Aerodynamic characteristics of trills and phonological patterning

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The present study attempts to characterize the aerodynamic conditions required for the production of apical trills and to account for some universal tendencies in the patterning of trills in terms of their aerodynamic and distinctiveness requirements. In order to ascertain the aerodynamic conditions required for trills, oropharyngeal pressure ($P_o$) and airflow were recorded simultaneously in two subjects producing voiced and voiceless trills. The backpressure during trills was intermittently bled with catheters of varying diameter, and thus impedance. It was found that (1) voiceless trills show a higher $P_o$ and a larger rate of flow than voiced trills, which generates friction noise across the lingual constriction; (2) voiceless trills are more robust to changing aerodynamic conditions but less distinct auditorily, as inferred from acoustic data; (3) the $P_o$ and airflow conditions for voiced trills and fricatives show very similar values, with trills showing a narrower range of allowable variation. The behavior of trills in varying aerodynamic conditions accounts for observed phonological patterns: the universal preference for voiced trills, the alternation between trills and fricatives, trill devoicing, and the lack of nasal trills.

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1. Introduction

The present study attempts (1) to characterize the aerodynamic conditions required for the production of tongue-tip trills, focusing specifically on the range of allowable variation in oropharyngeal pressure to initiate and sustain voiced and voiceless tongue-tip trilling, and (2) to account for the phonological patterning of trills in terms of their aerodynamic and distinctiveness requirements.

This study is primarily concerned with the articulatory stability of voiced and voiceless tongue-tip trills in a variety of aerodynamic conditions. Thus, it is in line with the notion that in the study of speech sounds it is necessary to characterize a set of parameters—physiological, aerodynamic and acoustic/auditory—and their

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of variation, and a set of values along these parameters which exhibit stable relations in the articulatory and auditory domains. These “optimal settings” are the likely seat of phonological features and segments which are common cross-linguistically (Ohala, 1983; Lindblom, 1986; Stevens, 1989). Some of the gradient physiological and aerodynamic variation will tend to result in discrete changes along these parameters due to the quantal nature of speech (Stevens, 1972, 1989); thus, the articulatory robustness of speech features, specifically trilling, under different contextual and prosodic conditions can be characterized as well as their auditory distinctiveness.

Apical trills, such as [r], are sounds which are mastered late in the acquisition process (in fact, they are, along with sibilants, the last segment types to be mastered (Jiménez, 1987; Vihman, 1996)), and are not present in the babbling stage when infants are exploring the possibilities of the vocal tract, whereas other trill types—bilabial and (ingressive) uvular trills—are reported at that stage (Stark, 1980; Vihman, 1996). They present difficulties to second language learners and also to native speakers, i.e., some speakers never succeed in rolling their [r]s. All this suggests that tongue-tip trills are sounds involving a complex production mechanism requiring critical positioning of the articulators, stiffness conditions, and aerodynamic requirements. Yet they are not uncommon sounds in phonological systems: of the languages that have r-sounds, half of these (47.5%) are trills, overwhelmingly dental/alveolar trills (99.1%) (Maddieson, 1984). Ruhlen (1975) reports lingual trills in 79.5% of languages with an r-sound. The extent to which lingual trills are common also needs to be judged relative to other manner of articulation classes. The data in Maddieson (1984) show that 36.4% of the languages of the world have a trill (36.1% an apical trill), vis-à-vis, 34.3% of languages with one or more voiced fricatives, 66.9% with a voiced stop, 80.9% with a glide, 81.3% with a lateral, and 96.8% with a nasal stop. Thus, trills are not rare segments, one in every three languages has an apical trill, but have a relatively low frequency in phonological systems as compared with other segment classes, presumably because the production mechanism is quite complex.

