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Effects of obstruent voicing on vowel $F_0$: Evidence from “true voicing” languages

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This study investigates consonant-related $F_0$ perturbations (“CF0”) in French and Italian by comparing the effects of voiced and voiceless obstruents on $F_0$ to those of voiced sonorants. The voiceless obstruents /p t/ in both languages are found to have $F_0$-raising properties similar to American English voiceless obstruents, while $F_0$ following the (pre)voiced obstruents /b v/ in French and Italian patterns together with /m/, again similar to English [Hanson (2009), J. Acoust. Soc. Am. 125(1), 425–441]. In both languages, $F_0$ is significantly depressed, relative to sonorants, during the closure for voiced obstruents, but cannot be differentiated from sonorants following the release of oral constriction. These findings are taken as support for a model on which $F_0$ perturbations are fundamentally the result of laryngeal maneuvers initiated to sustain or inhibit phonation, regardless of other language-particular aspects of phonetic realization.

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I. INTRODUCTION

It has been known for well over a century that speech fundamental frequency ($F_0$) can be affected by intrinsic properties (or “microprosody”) of both vowels and consonants. In particular, high vowels are known to have higher intrinsic $F_0$ than low vowels; similarly, $F_0$ following voiceless obstruents tends to be significantly higher than $F_0$ following voiced obstruents (House and Fairbanks, 1953). Following Kingston (2007), we will refer to these intrinsic $F_0$ perturbations as $V_{F_0}$ and $C_{F_0}$, respectively, but in this paper our focus will be on $C_{F_0}$.

Although the basic facts about $C_{F_0}$ have been established for some time, proposed explanations of its cause are not always compatible, and make sometimes contradictory predictions. In particular, while there is now a good deal of evidence that a voiceless obstruent can raise $F_0$ at the onset of a following vowel, it is less clear what effect, if any, voiced obstruents have on $F_0$. In this paper, we study $C_{F_0}$ in two languages with prevoiced stops, French and Italian, considering the time course of $F_0$ during both the consonant and the following vowel. We show that $F_0$ is lowered during the closure phase of voice obstruents and raised following release of voiceless obstruents, suggesting that both effects result from laryngeal maneuvers to facilitate or inhibit phonation, respectively. This, in turn, suggests that obstruent-related perturbations of $F_0$ arise primarily because of articulatory, rather than perceptual, contingencies related to the production of obstruents.

A. Background

1. Previous work on CF0

In what seems to have been the first systematic study of the “secondary” acoustic characteristics of vowels (i.e., duration, fundamental frequency, and intensity), House and Fairbanks (1953) measured the properties of six American English vowel phonemes flanked by identical consonants that differed in voicing, place and manner of articulation in isolated nonsense sequences like [ha’pip],[ha’mam], and [haz’dud]. They reported that “the [mean] fundamental frequencies of vowels in voiceless environments are invariably higher than those in voiced environments” (1953, p. 109). They also reported a small study showing that the acoustic differences are most pronounced at the beginning of the vowel.

A few years later, in a rather larger study motivated by questions related to intonation rather than the acoustics of vowels, Lehiste and Peterson (1961) refined and extended House and Fairbanks’s findings. They confirmed House and Fairbanks’s preliminary conclusion that $F_0$ perturbations at vowel onset are primarily due to the voicing of the consonant that precedes the vowel, not the whole consonantal context, and that voicing gives rise to a different $F_0$ trajectory across the vowel of test words spoken in carrier sentences. Especially important here is Lehiste and Peterson’s observation that the overall trajectory of $F_0$ is primarily determined by linguistic specifications of intonation, and that $C_{F_0}$ effects, whatever their underlying cause, must be defined relative to the course that $F_0$ would have taken if the conditions that give rise to the perturbations were not present. This idea was subsequently developed in work by Lea (1973), Kohler (1982, 1984, 1985), Silverman (1987), and Hanson (2009), and in what follows, we take it for granted that $C_{F_0}$ effects can best be

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understood as a deflection from an underlying linguistic intention (e.g., a lexical tone or an intonation contour).

In the subsequent decades, a large number of studies have replicated and extended the finding that voiceless obstruents raise F0 of the following vowels, in English as well as in other languages (for some reviews of the literature see Hanson, 2009; Chen, 2011). The question then naturally arises what the source of such an effect might be. An early and still influential account was that of Halle and Stevens (1971), who proposed that voiceless segments canonically involve a stiffening of the vocal folds (Halle and Stevens 1971, pp. 203–204). They suggest that while the primary purpose of this gesture is to inhibit phonation, the increase in vocal fold length and horizontal tension would also predict a rise in the frequency of any glottal vibration that does subsequently occur, as for example, at the onset of a following vowel. This “horizontal-tension” hypothesis later received support from the electromyographic study of Lölqvist et al. (1989), who demonstrated that a peak in cricothyroid (CT) activity occurs during the midpoint of closure for voiceless stops in both Dutch (where voiceless stops are canonically unaspirated) and American English (where they are canonically aspirated). On the basis of the relative timing of this gesture, Lölqvist et al. argued that its primary function is related to inhibition of vocal fold vibration, rather than to pitch control. Researchers have also suggested that intrinsic aerodynamic properties of the stop release may contribute to CFO (Kohler, 1985; Francis et al., 2006).

