensity of the following vowel to factor out the effect of differences in overall intensity across speakers. Intensity of the burst (in dB) was subtracted from the maximum intensity of the vowel (in dB) to obtain this measure of relative burst intensity (Stoel-Gammon *et al.*, 1994). On this measure, a softer burst is expected to have a greater intensity difference from the subsequent vowel.

The shape of the burst spectrum as characterized by the four spectral moments—mean, standard deviation, skewness, and kurtosis—was measured (Forrest *et al.*, 1988; Stoel-Gammon *et al.*, 1994). Spectral moments were derived from the power spectra over the entire burst duration for frequencies up to 11 025 Hz. To make the procedure for calculating spectral moments consistent with that used by Forest *et al.* (1998), bursts were preemphasized prior to making spectral measurements; above 1000 Hz the slope was increased by 6 dB/oct. Voiced tokens in CF, and sometimes in CE, are produced with prevoicing. Prevoicing is characterized by regular low-frequency glottal vibration during stop closure and sometimes through the burst. To compare intensity and spectral measures for voiced and voiceless stop consonants, all stops with lead VOT were filtered using a 200-Hz high-pass filter to remove the effects of voicing [a similar technique was used by Jongman *et al.*, (1985)].

III. RESULTS

A. VOT

As the results on the VOT measure are merely a replication of Caramazza *et al.*'s (1973) study, they are reported first. There was no reason to expect gender differences in production of VOT, thus data were pooled across gender for analyses. Group data for VOT are summarized in box plots in Fig. 2. The box stretches from the 25th to the 75th percentile and thus contains the middle half of the distribution; the bar in the middle of the box represents the median or the middle of the distribution—half the tokens have values greater than the median whereas the other half have values less than the median. The lower and upper brackets in the box plots denote the 10th and 90th percentile points, thus 80% of tokens lie within the limits defined by the brackets. Outliers are denoted by a circle (○) and have values between 1.5 and 3 times the box length whereas extremes are denoted by asterisk (*) and have values that are greater than 3 times the box length.

VOT values for tokens produced in isolation in this study were similar, in distribution and range of values, to those reported for CE and CF by Caramazza *et al.* (1973). VOT ranges observed in the present study for CE were also similar to VOT ranges previously reported for AE (Lisker and Abramson, 1964). For descriptive analysis, VOT values were separated into three bins: lead VOT, with values less than 0, short-lag VOT with values between 0 and 30 ms, and long-lag VOT with values greater than 30 ms. Mean, minimum, and maximum values are included in parentheses (mean, min: max) after the percentage of tokens produced with that VOT value.

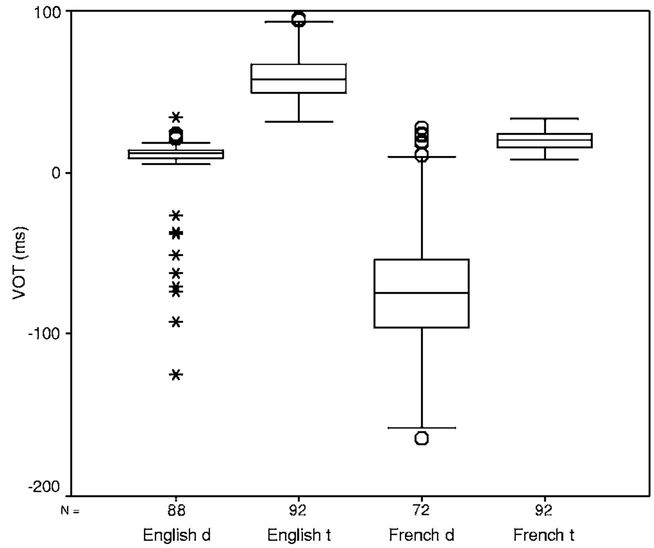

FIG. 2. Box plots of VOT distributions in CE and CF talkers. The middle half of the distributions lies in the box, the line in the middle of the box represents the median or centermost value in the distributions, and 80% of the distribution is within the brackets. Circle (○) denotes an outlier—a value between 1.5 and 3 times the box length, and asterisk (*) denotes extremes—values greater than 3 times the box length.

In CE, 87.5% of /d/ tokens were produced with short-lag VOT (16, 5:29) whereas 12.5% of the tokens were produced with lead VOT (−56, −125: −26); 100% of /t/ tokens were produced with long-lag VOT (60, 31:95). In CF, 90.8% of the /d/ tokens were produced with lead VOT (−82, −164: −17) whereas 9.2% of /d/ tokens were produced with short-lag VOT (19, 10:28); 100% of the /t/ tokens were produced with short-lag VOT (20, 8:30). Also CE talkers produced nonoverlapping distributions of VOT for voiced and voiceless tokens whereas CF talkers produced overlapping distributions of VOT because they produced some /d/ tokens with short-lag VOT. These results replicate Caramazza *et al.*'s findings; both report analyses for words produced in isolation.

For completeness and to make the comparison of VOT values consistent with the comparisons made on burst measures, VOT values for /d/ and /t/ were compared using a general linear model (GLM) repeated measures analysis of variance (ANOVA) with language (CE and CF) as the between-subjects variable and voicing (voiced and voiceless) as the within-subjects variable. A GLM analysis is more powerful for comparing unequal cell sizes. Significant interactions of language and voicing were explored using Bonferonni's *posthoc* analyses to confirm that language effects were significant for /d/ as well as /t/. Group patterns are reported followed by individual performance.