The mechanics of tongue-tip vibration have been described by Catford (1977), Ladefoged & Maddieson (1996), Spajic, Ladefoged & Bhaskararao (1996), Barry (1997), and modelled by McGowan (1992). These authors describe trills as the vibration of certain supralaryngeal articulators (tongue-tip, uvula, lips) caused by aerodynamic forces, as opposed to taps and flaps, which involve active muscular movements of the tongue. The conditions for initiating tongue-tip trilling involve muscle contraction of the tongue to assume the position, shape and elasticity requirements, and a sufficient pressure difference across the lingual constriction. Once trilling is initiated, tongue-tip vibration is maintained as a self-sustaining vibratory system. Fig. 1 shows the oropharyngeal pressure ($P_o$), airflow, and acoustic signal for [i'ɾi] (top) and [i'ɾi] (bottom) (see Section 2.1 for data obtention procedures). In time (a) the airflow (channel 3) decreases as muscle contraction raises the tongue sides to brace the upper molars, the tongue dorsum is lowered, and the relaxed tongue-tip is critically placed near the alveolar zone (or touching it). $P_o$ (channel 1) builds up behind the linguopalatal constriction until it overcomes the mass and torsional force of the tongue-tip and causes the relaxed tongue-tip to open (time b). The air rushes out of the open channel (resulting in a burst of flow) and $P_o$ drops. The recoil effect plus the reduction of pressure along the constriction due to
Figure 1. Low-pass filtered $P_o$ (cut-off frequency 50 Hz), unfiltered mouth airflow, low-pass filtered mouth airflow (cut-off frequency 50 Hz), and waveform for [i'ri] (above) and [i'ri] (below). Lines $a$ and $c$ indicate onset of $P_o$ build-up and decreased airflow for the tongue-tip contact; line $b$ indicates onset of $P_o$ drop followed by a burst of flow on release of the contact.
the Bernoulli effect make the tongue-tip spring back to the contact position and $P_o$
starts building up (time c) and the cycle starts again resulting in a series of
vibrations. The articulatory and aerodynamic processes involved in tongue-tip
vibration are similar to those involved in vocal fold vibration (Ladefoged &
Maddieson, 1996).

Fig. 1 illustrates that voiceless trills differ from voiced trills in the nature and rate
of airflow that the tongue-tip vibration modulates. While in voiceless trills the
vibrating tongue-tip modulates a large and continuous airflow—slightly turbulent
due to impedance at the glottis—voiced trills modulate periodic vibrations in airflow
and pressure produced by the vibrating vocal folds (channel 2 in Fig. 1). Thus, the
laryngeal vibrations for voiced trills reduce the amount of air flowing into the
cavity. The acoustic waveform for voiced trills in Fig. 1 shows a low amplitude
murmur during the tongue-tip closure and a burst of periodic noise on release.
Voiceless trills show aperiodic noise during the contact and release phase.

Articulatorily, trills exhibit more predorsum lowering and postdorsum retraction
than taps, thus leaving more room for the vertical movements of the tongue-tip and
blade, and a more retracted alveolar closure (Recasens & Pallarès, 1999). In addition,
the tongue body is more highly constrained for the trill than for the tap and
the former coarticulates less with neighboring vowels (Recasens, 1991; Recasens &
Pallarès, 1999). Unfortunately, the aerodynamic forces in trills have received little
attention (but see McGowan, 1992; Solé, Ohala & Ying, 1998). Understanding the
trade-offs between articulator movements and aerodynamic forces, and their acoustic
result is essential for accounting for the phonological behavior of trills, for speech
pathology and articulatory modelling and synthesis.

Every one of the requirements of positioning, shape, articulator mass, stiffness and
pressure difference is necessary for tongue-tip trill production (Barry, 1997). Thus,
lingual trills require fine neuromotoric adjustment of these different parameters,
which accounts for their intrinsic difficulty in inexperienced (or immature, in the
case of infants) speakers. Trills are very sensitive to variations in the articulatory
and aerodynamic conditions, which may result in lack of tongue-tip vibration. Thus,
it is common that trills are realized as nontrilled variants (e.g., for Spanish: Bleua,
1999; for Toda: Spajic et al., 1996; and for Italian: Ladefoged & Maddieson, 1996).
In addition, trills alternate historically, dialectally and allophonically with taps,
approximants and fricatives (Ladefoged & Maddieson, 1996; see Section 4 below).