However, there is also reason to believe that F0 could be lowered in the vicinity of voiced stops. Ewan (1976) and Hombert et al. (1979) advanced the notion that CFO is primarily a matter of vertical tension of the vocal cords, the result of articulations designed to enlarge the supraglottal cavity and facilitate voicing, such as expansion of the pharyngeal cavity or lowering of the larynx (Bell-Berti, 1975; Erickson et al., 1982; Westbury, 1983). This “vertical-tension” account predicts that F0 should be lowered following voiced stops, rather than raised following voiceless stops (Hombert et al., 1979, p. 45). Although Hombert and colleagues did not specify precisely how these articulations would affect vertical vocal fold tension, Honda et al. (1999) presented evidence that, at least in low F0 ranges, a downward vertical movement of the hyoid-larynx complex rotates the cricoid cartilage along the forward-inclined cervical vertebrae, thereby shortening the vocal folds and decreasing their horizontal (rather than vertical) tension, resulting in lower F0.

F0 lowering is also predicted by the auditory enhancement account of Kingston and Diehl (1994), who argued that certain articulations, such as those to sustain voicing and lower pitch, tend to covary because the resulting combination of acoustic effects integrate perceptually. In particular, they assert that “F0 is uniformly depressed next to [+voice] stops, regardless of how the [voice] contrast is otherwise realized” (1994, p. 432). There is also evidence that the lowered F0 following voiced obstruents (relative to their voiceless counterparts) may become phonologized, as in Shanghai Chinese (Chen, 2011) or Xhosa (Jessen and Roux, 2002), which further suggests an active gesture to explicitly lower pitch in this context.

2. Establishing a reference level

An important contribution to the understanding of CFO effects was made by Hanson (2009), who compared CFO of American English voiced and voiceless stops and fricatives. Hanson treated the time course of F0 following a nasal /m/ as a reference condition for interpreting the details of F0 after an obstruent onset.1 Hanson’s motivation for using nasals as a reference stemmed from the observation that they should have little, if any, effect on the intonationally specified pitch target, due to the facts that (a) nasal sounds do not require any articulatory adjustments to the supralaryngeal cavity or state of the glottis in order for vocal fold vibration to be maintained and (b) the nasal cavity itself offers little resistance to airflow and thus does not condition the kind of decrease in pressure drop across the glottis that would perturb pitch (Ohala, 1975; Hombert et al., 1979). With this approach, Hanson was able to provide clear evidence that, at least in English, it is more appropriate to speak of F0 raising following [−voice] consonants rather than F0 lowering following [+voice] consonants. Her results demonstrate that the time course of F0 after voiced obstruents is qualitatively identical to that after nasals, whereas F0 at voice onset is higher following voiceless obstruents, and may not converge with the nasal comparison contour for as much as 100 ms. Hanson also showed that the degree to which CFO is perturbed in this environment is a function of intonational context.2 She coached her speakers to produce test words at different pitch levels, from relatively high to relatively low in their speaking range. The summary just given of her findings about voiced and voiceless stops applies most clearly in high F0 contexts; Hanson also found that post-release F0 perturbations were present, but much smaller, in neutral and low F0 environments.

3. The relevance of “true voicing” languages

On the face of it, Hanson’s findings seem problematic for at least some theories that predict F0 lowering following phonologically voiced obstruents, especially those which predict that F0 is lowered after voiced obstruents relative to sonorants (e.g., Hombert et al., 1979). However, it may also be that an F0 lowering effect is evading detection, given that voicing during the closure of English [−voice] stops /b d g/ is allophonic and speaker- and dialect-specific (Flege, 1982; Jacewicz et al., 2009). As such, a lowering effect on F0 may be more easily observed in so-called “true voicing” languages, such as French or Italian, in which phonologically voiced obstruents are typically characterized by vigorous voicing throughout the closure (Benguerel et al., 1978; Vagges et al., 1978). That is, it may be that the explicitly depressed F0 predicted by the vertical-tension and auditory-enhancement hypotheses, though not found after English lenis stops, will nevertheless appear after, or during during, the fully voiced stops of a language like French or Italian.

A second reason for investigating CFO in “true voicing” languages is that the voiceless stops in such languages are typically characterized by relatively short-lag voice onset time (VOT; Lisker and Abramson, 1964), and are thus similar to a possible allophonic surface realization of English
[+voice] stops. This is of interest because past work provides some reason to think that it is the phonological, rather than phonetic, status of stops in a language that triggers local F0 raising (or lowering) in the following vowel. Both Ohde (1984) and Hanson (2009) found F0 following unaspirated allophones of English voiceless stops in /s+stop/ clusters to be similar to that following syllable-initial aspirated allophones, and in any event different from that found after syllable-initial [+voice] stops. That is, even though English syllable-initial voiced stops and the voiceless stops in /s+stop/ clusters are both in some sense “voiceless unaspirated,” they induce different F0 effects on the following vowel\(^3\) [Fig. 1(a)]. Furthermore, in a recent study comparing English stops with those of Spanish, another “true voicing” language, Dmitrieva et al. (2015) found that differences in CF0 are predictable only from the phonological specification of the stop, and not from the phonetic realization of VOT: English [+voice] stops that were realized with (canonical) short-lag VOT had CF0 effects indistinguishable from those realized with (less canonical) prevoicing, whereas Spanish [+voice] stops, which are canonically prevoiced, had different CF0 effects compared to [−voice] stops, which are canonically produced with short-lag VOT.