Differences in VOT distribution across CE and CF were confirmed by the analysis of variance. The main effects of language [$F(1,152)=370, p<0.01$] and voicing [$F(1,152)$

TABLE II. VOT values [Mean (SD, number of tokens)] for each talker in the CE & CF group. Data from a single talker is summarized in each row. Each of the subjects is identified by their language group (CE/CF), gender (M/F), and a number. SD values are not reported when only one token was produced with that value.

	CE talkers					CF talkers			
Subjects	/d/ lead	/d/ lag	/t/ short lag	/t/ aspirated	Subjects	/d/ lead	/d/ lag	/t/ short lag	/t/ aspirated
CEM1	−72.4 (1.8, 2)	35 (6.3,12)		51 (9, 16)	CFM1	−93 (32, 11)	10 (1)	13 (4, 16)	
CEM2	−77 (33, 5)	9 (2, 7)		58 (12, 16)	CFM2	−81 (34, 12)	⋯	22 (5, 16)	
CEM3	−53 (24, 2)	12 (3, 14)		58 (10, 14)	CFM3	−85 (38, 11)	27 (1)	24 (4, 16)	
CEF1	⋯	12 (4, 16)		76 (15, 16)	CFF1	−53 (23, 11)	16 (4, 3)	23 (5, 14)	
CEF2	−26 (1)	14 (4, 15)		61 (10, 14)	CFF2	−100 (35, 12)	23 (1, 2)	18 (5, 14)	
CEF3	−50 (1)	12 (3, 13)		58 (12, 16)	CFF3	−74 (27, 12)	⋯	22 (6, 16)	

$=640, p<0.01$] and the interaction of language and voicing [$F(1,152)=40, p<0.01$] were significant. Language effects were significant for /d/ and /t/ as measured by Bonferroni's *posthoc* tests ($p<0.01$). Thus, as expected, VOT for /d/ as well as /t/ tokens is longer in CE than in CF.

Talker-specific differences in VOT production (Kessinger and Blumstein, 1998; Volaitis and Miller, 1992) as well as perception (Summerfield, 1981) have been previously documented. VOT values for each subject (Table II) also revealed individual variability in this corpus. Talkers in both language groups varied in their production of /d/ tokens. One male CE talker (CEM2) produced about 40% of voiced tokens with lead VOT. In AE, several researchers (Flege and Eefting, 1987; Mack, 1989) have reported that voiced tokens may be produced with lead VOT. Although four out of six CF talkers produced /d/ tokens with short-lag VOT, contributing to the overlap in the distribution of voiced and voiceless tokens in CF, only one female talker (CFF1) was responsible for most of the overlap. She produced 20% of voiced tokens with short-lag VOT. One male (CFM2) and one female (CFF3) CF talker did not produce any /d/ tokens with short-lag VOT. Talker-specific differences in VOT production have been directly attributed to individual differences in rate of speech (Allen *et al.*, 2003) or to social, dialectal, or idiolectal differences.

B. Burst measures

1. Group patterns

Results are reported for each burst measure (relative intensity, mean frequency, SD, skewness, and kurtosis of burst spectra) separately. A GLM repeated measures ANOVA with language (CE and CF) as the between-subjects variable and voicing (voiced and voiceless) as the within-subjects variable was conducted for each burst measure separately. Voicing was included as a variable in the ANOVAs on burst measures as VOT differences are known to influence burst intensity, at least in English (Pickett, 1999), which in turn may influence burst spectral measures. Because spectral measures reflect vocal tract size and shape, which are likely to differ across gender, results are reported separately for each gender. Significant interactions of language and voicing were explored with Bonferroni's *posthoc* analyses ($p<0.01$ are reported) for voicing as well as language effects. Finally, in order to determine the relative contribution of each burst measure in differentiating CE and CF tokens, results from discriminant function analysis with all burst measures and VOT included as predictors are presented.

(a) Relative burst intensity: Relative intensity data from male and female talkers across voicing conditions and across language are summarized in box plots in Fig. 3. Overall as expected, for talkers of both genders, relative intensity of /d/ and /t/ tokens was lower in CE than in CF, confirming that CE bursts are louder than CF bursts. The mean relative intensity levels for CE /t/ and CF /t/ tokens by female talkers in our study are comparable to those reported by Stoel-Gammon *et al.* (1994) for AE and Swedish female talkers respectively.

For male talkers, the main effect of language [$F(1,70)=5.5, p<0.05$] and the interaction of language and voicing [$F(1,70)=14.5, p<0.01$] were significant. As expected, relative intensity for CE was lower than for CF for both /d/ and /t/ tokens, but *posthoc* tests revealed that this difference was significant only for /d/. Voicing differences were only significant in CF, with relative intensity of /d/ tokens greater than that of /t/ tokens. For female talkers, the main effects of language [$F(1,62)=41, p<0.01$], voicing [$F(1,62)=38, p<0.01$], and the interaction of voicing and language [$F(1,62)=12.6, p<0.01$] were significant. *Posthoc* tests

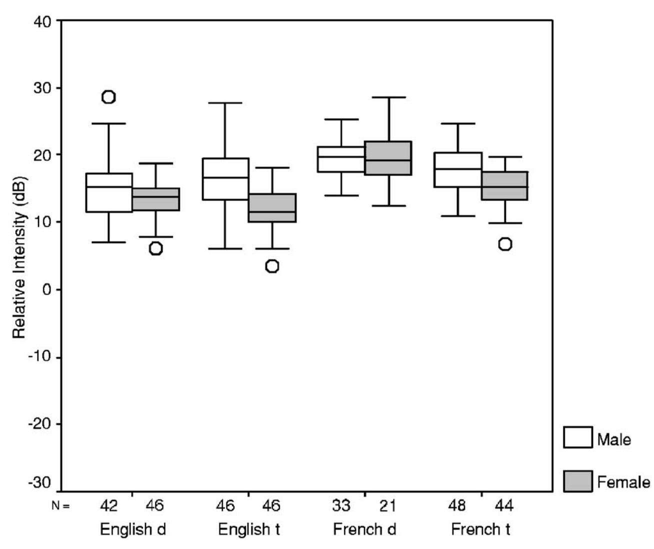

FIG. 3. Box plots of relative intensity for male and female talkers of CE and CF.