Aerodynamic conditions play a critical role in the production of trills, and their
pathologically (e.g., cleft palate), contextually (e.g., coarticulation, speaking rate,
etc.), or artificially (e.g., false palate) induced modification may seriously affect the
production of these sounds. The experiment reported here was designed to provide
information on the aerodynamic conditions for voiced and voiceless tongue-tip trills,
and the allowable range of aerodynamic variation in trills before their spectral
identity is compromised. The results may throw light on the role played by
aerodynamic factors in some universal tendencies in the patterning of trills. In
Sections 2 and 3, we present an experiment in which the pharyngeal pressure during
trills was varied and the associated effects on the production and acoustic properties
of trills were observed. In Section 4, we provide an account for some phonological
universals in the patterning of trills: the preference for voiced trills, the alternation
between trills and fricatives, trill devoicing and the lack of nasal trills. Section 5
presents the discussion and conclusions.
2. Method

2.1. Experimental procedure

Oropharyngeal pressure ($P_o$) during the production of trills was recorded in two trained phoneticians. MJ, the author of the paper, was a female speaker of Catalan, a language with contrastive voiced trills; and JJ was a male speaker of American English, where trills do not occur. The language background of the speakers, however, did not seem to have any bearing on the results. The speakers produced steady-state and intervocalic voiced and voiceless alveolar trills—bordering vowels were [a][a] and [i][i]—as well as prolonged trills with maximum exhalatory effort (i.e., until speakers ran out of breath). The choice of vowel context aimed at observing the stability of trills when conflicting articulatory demands for /i/ (tongue predorsum raising/fronting) are imposed on the tongue configuration for the trill (predorsum lowering/backing) (Recasens, 1991; Recasens & Pallares, 1999).

Prolonged trills were included to observe the maneuvers to sustain tongue-tip trilling with lowered subglottal pressure. A total of 120 intervocalic trills (15 repetitions $\times$ 2 glottal states $\times$ 2 vowels $\times$ 2 speakers), 20 steady-state and 20 prolonged trills (5 repetitions $\times$ 2 glottal states $\times$ 2 speakers) were produced and analyzed. Twenty uvular trills and 20 taps were also recorded for comparison. An audio signal was recorded by a Shure Prologue 14H microphone onto a DAT taperecorder. Oropharyngeal pressure was obtained (as an analog signal) by a catheter inserted into the pharynx via the nasal cavity and connected to a pressure transducer MS 100-A2 by Glottal Enterprises. The oropharyngeal pressure signal was low-pass filtered at 50Hz with a Khron-Hite filter, model 3364. The aerodynamic and acoustic data were recorded with the Windaq data acquisition system, which applies anti-aliasing filtering before sampling, and the signals were digitized at a sampling rate of 16kHz.

Oropharyngeal pressure during trills and taps was vented with catheters of circular cross-section and opening, and different cross-sectional areas (7.9, 17.8, 31.6, 49.5 mm$^2$), all 25 cm long. The catheters entered the speaker’s mouth at the side of the lips, then wound around between teeth and cheek, finally being inserted into the oropharyngeal cavity behind the back molars, as shown in Fig. 2. The catheters were vented on a random schedule; the frequency of vented vs. nonvented trills within a trial was approximately 1:4. The different size catheters were varied by block, which could have affected how subjects responded to aerodynamic perturbations. For example, anticipation of a larger vent size might have yielded a different compensation for the vent vis-à-vis a smaller vent size. The clip on the vent to release oropharyngeal pressure was operated manually by an assistant, who was separated from the subject by a screen (through which the venting tube was inserted) to avoid visual feedback. Airflow through the venting tubes was collected by fitting the different catheters securely against the Rothenberg mask (see Fig. 2). A photograph of the experimental setup is available at http://seneca.uab.es/msole/). The vent airflow traces allowed us to determine the timing of pressure venting.

The catheters venting the $P_o$ were intended to simulate variations in oropharyngeal pressure due to nasal leakage or contextual and prosodic factors (e.g., coarticulation with sounds of varying impedance, stress, speaking rate, phrasal position, etc.). However, variations in oropharyngeal pressure are not simply a
function of the cross-sectional area of the catheters (the smaller the area, the higher the impedance and the smaller the reduction in $P_o$), but of the total impedance or resistance to airflow. Impedance is also a function of the rate of flow and the properties of the channel through which the air passes (length, compliance, surface); so that the larger the amount of flow and the longer the channel, the higher the impedance. The vent tubes were all 25 cm long. The impedance of the vent tubes for the range of flow used in trills was calculated, as well as the vocal tract impedance during the production of these segments for each speaker (these are shown in Fig. 11).