**B. The present study**

The present study applies Hanson’s methodological approach to two languages with unambiguously prevoiced stops, French and Italian. Although there are a number of studies which report CF0 in languages with phonetically prevoiced stops (Hombert, 1976; Lofqvist et al., 1989; Chen, 2011; Dmitrieva et al., 2015), none of these studies include a baseline by which we might assess the direction in which F0 raising (or lowering) in the following vowel is being perturbed relative to the global intonation target. An important aspect in which we extend earlier studies is in studying the time course of F0 during the closure phase of voiced consonants, as well as during the following vowel. Our overall aim is to contribute to the understanding of possible sources of CF0 and, more generally, of the laryngeal adjustments that characterize voicing in different languages.

If languages like French and Italian employ articulatory strategies to (a) facilitate pharyngeal expansion and maintain the transglottal pressure differential necessary to promote voicing during the stop closure and/or (b) produce lowered F0 because it contributes to a cluster of perceptually integrated auditory properties, then in a “true voicing” language we might expect to find the opposite pattern to that reported by Hanson: that is, it might be that F0 is lowered relative to the (presumably unperturbed) nasal baseline after voiced stops but is unaffected after voiceless (unaspirated) stops [Fig. 1(b)]. A second possibility is that, despite the substantial phonetic differences in the realization of voicing, “true voicing” languages may present a picture similar to what Hanson found for English: namely, that voiceless stops induce raised F0 in the following vowel and (pre)voiced stops match the F0 pattern found with nasals [Fig. 1(a)]. Such a pattern would be consistent with the finding of Hanson, Ohde, and Dmitrieva et al. that English [−voice] stops are associated with raised F0 regardless of allophonic differences in VOT, as well as with the results of Hanson and Dmitrieva et al. that F0 following English [+voice] stops is unaffected by whether or not voicing is present during the closure. Finally, if both mechanisms are at work, one might find a raising effect following [−voice] obstruents but a lowering effect following [+voice] obstruents, with nasals somewhere in the middle [Fig. 1(c)]. Note that, because [+voice] obstruents are expected to be consistently prevoiced in French and Italian, we can also investigate the time course of F0 during the closure phase of the obstruent (which may not always be possible in a language like English).

**II. METHODS**

**A. Speech materials**

We used an approach very similar to that of Hanson (2009) to study CF0 in French and Italian. Our methods differ from hers primarily in that we used natural meaningful sentences with real words as test words rather than a single carrier sentence with non-words, and we controlled intonation by designing ordinary sentences that could most naturally be read only with the desired intonation pattern. We did this in order to avoid any potentially unnatural effects of detailed coaching and monitoring.

As noted earlier, several studies have shown that the magnitude of intrinsic F0 perturbations may be attenuated depending on prosodic context (Ladd and Silverman, 1984; Kingston, 2007; Hanson, 2009). To investigate this possibility, we embedded our test words (see the Appendix) into

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**FIG. 1.** Schematic comparisons of (a) time course of F0 production in a high intonational context in American English (after Hanson, 2009); (b) hypothetical pattern in a “true voicing” language where [+voice] obstruents lower F0; (c) hypothetical pattern in a “true voicing” language where [+voice] obstruents lower F0 and [−voice] obstruents raise F0. Note that panels (b) and (c), unlike panel (a), plot the predicted F0 trajectory during the voiced stop closure as well as during the following vowel.
the LMU Institute of Phonetics and Speech Processing.

Maximilian University (LMU) in Munich, and recorded at ages 20–29 years) were exchange students at the Ludwig Laboratory. The Italian speakers (four female, two male, recorded at the University of Edinburgh Phonetics undergraduates at the University of Edinburgh, and were (nine female, one male, ages 18–23 years) were all visiting levels and to allow them to become comfortable with the intonation patterns. The French participants then read a total of 38 items in 116 unique test sentences: 12 sentences each with targets /b f v/ and 11 sentences each with targets /p m/ in two different intonation conditions (high and low). Italian participants read a total of 67 items in 134 test sentences: 12 sentences each with targets /b f v/ and 11 sentences each with targets /p m/ in two different intonation conditions (high and low). Italian participants had varying degrees of foreign language competency, but in all cases high enough to facilitate study in a foreign country (the United Kingdom or Germany, respectively). All participants reported normal hearing and no history of speech or language deficit and were paid a small sum for their participation.

C. Recording procedure

Recordings were made in a sound-treated recording booth at the University of Edinburgh or Ludwig Maximilian University, Munich. Before the recording, participants were given brief oral instructions (in English or German, as appropriate), provided basic demographic information (age, place of birth, other languages spoken) and signed informed consent forms. The intended intonation pattern was then illustrated in French or Italian by a fluent L2 speaker, who emphasized that the sentences were intended to be everyday language and should be read as naturally and colloquially as possible. With these instructions, and without close coaching or monitoring, the speakers all easily produced the intended intonation pattern (as judged by the fluent L2 speaker) on all or nearly all sentences.

Speakers were seated approximately 20 cm from an omnidirectional microphone, with sentence prompts appearing on a computer screen (for the Italian participants) or on sheets of paper printed and placed on a music stand in front of the speaker (for the French participants). All recordings were made direct to disk at a 44.1 kHz sampling rate using the BAS SpeechRecorder software package, version 2.12.10 (Draxler and Jänsch, 2004).