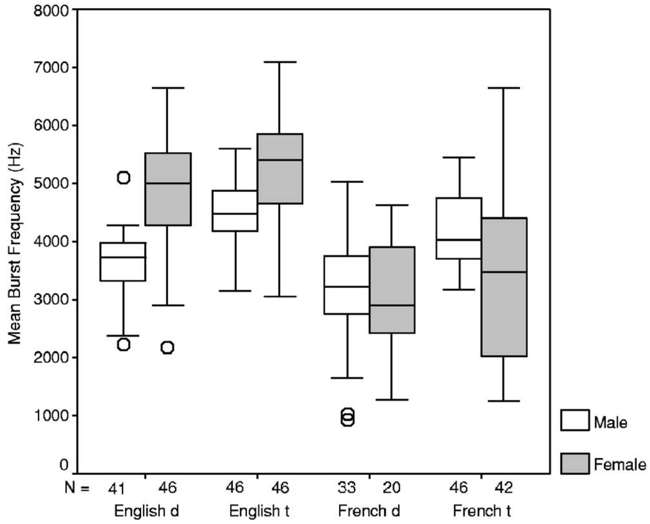

FIG. 4. Box plots of mean burst frequency for male and female talkers of CE and CF.

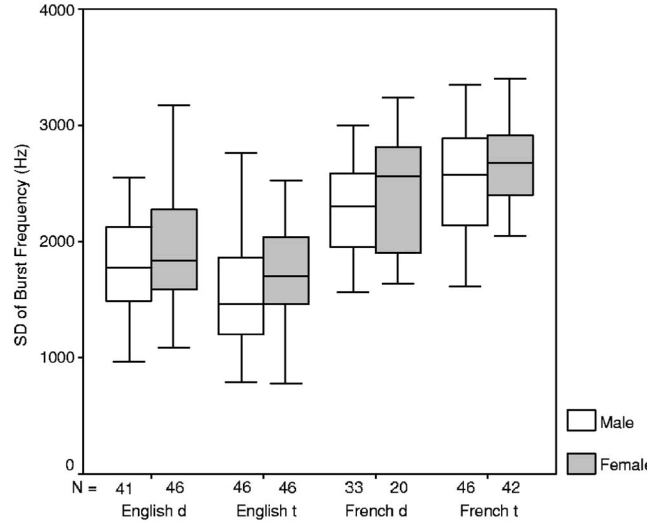

FIG. 5. Box plots of SD of burst frequency for male and female talkers of CE and CF.

confirmed that relative intensity for CE was lower than for CF for both /d/ and /t/. The relative intensity for /d/ was greater than that of /t/ in both CE and CF, but the voicing difference was only significant in CF.

As evidenced by the significant interaction of language and voicing for data from male and female speakers, voicing differences modulated burst intensity. In CE, although the direction of relative intensity difference was consistent with Pickett's (1999) prediction, the voicing difference was not significant for either male or female talkers. In CF, voiceless tokens were significantly louder than voiced tokens. Clearly, burst intensity provides a cue to voicing in CF.

Relative intensity ranges reported in the present study for CE and CF voiced and voiceless tokens are similar to those reported by Jongman *et al.* (1985) for AE and Dutch isolated stops, respectively. Note that the inclusion of the /d/ tokens in CF produced without clear bursts would effectively guarantee a large relative intensity difference between the vowel and the burst. Tokens with large relative intensity difference are consistent with the pattern seen above for CF talkers; in fact, exclusion of tokens without clear bursts, as has been done, underestimates the difference between relative intensity in CE and CF.

(b) Mean burst frequency: Mean burst frequency data from male and female talkers across voicing conditions and across language are summarized in box plots in Fig. 4. Overall as expected, for talkers of both genders, mean burst frequency was higher for CE tokens than CF tokens. Mean burst frequencies reported in our study for CE /t/ produced by female talkers are comparable to those reported by Stoel-Gammon *et al.* for AE /t/ tokens. The values are also consistent with those reported for AE /t/ by Forrest *et al.* (1988). However, compared to mean burst frequency reported by Stoel-Gammon *et al.* for Swedish female talkers, mean burst frequency for CF /t/ tokens produced by female talkers is lower (over 1000 Hz). When compared to the same Swedish corpus corrected for differences in recording conditions (Buder *et al.*, 1995), mean burst frequency of CF /t/ tokens is still lower but the difference is reduced to about 1000 Hz.

For male talkers, only the main effects of language $[F(1,70)=13, p<0.01]$ and voicing $[F(1,70)=56, p<0.01]$ were significant; CE bursts had a higher mean frequency than CF bursts, and voiceless stops had a higher mean frequency than voiced stops. For female talkers, only the main effect of language $[F(1,62)=109, p<0.01]$ was significant. Again, CE bursts had a higher mean frequency than CF bursts.