Masking noise was presented to the speaker over headphones during data acquisition to minimize auditory feedback and possible compensatory adjustments. Masking noise did not appear to interfere with articulation. Kinesthetic feedback could not be eliminated and measurements were made during the first 60 ms after $P_o$ was varied to avoid the effect of compensatory maneuvers (e.g., decreasing the volume of the oropharyngeal cavity by raising the tongue body or larynx decreasing the compliance of the supraglottal walls or removing the glottal resistance). Oropharyngeal pressure was recorded and measured for the different conditions and the variation, impairment or extinction of trilling as a function of varying oropharyngeal pressure was analyzed acoustically.

Oral airflow could not be collected in the same session since the catheters venting the $P_o$ interfered with the Rothenberg mask. The same experimental setup was used to record simultaneous airflow and pressure for the same speakers and speech material in a separate session. Airflow was collected with a Rothenberg mask and a MCU-4 Pneumotachograph by Glottal Entreprises. Oropharyngeal pressure was measured simultaneously using one of the outlet holes in the mask for the pressure.

Figure 2. Schematic representation of the experimental setup for varying $P_o$. The catheter inserted through the nose and into the pharynx sampled the oropharyngeal pressure. The catheter inserted in the mouth was randomly blocked and unblocked venting the oropharyngeal pressure. Audio was recorded using a unidirectional microphone (see text).
tube. The pressure and the airflow signals were low-pass filtered at 50 Hz. The pressure values for the two recording sessions were compared for each speaker and found not to differ significantly. This allowed us to use combined data from the two sessions.

The pressure values were calibrated with a U-tube water manometer, by recording known pressure values—ranging from 0 to 16 cm H₂O, in 2 cm H₂O step changes—with a syringe. Flow values were calibrated with the help of the calibration unit of the MCU-4 Pneumotachograph by Glottal Entreprises, using values ranging from −1 l/s to +1 l/s in half a l/s step changes.

2.2. Measurements and analysis

Oropharyngeal pressure was measured in intervocalic and steady-state voiced and voiceless trills. Peak $P_o$ (in cm H₂O) was measured at the first two contacts for the trill ($I = P_o$ required to initiate trilling), and at subsequent contacts ($S = P_o$ to sustain trilling). Mean $P_o$ for trills (i.e., averaging through peaks and valleys) was also obtained. A single flow measure was made for the entire trill, rather than separating initiating and sustaining values as with pressure. The average values for flow (in l/s) were obtained with the help of Matlab over the time interval shown in Fig. 3. The segmentation criteria for measuring average $P_o$ are also illustrated in Fig. 3. The first cursor was placed at the onset of $P_o$ build up—channel 1—for the first contact for the trill (which coincides with onset of decreased airflow, channel 2) and the second cursor was at the offset of $P_o$ release for the last contact (offset of released airflow). When there were discrepancies between the channels, spectrograms were used in the segmentation decisions. Variation in $P_o$ associated with catheter venting was also measured using the same criteria.

Impedance ($Z$) at the lingual constriction during the production of trills was calculated by applying the following equation (adapted from Small, 1973, p. 31):

$$Z_{\text{supraglottal}} = \frac{P_o}{U}$$

where $P_o$ is the oropharyngeal pressure in cm H₂O, and $U$ is the volume velocity in l/s (i.e., the airflow or volume of air moving past a given point per unit of time). The values for oropharyngeal pressure and volume velocity collected simultaneously (in the second recording session) were used to calculate supraglottal impedance. The values for impedance, however, are only approximate since $P_o$ and $U$ were measured simultaneously but not at the same place (at the oropharyngeal cavity and at the lips, respectively). The impedance for the different tubes at various pressures and flowrates was determined using the same equation. The values used in these calculations were obtained in the first recording session, measuring pressure at the oropharyngeal cavity and volume velocity through the venting tubes simultaneously but not at the same place. Calibrated pressure and flow values were obtained using the calibration method mentioned above.