The speakers all read the same list of sentences for their language. After the experimenter’s introduction, participants read 10–20 warm-up sentences to insure optimum recording levels and to allow them to become comfortable with the intonation patterns. The French participants then read a total of 38 items in 116 unique test sentences: 12 sentences each with targets /b f v/ and 11 sentences each with targets /p m/ in two different intonation conditions (high and low). Italian participants read a total of 67 items in 134 test sentences: 12
with target /b/, 13 each with targets /p/ and /f/, 14 with target /m/, and 15 with target /v/, again in two different intonation conditions. Examples of the intonation contours produced are given in Figs. 2–5.

D. Acoustic analysis

The segments of interest (consonant and following vowel) were manually labeled by the first author using Praat 5.4.03 (Boersma and Weenink, 2015) based on the periodicity in the acoustic waveform, supplemented by spectrographic analysis where appropriate. Four primary acoustic landmarks were annotated: the onset and offset of stop closure (or frication, as appropriate), the onset of voicing, and the duration of the following vowel. For voiced obstruents, onset of voicing was usually coextensive with the onset of oral constriction; in the event of voicing cessation, either during the closure or immediately following the burst, the post-release re-establishment of periodic voicing was also noted. For this data set, we defined the onset of voicing as the onset of the first periodic pattern in the acoustic waveform (see supplementary material for examples). Vowel offset was defined as the last pitch cycle before a significant drop in amplitude when preceding a stop, or the last pitch cycle before significant frication noise when preceding a fricative.

Following segmentation, acoustic measurements were taken using Praat. Pitch analysis was performed using the autocorrelation method of Boersma (1993), with a Gaussian analysis window of 80 ms, a 5 ms frame duration, a pitch floor of 50 Hz, and a pitch ceiling of 500 Hz. Each pitch object was examined visually and checked by hand to correct any instances of pitch halving (or, less commonly, doubling). The resulting F0 contours were then sampled at 29 equidistant points in each of the closed and open phases (equivalent to once every 5–7 ms). Prior to further analysis, by-speaker raw F0 measurements were standardized using a z-score transform to facilitate comparison of total degree of pitch change across subjects and tokens.

In addition to F0, we took a number of durational measures. For voiceless stops, we measured VOT (Lisker and Abramson 1964), defined here as the duration of the period from stop release to the onset of periodic voicing. Voiceless stops were never prevoiced in our corpus. For stops, we also measured closure duration, and for fricatives, frication noise duration, as both measures are known to vary as a function of voicing in connected speech (e.g., Crystal and House, 1988). Finally, we recorded the duration of the vowel following the onset to use as a proxy for speech rate. Spectrographic examples of each of these segment types can be found in the supplementary material.

III. RESULTS

All results were analyzed using linear mixed-effect models implemented in the R package lme4 (Bates et al., 2015), with lsmeans (Lenth and Hervé, 2014) used for post hoc and pairwise comparison between the predicted marginal means.

A. F0

The basic result is presented in graphic form in Fig. 6, which shows the mean standardized F0 contours over the CV sequence by language, manner, and voicing for both high intonation (test word in X position) and low intonation (Y position) contexts. Focusing first on the open (post-release) phase, visual inspection of the contours for the high context shows clearly that the F0 pattern following voiced obstruents is similar to that of nasals, while that following voiceless obstruents starts markedly higher and gradually converges with the nasal and voiced-obstruent F0 contours (more quickly for Italian than for French). A similar pattern is visible in the low intonation context, especially in Italian, though the differences are very small. Any influence of manner (stop vs fricative) on immediate post-release F0 appears minimal. While some individual differences were observed, the shape and magnitude of the contours was quite similar.
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From the series of multilevel regression models, each predicting the hypothetical pattern sketched in Fig. 1(c) (Sec. 1B), uncorrelated by-subject random slopes for both lower than nasals, but could not be statistically distinguished from one another.

In the low context, voiced stops and fricatives were both voiced stops and voiced fricatives was lower than that of /m/ at this point. In the low context, /p/ is still raised relative to /m/ in the high context, but /l/ cannot be distinguished from either /m/ or /p/; in the low context F0 is the same for all segment types. By vowel offset, no segments can be distinguished from /m/ on the basis of F0.

B. Durational properties
To assess the extent to which VOT, closure duration, and/or frication duration co-vary with CF0, we first describe the distribution of these properties in our data.

1. Stop VOT
Figure 7 shows the distribution of (positive) VOT in both languages by intonation context, with means and standard deviations given by language and intonation context in Table 1. With a few exceptions (two instances of ballo and one of cubana produced by three different Italian participants), [+voice] stops in both languages were consistently voiced throughout the closure; we removed the three exceptional items from the subset distribution considered here before further analysis. Our VOT model included the two-way interaction of LANGUAGE (French, Italian) and INTONATION CONTEXT (high, low), with random intercepts for subjects and items and by-subject random slopes for INTONATION CONTEXT. The addition of following vowel duration (as a correlate of speech rate) resulted in an improved model fit (p < 0.001, df = 1), but the estimated effect size was quite small ($\beta = 0.05$, $SE = 0.01$, $t = 4.2$). French voiceless stops showed slightly greater variation (and slightly higher mean VOTs) than those of Italian (7 ms, $SE = 3.1$, df = 19.79, $t = 2.38$, $p = 0.03$). Our Italian findings are roughly comparable to those of Vagges et al. (1978) and Esposito (2002), while the French data indicate a slightly longer voicing lag compared to some previous reports (Caramazza and Yeni-Komshian, 1974), although this may be an effect of the following vowel quality (Nearay and Rochet, 1994). Most germane for present purposes, it is clear that the VOT distributions differ significantly from those of languages like English (see Lisker and Abramson, 1964, and much subsequent work).