We know little about the effects of voicing on spectral mean burst frequency of coronal stops because all previous studies measuring burst spectral cues to consonant place have analyzed voiceless stops. In both CE and CF, voiceless stops had a higher mean burst frequency when compared to voiced stops for male and female talkers, but reached significance only for male talkers. Thus, mean frequency of burst may serve as a supplemental cue to stop voicing in both CE and CF.

(c) SD of burst frequency: SD of burst frequency from male and female talkers across voicing conditions and across language is summarized in box plots in Fig. 5. Overall as expected, for talkers of both genders, SD of burst frequency was lower for CE tokens than for CF tokens, confirming that CE bursts are compact whereas CF bursts are diffuse. In other words, energy in CE bursts is spread over a smaller range of frequencies than CF bursts. SDs of burst frequency reported in this study for CE and CF /t/ tokens produced by female talkers are systematically higher (approximately 500 Hz) than those reported by Stoel-Gammon *et al.* for AE and Swedish female talkers, respectively; they are also higher than the corrected values reported by Buder *et al.* (1995).

For male talkers, the main effect of language $[F(1,70)=78, p<0.01]$ and the interaction of language and voicing $[F(1,70)=20, p<0.01]$ were significant. SD for CF was significantly greater than for CE for both /d/ and /t/. Voicing effects were significant in both CE and CF, however they were in opposite directions. For female talkers as well, the main effect of language $[F(1,62)=87, p<0.01]$ and the interaction of language and voicing $[F(1,62)=6.1, p<0.05]$

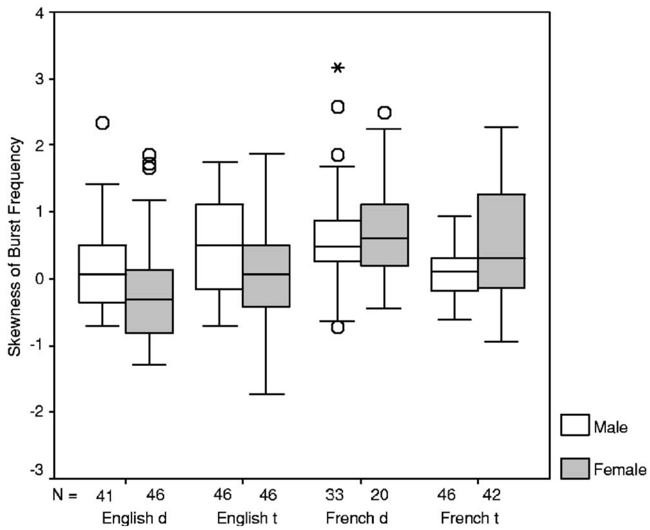

FIG. 6. Box plots of skewness of burst frequency for male and female talkers of CE and CF.

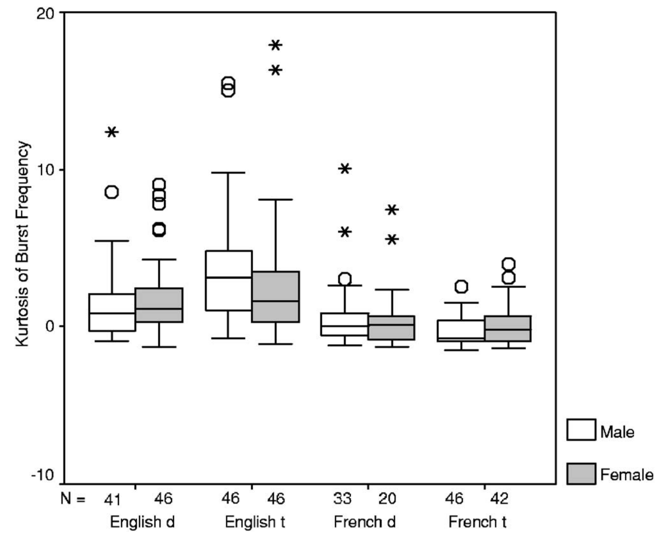

FIG. 7. Box plots of kurtosis of burst frequency for male and female talkers of CE and CF.

were significant. Language effects were significant for both /d/ and /t/, but voicing effects were not significant in either CE or CF. Because voicing effects were not consistent across gender for either language, it is unlikely that differences in SD of burst frequency cue voicing.

(d) Skewness: Skewness of burst frequency from male and female talkers across voicing conditions and across languages is summarized in box plots in Fig. 6. Overall, results were as expected only for female talkers. For female talkers, skewness of burst frequency was lower for CE tokens than for CF tokens. CE bursts have a negative (or 0) spectral tilt, implying that they have a concentration of energy in the frequencies above mean frequency (or are symmetric with respect to distribution of energy). CF bursts have a positive spectral tilt, implying that they have a concentration of energy in the frequencies below mean frequency.

For male talkers, the interaction of language and voicing $[F(1,70)=19.4, p<0.01]$ was significant. Language effects were significant for /d/ as well as /t/. However, the direction of the language effect was not consistent; the skewness of /d/ tokens was greater in CF whereas the skewness of /t/ tokens was greater for CE tokens. Voicing differences, although significant in both CE and CF, were also not consistent. For female talkers, only the main effect of language $[F(1,62)=27, p<0.01]$ was significant, supporting the predicted pattern. Skewness is not a consistent cue for differentiating between CE and CF talkers across gender or for signaling voicing differences within either language.

(e) Kurtosis: Kurtosis of burst frequency from male and female talkers across voicing conditions and across languages is summarized in box plots in Fig. 7. Overall as expected, for talkers of both genders, kurtosis of burst frequency was higher for CE tokens than for CF tokens. CE bursts have positive kurtosis values, implying that they have peaked energy distributions and thus spectra with clearly defined, well-resolved peaks. CF bursts have kurtosis values that are negative or around 0, implying that they have relatively flat spectra with no clear peaks. There was a greater difference between the kurtosis values for CE and CF than those reported for AE and Swedish (Stoel-Gammon *et al.*, 1994).