Trills usually involved four contacts and, less often, five or six. This is a higher number of contacts than the 2–5 contacts reported by other investigators for multiple contact trills (Blecua, 1999; Recasens, 1999). Barry (1997) and Blecua (1999) suggest that the number of contacts in a trill decreases with more casual (and faster) articulation, which suggests that trills were often hyperarticulated in such laboratory
Figure 3. Filtered oropharyngeal pressure in cmH₂O, filtered mouth airflow in l/s, and acoustic signal for an intervocalic voiced (left) and voiceless (right) trill between [a] (top) and [i] (bottom). Speaker MJ. The vertical lines mark the boundaries for measuring mean $P_o$ and flow.
conditions. Trill duration was measured on the spectrogram and $P_o$ trace from onset of the first complete tongue-tip contact (onset of decreased intensity on the spectrogram which approximately coincides with onset of $P_o$ rise) to offset of the last contact (offset of the last period of decreased energy which coincides with peak pressure of the last cycle), or from point of maximum constriction to release of the constriction for fricative realizations.

The aerodynamic and acoustic criteria for determining trill failure/impairment (i.e., fricative and approximant realizations) were the absence of distinct pressure and flow pulses, and the absence of temporal–spectral discontinuities on the spectrographic representation. The criteria for determining fricative or approximant realizations were the presence/absence of high-frequency noise on the spectrogram and of audible friction.

3. Results

The aerodynamic features of voiced and voiceless trills are analyzed first. Second, we explore the range of allowable variation in oropharyngeal pressure during the production of voiced and voiceless trills in order to determine which segment type is more highly constrained. Third, we address the aerodynamic conditions required to initiate, sustain and reinitiate tongue-tip vibration and the compensatory articulatory maneuvers to sustain prolonged trilling.

3.1. Aerodynamic characteristics of voiced and voiceless trills

In each section below we first analyze the aerodynamic differences between voiced and voiceless trills and then we consider the effect of vowel context on the aerodynamics of trills. As noted in the introduction, the laryngeal vibrations for voiced trills reduce the amount of air flowing into the oropharyngeal cavity, vis-à-vis voiceless trills. The higher rate of flow through the open glottis for voiceless trills, vis-à-vis voiced trills, resulted in the following differences.

3.1.1. Oropharyngeal pressure

Voiceless trills show a higher $P_o$ than voiced trills, as illustrated in Fig. 3, which shows oropharyngeal pressure, airflow and acoustic signal for intervocalic voiced (left panels) and voiceless trills (right panels) produced by speaker MJ. The pressure traces in channel 1 exhibit higher $P_o$ values for voiceless than for voiced trills. Average values for peak oropharyngeal pressure for steady-state and intervocalic voiced and voiceless trills for the two speakers are shown in Fig. 4 (the differences in the absolute values in the two speakers stem from the net differences in the overall size of the vocal tract). The difference in $P_o$ values for voiced vs. voiceless trills is in accordance with similar differences found for voiced and voiceless obstruents (Stevens, 1971, p. 1190, 1998) and reflects the reduced flow of air through the vibrating vocal folds for voiced sounds.

Fig. 4 also shows vowel-to-consonant coarticulatory effects in intervocalic trills. Trills in the /i/ context exhibit a higher $P_o$ than in the /a/ context, which is most likely due to the high tongue position in the /i/ context offering a higher resistance
to exiting air even when the tongue-tip is down between trill contacts. It is also possible that tongue-tip tension is higher in the [i] context, so that higher pressure is needed to make the tongue-tip vibrate.

Two-factor ANOVAs were performed for each individual speaker to evaluate the effects of voicing in trills (voiced vs. voiceless) and vowel context ([a] vs. [i]) on mean pressure values (i.e., averaged pressure values through peaks and valleys along the entire trill). The results are shown in Table I(a). For both speakers the main effects of voicing in trills and vowel context were significant at the \( p < 0.01 \) level. Interaction effects were not significant for speaker MJ but they were significant for speaker JJ. Because the interaction between the two main factors was significant for speaker JJ, one-factor ANOVAs were used to examine the differences between voiced and voiceless trills for each vowel context separately for this speaker. The voicing in trills simple main effect showed significant differences in pressure values both in the [a] \( (F(1, 30) = 135.64, p < 0.0001) \) and in the [i] contexts \( (F(1, 30) = 17.77, p < 0.001) \), with a larger difference in the low vowel condition. The ANOVA results indicate that voiceless trills show significantly higher \( P_o \) values than voiced trills, which we suggest is caused by the unimpeded flow of air through the open glottis for the former, and that trills coarticulated with high front vowels exhibit significantly higher \( P_o \) values than with low vowels.