![Graph showing average time-normalized standardized pitch contours](image)
2. Stop closure duration

Summary statistics for closure duration are provided in Table II and presented graphically in Fig. 8. Our model for stop closure duration included a three-way interaction of LANGUAGE (French, Italian), VOICING (voiced, voiceless, nasal), and INTONATION CONTEXT (high, low), with random intercepts for subjects and items and by-subject random slopes for repeated measures VOICING, INTONATION CONTEXT, and their interaction. Addition of a VOWEL DURATION predictor, as a surrogate for speech rate, significantly improved model fit in a likelihood-ratio test ($p = 0.04, df = 1$). No significant differences in closure duration were found within each language and intonation context, e.g., the distribution of closure duration for French /p/ in high context is the same as for /b/ in that context.

Within each language and segment type, small but significant differences between predicted marginal means in high versus low intonation context were observed for nasals in French [6 ms, standard error (SE) = 2.2, df = 25.40, $t = 2.7$, $p = 0.01$], and for both voiced (10 ms, SE = 2.65, df = 20.51, $t = 3.92$, $p < 0.001$) and voiceless (7 ms, SE = 2.9, df = 17.75, $t = 2.4$, $p = 0.03$) stops in Italian. In all cases, closure durations were longer in the high compared to the low intonation context. Within language and intonation context, significant differences by segment type were found only between Italian /b/ and /m/ in low intonation environments, with /m/ closures here lasting longer on average (18 ms, SE = 5.23, df = 80.14, $t = 3.4$, $p < 0.01$). Between languages, differences in closure duration were not significant for any segment types within a intonation context.

Our findings agree with those of Esposito (2002) who also did not observe voicing-related differences in closure duration between /p/ and /b/ in Italian, and are consistent with Abdelli-Beruh (2004), who found French voiceless stops to have longer closure durations than corresponding voiced stops, a trend that is also present in our data.

3. Frication duration

Figure 9 shows the distribution of frication duration in our data for voiced and voiceless fricatives in both languages by intonation context, with means and standard deviations given in Table III. All voiced fricatives in both languages were consistently and robustly voiced throughout the closure period, and we did not observe any instances of spontaneous voicing of the voiceless fricatives. As with closure duration, we modeled frication duration from the three-way interaction of LANGUAGE (French, Italian), VOICING (voiced, voiceless) and INTONATION CONTEXT (high, low), together with a predictor VOWEL LENGTH, random intercepts for subjects and items, and by-subject random slopes for repeated measures VOICING, INTONATION CONTEXT, and their interaction. As seen in Fig. 9, frication duration was significantly longer for /f/ compared to /v/ in both languages and intonation contexts (mean over both languages: 53 ms, SE = 3.15, df = 68.09, $t = -16.8$, $p < 0.001$). Friction durations were slightly

![FIG. 7. Distribution of VOT values by language and intonation context.](image)

![FIG. 8. Distribution of closure durations by segment, language and intonation context.](image)

### TABLE II. Mean (standard deviation) closure durations (in ms) by segment, language and intonation context.

<table>
<thead>
<tr>
<th>Segment</th>
<th>Language</th>
<th>French</th>
<th>Italian</th>
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</thead>
<tbody>
<tr>
<td>/b/</td>
<td>high</td>
<td>65 (14)</td>
<td>70 (26)</td>
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<tr>
<td></td>
<td>low</td>
<td>62 (13)</td>
<td>59 (24)</td>
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<tr>
<td>/m/</td>
<td>high</td>
<td>73 (17)</td>
<td>77 (18)</td>
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<tr>
<td></td>
<td>low</td>
<td>67 (15)</td>
<td>77 (24)</td>
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<tr>
<td>/p/</td>
<td>high</td>
<td>70 (20)</td>
<td>77 (18)</td>
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<td>low</td>
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longer for voiced fricatives in high compared to low intonation contexts in both French (6 ms, SE = 1.85, df = 29.85, t = 3.2, p < 0.01) and Italian (5 ms, SE = 2.19, df = 20.93, t = 2.2, p < 0.05). Frication durations for French voiced fricatives were longer than those of Italian in both high (15 ms, SE = 6.1, df = 46.31, t = 2.4, p < 0.05) and low (14 ms, SE = 5.5, df = 65.06, t = 2.5, p < 0.05) contexts. Descriptively, Italian voiced fricatives were produced with slightly less variation than those of French. The general pattern observed here (significant temporal overlap but voiceless longer than voiced) is consistent with previous acoustic studies of frication duration (Crystal and House, 1988; Jongman et al., 2000).