For male talkers, the main effect of language $[F(1,70)=24.8, p<0.01]$ and the interaction of language and voicing $[F(1,70)=13.8, p<0.01]$ were significant. CE bursts had a greater kurtosis than CF bursts for both /d/ and /t/ but the difference was significant only for /t/. Voicing effects were significant only in CE, with kurtosis of /d/ tokens significantly lower than that of /t/ tokens. For female talkers, only the main effect of language $[F(1,62)=12.1, p<0.01]$ was significant. As in the case of burst SD and skewness, kurtosis differences across voiced and voiceless stops were not consistent and thus are unlikely to provide a cue for stop voicing.

(f) Discriminant function analysis: To ascertain the relative efficiency of burst intensity and spectral measures, each variable was entered into a stepwise discriminant function analysis to predict whether tokens belonged to the CE or the CF group. Because CE and CF tokens were also significantly different on VOT, VOT was included in the discriminant function analysis as a predictor. When the variable to be predicted, in this case CE / CF, is categorical and binary, stepwise discriminant analysis is more appropriate than regression. As in Forrest *et al.* (1988), tokens were averaged to yield one entry per subject so as not to violate the assumption of independence of cases. Analysis was conducted separately for /d/ and /t/. Only variables for which Wilk's lambda was significant $(p<0.05)$ are reported.

For /d/ tokens, VOT alone accounted for 58.4% of the variance $[(1,10)=59, p<0.01]$; the only other variable that was significant after VOT was included was SD $[(2,9)=141, p<0.01]$. Together, VOT and SD accounted for 83.1% of the variance. For /t/ tokens as well, VOT accounted for 83.9% of the variance $[(1,10)=106, p<0.01]$; again the only other variable to significantly add to the prediction was SD $[(1,9)=93, p<0.01]$. VOT and SD accounted for 89.9%

TABLE III. Composite CE/CF-ness scores for each talker on each measure. Variables are listed in rows, and subjects in columns.

	Canadian-English						Canadian-French					
Measure	CEM1	CEM2	CEM3	CEF1	CEF2	CEF3	CFM1	CFM2	CFM3	CFF1	CFF2	CFF3
Relative intensity	0.37	0.68	0.93	0.75	0.77	0.87	0.63[a]	0.42[a]	0.81	0.57[a]	0.82[a]	0.82[a]
Mean frequency	0.67	0.64	0.66	0.97	0.73	0.87	0.63	0.54	0.73	0.91	0.73	0.53
SD	0.50	0.96	0.83	0.69	0.87	0.80	0.67	0.77	0.88	0.74	0.86	0.88
Kurtosis	0.33	0.79	0.52	0.53	0.60	0.50	0.96	0.88	0.85	0.83	0.86	0.94

[a]When tokens without bursts were included the proportions increased slightly to 0.64 for CFM1, 0.46 for CFM2, 0.62 for CFF1, 0.85 for CFF2, and 0.88 for CFF3.

of the variance. Recall that even when AE and Swedish talkers were recorded under different conditions, Stoel-Gammon *et al.* (1994) reported a significant difference in SD of burst frequency. Moreover, this difference remained significant even after corrections were made for differences in recording conditions. Thus, apart from VOT, SD appears to be the most robust acoustic cue distinguishing coronal stops in CE and CF.

For both /d/ and /t/, the variable accounting for the highest degree of variance after SD was mean burst frequency. However, because 12 subjects in the analyses provide power for only up to two variables in the discriminant analyses, mean frequency was never significant.

2. Individual patterns

Individuals within each group varied on the various burst measures and the range of their tokens (data available upon request). Recall that Jongman *et al.* (1985) and Stevens *et al.* (1985) have suggested that a direct consequence of having one or the other (but not both) subgroup of coronal stops in the phonetic inventory is greater inter-speaker variability in production by talkers. Because greater variability may potentially lead to overlap in distributions, production by individual talkers needs to be evaluated to obtain some index of overlap on each measure.

Jongman *et al.* (1985) applied a metric generated from voiceless tokens produced in Malayalam to differentiate between AE and Dutch voiced and voiceless tokens. Recall that they used an amplitude ratio of 5, corresponding to an intensity difference of about 15, to differentiate between alveolar and dental stops. To compare the data from this study to Jongman *et al.*'s investigation, the percentage of CE tokens produced with relative intensity values less than 15 dB and the percentage of CF tokens produced with relative intensity values greater than 15 dB were calculated. Sixty percent of tokens in CE had relative intensity lower than 15 dB and 74% of tokens in CF had relative intensity greater than 15 dB. Using this metric, over 80% of tokens produced by three talkers (one CE and two CF), and between 50% and 80% of tokens by six other talkers (three CE and three CF) were correctly classified. Fewer than 50% of tokens were classified correctly for two male CE talkers (13% and 43%) and one female CF talker (43%). Recall that fewer than 36% of stops from one AE and one Dutch speaker were correctly classified using the metric derived from stops in Malayalam; over 85% of tokens produced by Malayalam talkers were correctly classified. Thus, the variability of the relative intensity measure and subsequently the overlap in distribution of relative amplitude is much greater when the comparison is cross-language than when it is within a language.