C. VOT-F0 covariance

In an acoustic study of CF0 based on French and Italian word lists, Kirby and Ladd (2015) found a positive correlation between the duration of voicing lead and post-release onset F0: longer voicing leads were associated with lower onset F0 in both languages. This effect was not replicated in the current study. While there is a very weak negative correlation between closure duration and onset F0 for French voiced stops in the high intonation context (r = -0.08), the effect is in the opposite direction in the low context (r = 0.2); in Italian, the pattern is reversed (rhigh = 0.22, rlow = -0.06; see the supplementary material4 for covariance plots). This is likely due to the fact that, in the present study, [+voice] stops are in intervocalic and often intramorphemic position: because voicing had been initiated prior to the stop closure, it may be that speakers were not controlling articulations related to CF0 in the same way as when voicing is initiated in utterance-initial position, as in the word-list condition of Kirby and Ladd (2015).6

Although there is an overall moderate positive correlation between scaled F0 and VOT for French voiceless stops in the high intonation context (r = 0.39), inspection of this relationship on a by-speaker basis (not shown here) suggests considerable variation, with some speakers having a negative correlation or no correlation at all. In the low context, no overall correlation was observed (r = 0). For Italian, correlations were weakly positive in both contexts (r = 0.16/0.17), but once again there is considerable individual variation in the direction of the correlation (cf. Dmitrieva et al., 2015, who report within-category VOT and onset F0 to be uncorrelated in Spanish). Correlations between noise duration and F0 at vowel onset for fricatives were similarly weak or absent (r < ±0.3 in all cases).

IV. DISCUSSION

A. General discussion

Despite the considerable phonetic difference in what it means to be “voiced” (or “voiceless”) in English, French, and Italian, it is clear that in all three languages, voiceless or “fortis” obstruents raise F0 in the following vowel, regardless of the temporal duration of voicing lag. This effect was attenuated, but not completely obliterated, in the low intonation context (Hanson, 2009), and is consistent with previous studies of CF0 in “true voicing” languages (Hombert, 1976; Löfqvist et al., 1989; Dmitrieva et al., 2015). Moreover, F0 immediately following the release of voiced/lenis obstruents is statistically indistinguishable from F0 following nasals. Thus, in French and Italian as well as in English, post-release F0 perturbations appear to be primarily a result of laryngeal adjustments that raise, rather than lower pitch (Halle and Stevens, 1971; Löfqvist et al., 1989; Hanson, 2009), although the magnitude of this effect is clearly dependent on the global intonation target (Lea, 1973; Kohler, 1982; Silverman, 1986; Hanson, 2009).

It is also clear from our data that there is pronounced F0 lowering during the closure phase for voiced obstruents (stops and fricatives) relative to nasals in both languages and in both intonation contexts (although, as with post-release raising, the effect is attenuated in the low intonation context). However, no such lowering was observed during the oral closure for nasals. This supports the use of sonorants as a baseline when studying whether F0 is perturbed from a global intonation target (Löfqvist et al., 1995; Hanson, 2009), and reinforces the expectation that the linguistic F0 target of an utterance should be perturbed minimally, if at all, by the production of (voiced) sonorants, for which maintaining transglottal airflow necessary for continued voicing should not require any active or passive vocal tract enlargement (Ohala, 1975) or otherwise require articulatory

<table>
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<th>Voicing</th>
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<th>Language</th>
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</table>

FIG. 9. Distribution of frication duration by segment, language, and intonation context.
adjustments of the glottis or supralaryngeal cavity (see Sec. IV B, below).

However, these findings are accompanied by two caveats. First, as shown in Sec. III A, there is a difference between the F0 lowering effects of voiced stops and voiced fricatives in French, but not in Italian. In Italian, that is, the lowering effect of voiced obstruents does not seem to depend on the degree of stricture, whereas in French, voiced stops lower F0 more than voiced fricatives do, at least in the high-pitch environment. Is there any reason to expect such a difference? It is known that the production of voiced fricatives is aerodynamically challenging (Stevens, 1971; Ohala, 1997), involving both glottal addition as well as maintenance of sufficient airflow to generate friction noise. If the F0 lowering effect of voiced obstruents is due to active laryngeal adjustments to reduce supraglottal pressure ($P_O$) in order to maintain phonation, this difference suggests that in Italian, stops and fricatives have comparable effects on $P_O$, whereas French fricatives have a weaker effect than stops. This may be the case if the production of voiced fricatives in Italian involves greater obstruction of oral airflow (e.g., via a narrower constriction or greater peak closing velocity) than is the case in French. To our knowledge there are no relevant instrumental studies that would confirm or refute this speculation, but it seems very likely that such differences between languages exist. In this connection we note that the second author has had considerable experience analyzing F0 contours in both English and Greek, and reports impressionistically that Greek voiced fricatives are much more likely than English ones to be fully voiced and to have a substantial lowering effect on F0.

Second, while we do observe post-release F0 raising in high-pitch focus contexts following voiceless (short-lag) stops of French and Italian, the overall magnitude and duration of this raising differed across the two languages, and appears to differ somewhat from languages such as English and German. Compared to Italian, CF0 in French is in general of greater magnitude at voicing onset and persists for longer into the vowel (Sec. III A, Fig. 6), and is more robustly observed across the speakers in our sample (see the supplementary material for by-speaker plots). Furthermore, our data show a clear difference between the trajectory of F0 following voiceless obstruents in French and Italian: the post-voiceless contour remains raised relative to the sonorant baseline for much longer in French than in Italian. It is possible that this reflects some fundamental difference in the extent or manner of voicing inhibition, but we suggest that the explanation may lie instead with the prosodic difference between the test syllables in the two languages (for discussion of such prosodic differences see, e.g., Ladd, 2008, pp. 55–61). In French, because intonational pitch accents always associate with the edges of phrases (Jun and Fougeron, 2002), the local F0 peak after the first constituent of the alternative question (i.e., at the edge of “X” in “X or Y?”) is aligned with the very end of the test syllable (see Figs. 2 and 3). In Italian, on the other hand, the intonational pitch accent associates with the lexically stressed syllable, which was on the penultimate syllable in all our test words. In other words, the later timing of the F0 peak in French may provide a more favorable pitch environment in which to observe the effect of CF0. One possibility is that this may result from an interaction between the timing of the gestures programmed to produce the intonation target and those associated with suppression of voicing for production of the onset. This idea could be tested by repeating the Italian portion of the present experiment using oxytone test words (parole tronche, words with lexical stress on the final syllable), though there is the practical difficulty that such words are not very common. In any case these are questions for further research.

B. Implications for theories of CF0

In our French and Italian data, as in much previous work on other languages, we find that F0 is clearly raised, relative to nasals, following the release of voiceless obstruents, and can continue to differ significantly by over 20 Hz from post-sonorant F0 at vowel midpoint (Sec. III A 1). This finding supports previous proposals that post-release CF0 effects result from an active gesture to inhibit phonation, such as stiffening of the vocal folds and/or engagement of the cricothyroid (CT) musculature (Halle and Stevens, 1971; Löfqvist et al., 1989). If contraction of the CT is generally employed as a means to inhibit phonation, this would help explain why languages like Italian and French pattern together with English with respect to their CF0 behavior. Moreover, if the effects of CT relaxation on vocal fold tension take longer to dissipate than do those of CT contraction, a decline in F0 should lag behind a decline in visible CT activity, despite peak CT activity being temporally coextensive with the midpoint of the consonantal closure (Löfqvist et al., 1989; Sawashima et al., 1982). During the closure phase of voiced obstruents, on the other hand, we observe clear F0 lowering, as would be expected if speakers employ one of several previously documented strategies to reduce $P_O$, such as larynx lowering, velopharyngeal venting, or engagement of the levator palatine and sternohyoid muscles to expand the pharyngeal cavity (Bell-Berti, 1975; Erickson et al., 1982; Westbury, 1983; Solé, 2011). In other words, CF0 may be explained as a side-effect of the successful production of an obstruct, with the direction of the perturbation (raising or lowering) involved depending on (a) the particular constellation of gestures associated with the phonetic expression of the voicing contrast in a given language, dialect, or idiolect, as well as (b) the point in the speech stream where F0 is considered.

We emphasize, however, that even if CF0 arises in the first instance due to articulatory contingencies, awareness of perceptual benefits of certain cue combinations may lead speakers to exaggerate these adjustments for the listener’s benefit: as noted by Hanson (2009, pp. 436–438), there is no necessary contradiction between the kind of evidence presented here and a more general notion of phonologically or auditory-driven enhancement consistent with Kingston and Diehl’s notion of “phonetic knowledge” (on this point see also Hoole and Honda, 2011). Indeed, as has been frequently observed, the very fact that CF0 perturbations are seemingly crucial components of tonogeneric processes entails that they must at some point come under speaker control. Our contention is simply that, at least in the first instance,
perceptual considerations may not be necessary to account for intrinsic F0 effects, at least in some languages.

If post-release F0 raising is the result of gestures intended to suppress phonation, then we might also expect F0 to be raised following voiceless sonorants in languages with such segments. Maddieson (1984) has shown that in Burmese, a language that contrasts voiced with voiceless nasal and lateral sonorants, F0 is higher following the voiceless than the voiced sonorant series (see also Ohala, 1975). Although Maddieson does not compare with data from obstruents, he points out that this is consistent with much of the historical data on tonogenesis, in which voiced obstruents and sonorants pattern together in terms of their tonal reflexes, as do voiceless obstruents and (voiceless) sonorants. This patterning is predicted if the production of voiceless sonorants in these languages involves an active laryngeal gesture to inhibit phonation similar to that of voiceless obstruents.

C. Implications for laryngeal phonology

It has at times been suggested that, in languages with two-way laryngeal contrasts, the primary or “active” phonetic indicator of (word-initial) obstruents will be either aspiration or closure voicing, but not both (e.g., Keating, 1984; Kohler, 1984). For example, Keating (1984) argues that in a language like English, where the fortis member of the opposition is marked by aspiration, then the lenis member does not require active voicing. In a language like French, the reverse should hold: if the lenis series involves active gestures to maintain voicing during closure, the fortis series will not be characterized by any particular enhancement. Languages like English may then be described as having an active “devoicing” gesture, associated with the fortis series only, while languages like French will have an active specification for vocal fold vibration associated with the lenis series, with the fortis series accordingly underspecified. A similar idea is made formally explicit in so-called “laryngeal realism” literature (e.g., Beckman et al., 2013). However, the present results suggest that in languages like French, while the lenis series is characterized by a gesture to support voicing, so too is the fortis series characterized by a gesture to support devoicing, i.e., something like [stiff vocal folds]. It is not clear to us in what sense one of these gestures is more essential than the other; rather, they simply reflect the empirical reality of language-specific differences in the implementation of voicing (cf. Kingston, 2007, p. 172). Additional evidence in support of this view comes from Chasaide and Gobl (1993), who found language-specific differences in voice source parameters on the vowel following voiced and voiceless stops in a number of European languages even though these differences would not normally be considered phonologically distinctive. Such findings are problematic only if one insists that phonological contrasts need to be in some sense “ecumenical” or otherwise non-redundant (see Beckman et al., 2011, for some discussion).