Jongman *et al.*'s approach relies on a comparison of burst intensity in contrastive and noncontrastive languages. However, because burst spectral measures are not available from Malayalam or other languages where this distinction is contrastive, there is a need for an alternative way to index overlap in distributions with respect to productions by each subject. One such way is to characterize how well tokens produced by each talker conform to group distributions. Consider two distributions with means M1 and M2. For well-separated, nonoverlapping distributions, all tokens in distribution 1 are closer to M1 whereas all tokens in distribution 2 are closer to M2. However, with overlap in distributions, some tokens—specifically ones in the tails of the distribution—will be produced with values closer to the mean of the other distribution.

A CE-like (or CF-like) score was obtained for each individual by calculating the percent CE (or CF) tokens produced by a talker that are closer to the mean of the CE (or CF) group than the mean of the CF (or CE) group. Because distributions are different across voicing conditions, tokens were always compared to the mean of the specific condition. They were finally combined to give a composite CE-like/CF-like score. Skewness was not included because there was no significant group difference between CE and CF tokens on this measure. Besides indexing the overlap in the distribution, this composite score also allows a comparison of the efficiency of each measure in distinguishing between CE and CF tokens by providing a measure of overlap between the CE and CF distribution. The measures on which higher percentage of tokens produced by most CF talkers are CF-like, and tokens produced by most talkers of CE are CE-like, have less overlap, and hence are more efficient in categorizing CE and CF tokens. Composite CE-like/CF-like scores are summarized in Table III.

The composite scores in Table III illustrate the variability and ambiguity of /d/ and /t/ produced in CE and CF. Only half the tokens produced by talkers CEM1, CEM2, CFM1, and CFM2 are likely to be similar in relative intensity and spectral measures to the distribution of their language group. Of the variables measured, talkers across the two groups produced the most distinct tokens on the SD measure. At least half the tokens produced by every talker were classified correctly using the SD measure; of 12 talkers, 7 (2 male and 2 female CE talkers and 1 male and 2 female CF talkers) produced over 80% of tokens with well-separated SD values. Of 12 talkers, only 5 (1 male and 1 female CE talker and 1 male and 2 female CF talkers) produced over 80% tokens with well-separated relative intensity values. This was the case even when the tokens that had been excluded from analyses due to unclear bursts were included to get an estimate of tokens correctly classified using the relative intensity measure (values in Table III, footnote a). Thus, of all measures, SD most consistently distinguished between individual talkers of CE and CF.

IV. GENERAL DISCUSSION

What emerges from the present study is an acoustic description of both voiced and voiceless coronal stops in CE as well as in CF. Data confirm that for coronal bursts produced in syllable-initial position, CE stops, like AE stops, contrast short-lag VOT with long-lag or aspiration; CE bursts are loud, have a higher mean burst frequency, and are more compact as measured by standard deviation, with a more peaked spectral shape as measured by the kurtosis of burst frequency. CF stops, on the other hand, contrast lead VOT and short-lag VOT values with some overlap; CF bursts are lower in intensity, have a lower mean burst frequency, and are more diffuse as measured by standard deviation, with a less peaked spectral shape as measured by the kurtosis of burst frequency. Thus, acoustic data confirm that coronal stops differ in their phonetic implementation across the two languages.

Analyses of voicing differences in CE and CF as measured by VOT for coronal stop-initial words replicate those reported in Caramazza *et al.*'s (1973) study. CF talkers produce overlapping distributions of VOT for voiced and voiceless stops. The distribution of VOT in CF has been reported to be different from French from France (European French or EF); Caramazza and Yeni-Komshian (1974) report that unlike in CF, VOT for voiced and voiceless stops in EF do not overlap. They attribute the differences between EF and CF to the extensive contact of CF with CE. An overlap in the distribution of VOT for /d/ and /t/ precludes VOT from being a sufficient cue for voicing in CF.

In the present study, in addition to differences in VOT, voiced and voiceless tokens in CF differed systematically on relative burst intensity and mean burst frequency. Thus, in CF, burst intensity and mean burst frequency may supplement VOT differences to cue voicing differences. Although there have been suggestions that burst intensity differences may signal voicing (Pickett, 1999), previously there has been little discussion of mean burst frequency as a cue to voicing. Despite low-pass filtering of voiced tokens, a lower mean frequency for voiced stops may have resulted from greater low-frequency energy accounting for the pattern of results obtained here.

Besides providing information about voicing differences in CF, burst intensity and mean burst frequency were also significantly different across CE and CF. CE and CF stops also differed in SD and kurtosis of burst frequency. Perhaps not surprisingly, the burst intensity and spectral measures were correlated. A strong negative correlation was observed between SD and kurtosis (−0.83 for male talkers and −0.70 for female talkers). Other significant correlations for male talkers include correlations between SD and relative intensity (0.37), SD and skewness (−0.32), skewness and mean frequency (−0.32), skewness and kurtosis (0.56), and relative intensity and kurtosis (−0.38). Significant correlations for female talkers include SD and relative intensity (0.40), SD and mean frequency (−0.40), and mean frequency and skewness (0.70).

A strong correlation between SD and one (or more) of the other three moments would explain why the other three moments did not account for any significant variance in the discriminant analyses. Stoel-Gammon *et al.* (1994) do not report correlations between the various spectral measures. Of the correlations reported above, the strong negative correlation between SD and kurtosis is most remarkable. Specifically, it is possible that SD and kurtosis of burst frequency are consequences of the same underlying articulatory gesture.