On the basis of their findings that Spanish and English short-lag stops were indistinguishable in terms of VOT, but well separated in terms of onset F0, Dmitrieva et al. (2015) argued that “the phonological status of the consonant may carry more weight in determining the onset F0 patterns than do its phonetic properties, such as the presence or absence of laryngeal voicing” (p. 91). Similar arguments have previously been advanced by Keating (1984, p. 294) and Kingston (2007, p. 173). While it is clear that onset F0 behavior cannot be predicted directly from VOT, we believe that the ultimate determinant of CF0 patterns is fundamentally phonetic in nature, as argued in Sec. IV B above: the reason that the voiceless stops of French, Spanish, and English pattern together with respect to post-release F0 raising is not because they share a phonological feature, but because they share a gesture aimed to inhibit phonation (see also Goldstein and Brownman, 1986). The fact that Dmitrieva et al. found English lenis stops to have the same (non-)effect on onset F0 regardless of whether or not they were phonated during closure is consistent with this category not having an associated phonation-inhibiting gesture in this language; and in general, we should not expect that the presence or absence of such a gesture is predictable from the surface duration of voicing lag (or lead). In a language like French, the perceptual importance of robust prevoicing may mean that speakers are more likely to take action to insure voicing is sustained throughout the closure, leading to depressed F0 during the closure (and possibly to some residual F0 lowering immediately following the release, although we did not find statistical support for this in our data). In English, on the other hand, if voicing during the closure is less perceptually critical, we would not expect the same degree of F0 lowering either during the closure or in the following vowel (at least, for those speakers/dialects/utterances where [+voice] stops are actually produced with vocal fold vibration during the closure: Flege, 1982; Hanson, 2009).

Taken together, studies of CF0 serve as an important reminder that cross-linguistic variation in “voicing” is not restricted to the relative timing of laryngeal and supralaryngeal gestures and the resultant differences in VOT; states of the glottis (e.g., spread vs constricted, stiff vs slack) can vary as well, even if VOT alone appears to be acoustically sufficient to distinguish the voicing contrasts in any given language. Indeed, listeners appear to take CF0 information into account even when the phonological contrast is unambiguously signaled by VOT differences (Whalen et al., 1990; Whalen et al., 1993). These findings support the contention that it is inappropriate to represent obstruent contrasts along a single-dimension acoustic-phonetic continuum, either of timing (e.g., VOT: Lisker and Abramson, 1964; Keating, 1984) or glottal constriction (e.g., a continuum from open to closed: Kim, 1970; Gordon and Ladefoged, 2001). Instead, it should be kept in mind that the articulatory mechanisms underlying the production of laryngeal contrasts of all kinds are considerably more complex (Halle and Stevens, 1971; Kingston and Diehl, 1994; Edmondson and Esling, 2006; Keyser and Stevens, 2006; Hanson, 2009).

V. CONCLUSIONS

The present findings provide evidence for two types of CF0 effects. The first—raised F0 following the release of a voiceless consonant—can be understood as the result of laryngeal adjustments to inhibit phonation, while the second—depressed F0 during the closure phase of a voiced
obstruct— is consistent with known laryngeal adjustments which sustain phonation. In both cases, however, the F0 perturbations accompany, and are thus predicted by, articulatory maneuvers otherwise required for the successful implementation of voicing. While this in no way precludes subsequent enhancement of CF0 for perceptual purposes, it supports the position that the source of the effect is fundamentally due to articulatory, rather than perceptual, contingency (Halle and Stevens, 1971; Kohler, 1985; Löfqvist et al., 1989; Hanson, 2009; Hoole and Honda, 2011).

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APPENDIX: WORDLISTS

Table IV gives wordlists for French and Italian.

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<th>/v/</th>
<th>/l/</th>
<th>/n/</th>
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2. Italian

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1The early studies by House and Fairbanks and Lehiste and Peterson included both obstruents and sonorants, but much of the experimental work of the 1970s and 1980s focused only on obstruents. Hombert seems to have recognized the importance of establishing some sort of basis of comparison, and anticipated Hanson’s idea of comparing obstructions to nasals (Hombert, 1978; Hombert et al., 1979, p. 45). However, these studies were fairly preliminary, and the idea does not seem to have taken up in most subsequent research.

2See also Kingston (2007), who studied CF0 effects in different intonational contexts in the speech of four American English speakers. Control of intonation is important, as earlier studies (e.g., Ladd and Silverman, 1984) have shown that the magnitude of intrinsic F0 perturbations may be attenuated in some prosodic contexts, a finding confirmed by Hanson’s and Kingston’s more recent studies, and in the present paper.

3Kingston and Diehl (1994, pp. 433–434) present data showing that F0 following /i/ or /u/ clusters is in general intermediate between those of voiced and voiceless singletons, a fact they attribute to the neutralization of the [voice] contrast in this context.

4See supplementary material at http://dx.doi.org/10.1121/1.4962445 for audio examples, additional plots, predicted marginal means, and R code to reproduce our figures and analyses.

5The addition of by-item random slopes for CONTEXT was not justified by the data, and by-item random slopes for voice do not seem to make sense given that each item only ever occurs with one level of voice.

6We thank John Kingston for suggesting this possible explanation.

7It is also possible that sudden post-release activation of the vocalis muscle, which Löfqvist et al. (1984) and Hutters (1985) show to be suppressed during voiceless closures in Swedish and Danish, respectively, may also contribute to raised F0 (Hoole and Honda, 2011, fn. 9).