Although differences in the intensity of burst are thought to be consequences of place of articulation differences (Jongman *et al.*, 1985), we know little about how the spectral moments map on to articulation. Note that the mean burst frequency or the first spectral moment measured in this experiment is not to be confused with the peak spectral location. The former is the average frequency of the burst power spectra, while the latter is the highest amplitude peak of the FFT spectrum. While the peak spectral location is correlated with the length of the front cavity, there is no evidence that the mean burst frequency is determined by the location of the constriction [Forrest *et al.*, 1988; see also Jongman *et al.* (2000) for evidence of this distinction in the analysis of fricatives].

Instead of being consequences of differences in place of articulation, differences in spectral shape of coronal stops between CE and CF stops may relate to variations in the degree of damping of the active articulator. Tokens produced with longer constriction length are likely to be more damped. Due to greater damping, these tokens are likely to have a greater bandwidth and lesser energy in the higher frequencies. In this study, CF stops have higher SD and lower kurtosis and lesser energy in the higher frequencies than CE stops.

Currently, there are no articulatory data on CE and CF coronal stops to directly test this hypothesis. However, neither the acoustic data presented in this study nor Dart's articulatory data support Stevens *et al.*'s (1985) claim that the active articulator determines the place of articulation. Dart's data indicate that while place and active articulator used are often correlated, individuals may use one or the other or both. Similarly, in the acoustic data presented here, although the relative intensity measure was significantly correlated with all other measures of spectral shape, there was individual variability in the measures used by each talker. Some of the correlations in Dart's articulatory data as well as the acoustic data presented here no doubt arise from anatomical and biomechanical constraints on the movement of articulators. As Dart succinctly points out, "it is very difficult for someone with normal dentition to put the tip of the tongue on the teeth without the blade also touching the base of the teeth" (1998, p. 73), confounding place of articulation with active articulator used to produce coronal stops.

In this study, only burst intensity and spectral measures, one set of cues relating to stop place of articulation, were measured for CE and CF coronal stops. Given that between 8% and 40% of voiced stops produced by CF talkers were produced without clear bursts, place differences must be signaled by acoustic cues relating to more than just the burst. Besides acoustic information in the burst, formant frequency changes or transitions have been previously used to identify place of articulation for stop consonants (Delattre *et al.*, 1955; Kewley-Port, 1983; Klatt, 1979, 1987). However, comparison of formant frequency transitions across languages to identify place distinctions is confounded by systematic differences in the formant values of vowel targets themselves.

A comparison of F_1-F_2 space in CE and CF (Fig. 1) indicates that CE vowels are produced with a tongue position that is more posterior and lower, whereas CF vowels are produced with a tongue position that is more forward and higher. Although this difference in the vowel systems could be attributed to the CE vowels having been produced in alveolar context and CF stops in dental context, it is unlikely for two reasons. First, F_1 and F_2 measurements were made at the mid-point between vowel onsets and offset and the effects of consonant context are less likely to extend to such vowel targets. Second, other researchers (Dart, 1991) have previously reported systematic differences unrelated to phonetic context between the vowel systems of AE and EF. Articulatory and vowel formant data for stops produced in several additional phonetic contexts (i.e., bilabial or velar) are required to disambiguate between these two accounts.

Not only is it problematic to compare transition information across languages in view of systematic differences in vowel targets across the languages unrelated to phonetic context, but there is also evidence to suggest that even in languages that contrast more than one coronal place, transition data are inadequate to specify place information. In a recent investigation of Australian aboriginal languages, Yanyuwa and Yindjibarndi, Tabain and Butcher (1999) report that F_2 transition information (incorporated into locus equations) does not provide sufficient information to uniquely identify place differences within coronal consonants. These aboriginal languages share an extensive set of place contrasts, including four coronal place distinctions, but not voicing or manner contrasts for stops (Busby, 1980; Dixon, 1980).

To summarize, the VOT results presented in this study replicate Caramazza *et al.*'s (1973) findings; of the burst cues measured in this study, CE and CF bursts differ consistently across gender and voicing in mean frequency, SD, and kurtosis of burst spectra. Relative intensity and skewness of burst spectra are less consistent and help to differentiate tokens produced only by female talkers. Analyses of differences in CE and CF coronal stops as measured by burst intensity and spectral cues support and extend investigations by Jongman *et al.* (1985) and Stoel-Gammon *et al.* (1994). Results from the present study provide a quantitative analysis of acoustic correlates of subgroups of coronal stops across gender, voicing, and languages. Moreover, individual patterns are presented and discussed in addition to group data. Given the potential for variability in production of coronal stops cross-language, the discussion of individual patterns is particularly useful.

Data from this study provide the first step in establishing measurable and reliable differences in the language-specific characteristics of bursts associated with CE and CF coronal stops. Apart from providing an acoustic description of language-specific characteristics of coronal stops in CE and CF, results from this study will provide an essential baseline for investigations of monolingual and bilingual acquisition of coronal stops. Empirical data are needed from further investigations to clearly delineate the articulatory characteristics of coronal stops in CE and CF. There is also a need for systematic articulatory-acoustic investigation to ascertain which acoustic properties of the burst map on to observed articulatory differences between CE and CF stops.

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Allen, J. S., Miller, J. L., and DeSteno, D. (**2003**). "Individual talker differences in voice-onset-time," J. Acoust. Soc. Am. **113**, 544–551.

Blumstein, S. E., and Stevens, K. N. (**1979**). "Acoustic invariance in speech production: Evidence from measurements of the spectral characteristics of stop consonants," J. Acoust. Soc. Am. **66**, 1001–1016.

Boersma, P., and Weenink, D. (1992). The Praat program, University of Amsterdam.

Buder, E., Williams, K., and Stoel-Gammon, C. (**1995**). "Characterizing the adult target: Acoustic studies of Swedish and American-English /t/ and /p/," in *Proceedings of the 13th International Conference of Phonetic Sciences*, edited by K. Elenius and P. Brandevud, Stockholm, Vol. **3**.

Busby, P. (**1980**). "The distribution of phonemes in Australian aboriginal languages," Papers Austral. Linguist. **4**, 73–139.

Caramazza, A., and Yeni-Komshian, G. H. (**1974**). "Voice onset time in two French dialects," J. Phonetics **2**, 239–245.

Caramazza, A., Yeni-Komshian, G. H., Zurif, E. B., and Carbone, E. (**1973**). "The acquistion of a new phonological contrast: The case of stop consonants in French-English bilinguals," J. Acoust. Soc. Am. **54**, 421–428.

Chen, M. (**1970**). "Vowel length variation as a function of the voicing of the consonant environment," Phonetica **22**, 129–159.

Chomsky, N., and Halle, M. (**1968**). *The Sound Pattern of English* (Harper and Row, New York).

Cole, J., Choi, H., Kim, H., and Hasegawa-Johnson, M. (**2003**). "The effect of accent on the acoustic cues to stop voicing in Radio News Speech," in *Proceedings of the 15th International Congress of Phonetic Sciences*, edited by M. J. Solé, D. Recasens, and J. Romero, 2665–2668.

Dart, S. N. (**1991**). "Articulatory and acoustic properties of apical and laminal articulations," UCLA Work. Pap. Phonetics **79**, 1–155.

Dart, S. N. (**1998**). "Comparing French and English coronal consonant articulation," J. Phonetics **26**, 71–94.

Delattre, P., Liberman, A. M., and Cooper, F. S. (**1955**). "Acoustic loci and transitional cues for consonants," J. Acoust. Soc. Am. **27**, 769–774.

Dixon, R. M. W. (**1980**). *The Languages of Australia* (Cambridge U. P., Cambridge).

Flege, J. E., and Eefting, W. (**1987**). "Cross-language switching in stop consonant perception and production by Dutch speakers of English,"

Speech Commun. **6**, 185–202.
Forrest, K., Weismer, G., Milenkovic, P., and Dougall, R. N. (**1988**). "Statistical analysis of word-initial voiceless obstruents: Preliminary data," J. Acoust. Soc. Am. **84**, 115–123.
Francis, W. N. (**1958**). *The Structure of American English* (Ronald, New York).
Henton, C., Ladefoged, P., and Maddieson, I. (**1992**). "Stops in the world's languages," Phonetica **49**, 65–101.
Jongman, A., Blumstein, S. E., and Lahiri, A. (**1985**). "Acoustic properties for dental and alveolar stop consonants: a cross-language study," J. Phonetics **13**, 235–251.
Jongman, A., Wayland, R., and Wong, S. (**2000**). "Acoustic characteristics of English fricatives," J. Acoust. Soc. Am. **108**, 1252–1263.
Kessinger, R. H., and Blumstein, S. E. (**1998**). "Effects of speaking rate on voice-onset time and vowel production: Some implications for perception studies," J. Phonetics **26**, 117–128.
Kewley-Port, D. (**1983**). "Measurement of formant transitions in naturally produced stop consonant-vowel syllables," J. Acoust. Soc. Am. **72**, 379–389.
Klatt, D. H. (**1979**). "Synthesis by rule of consonant-vowel syllables," Speech Commun. Group Working Pap. **3**, 93–105.
Klatt, D. H. (**1987**). "Review of text-to-speech conversion for English," J. Acoust. Soc. Am. **82**, 737–793.
Lieberman, P., and Blumstein, S. E. (**1988**). *Speech Physiology, Speech Perception, and Acoustic Phonetics* (Cambridge U. P., Cambridge).
Lisker, L., and Abramson, A. S. (**1964**). "A cross-language study of voicing in initial stops: Acoustical measurements," Word **20**, 384–422.
Mack, M. (**1989**). "Consonant and vowel perception and production: Early English-French bilinguals and English monolinguals," Percept. Psychophys. **46**(2), 187–200.
Mayer, M. (**1969**). *Frog, where are you?* (Puffin Pied Piper, New York).
Picard, M. (**1987**). *An Introduction to the Comparative Phonetics of English and French in North America* (Benjamin, Amsteram).
Picard, M. (**2001**). *Phonetics and Phonology for ESL and TESL Teachers: Comparing Canadian English and French* (Concordia Univ., Montreal).
Pickett, J. M. (**1999**). *The Acoustics of Speech Communication* (Allyn and Bacon, Boston).
Stevens, K. N., Keyser, S. J., and Kawasaki, H. (**1985**). "Toward a phonetic and phonological theory of redundant features," in *Invariance and Variability of Speech Processes*, edited by J. S. Perkell and D. H. Klatt (Erlbaum, Hillsdale, NJ), pp. 426–463.
Stoel-Gammon, C., Williams, K., and Buder, E. (**1994**). "Cross-Language Differences in Phonological Acquisition: Swedish and American /t/," Phonetica **51**, 146–158.
Summerfield, Q. (**1981**). "Articulatory rate and perceptual constancy in phonetic perception," J. Exp. Psychol. Hum. Percept. Perform. **7**, 1074–1095.
Tabain, M., and Butcher, A. (**1999**). "Stop consonants in Yanyuwa and Yindjibarndi: locus equation data," J. Phonetics **27**, 333–357.
Volaitis, L. E., and Miller, J. L. (**1992**). "Phonetic prototypes: Influence of place of articulation and speaking rate on the internal structure of voicing categories," J. Acoust. Soc. Am. **92**, 723–735.