Fig. 4 also shows that for steady-state trills the \( P_o \) required to sustain \((S)\) tongue-tip vibration is lower than that required to initiate \((I)\) (see Section 3.4 below). Two-factor ANOVAs with initiating vs. sustaining tongue-tip vibration and voicing in trills (voiced vs. voiceless) as independent variables, and peak pressure values as the dependent variable, were performed for each speaker separately. The results for the ANOVAs are shown in Table I(b). Significant main effects of initiating vs. sustaining a trill, and voicing in trills, were found for both speakers. Interaction

![Figure 4. Mean peak oropharyngeal pressure, in cm H2O, for voiced (gray bars) and voiceless (white bars) steady state and intervocalic trills for speakers MJ and JJ. The average peak \( P_o \) needed to initiate \((I)\) and sustain \((S)\) a trill is indicated in the steady-state trills. Each bar represents an average of approximately 30 observations.](image-url)
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<th>Table I. (a–d) Significant differences for the two-factor ANOVAS performed for the independent variables in the rows and the dependent variables in the columns for speakers MJ and JJ</th>
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effects also reached significance. Further analyses examined the simple main effect of initiating vs. sustaining a trill for voiced and voiceless trills separately. The differences reached significance for voiced (speaker MJ, $F(1, 46) = 59.77, p < 0.0001$; speaker JJ, $F(1, 38) = 251.11, p < 0.0001$) and voiceless trills (speaker MJ, $F(1, 46) = 78.62, p < 0.0001$; speaker JJ, $F(1, 38) = 500.51, p < 0.0001$) for both speakers, with larger differences for voiceless trills. The ANOVA results indicate that initiating a trill involves significantly higher peak pressure values than sustaining a trill, with a significantly larger difference for voiceless trills.

3.1.2. Translingual flow

Voiceless trills exhibit a higher rate of flow across the lingual constriction than voiced trills, as can be observed in Fig. 3, channel 2. Flowrate ($U$) is a function of the difference in pressure ($\Delta P$) between two cavities and the area of the aperture of the channel ($A$), $U = A (\Delta P)^a c$, where the exponent, $a$, varies between 0.5 (for turbulent flow) and 1 (for laminar flow), and $c$ is a constant. Since there is no other narrow constriction downstream, the pressure difference across the lingual constriction for trills is equal to $P_o (\Delta P_{\text{supraglottal}} = P_o - P_a$, where atmospheric pressure, $P_a$, is assumed to be 0). The larger pressure difference between the oral cavity and the atmosphere for voiceless than for voiced trills is responsible for the larger rate of flow across the lingual constriction for the former (voiceless, 1.56/s vs. voiced, 0.66 l/s for speaker JJ; voiceless, 0.58/s vs. voiced 0.20 l/s for speaker MJ). Fig. 5, which plots airflow as a function of oropharyngeal pressure in voiced and voiceless trills in

![Figure 5. Mean oropharyngeal air-pressure and mouth airflow in intervocalic and sustained voiced ([r]) and voiceless ([r]) trills for speakers MJ and JJ.](image-url)
a variety of contexts, illustrates that translingual flow increases with higher oropharyngeal pressure values ($=\Delta P$).

Fig. 5 also shows that for speaker JJ, but not clearly for MJ, trills in the [i] context have a higher rate of flow than those in the [a] context, due to the relationship between $P_o$ and flow. The higher flowrate across the lingual constriction, when trills are coarticulated with high front vowels, tends to result in the generation of some friction noise.

Two-factor ANOVAs with voicing in trills (voiced vs. voiceless) and vowel context ([a] vs. [i]) as independent variables were performed on airflow values for the two speakers separately. The ANOVA results, in Table I(a) right, show a significant effect of trill voicing on flowrate for both speakers. The main effect of vowel context, with trills between high vowels showing higher flow values than between low vowels, was significant for speaker JJ, but did not reach significance for speaker MJ. Interaction effects were significant for speaker JJ but not for speaker MJ. One-factor ANOVAs were used to examine the differences between voiced and voiceless trills for each vowel context separately for speaker JJ. Voiced and voiceless trills showed significant differences in flow both in the [a] ($F(1, 30)=559.46, p<0.0001$) and the [i] context ($F(1, 30)=204.87, p<0.0001$), with a larger difference in the low vowel context. The ANOVA results indicate that there is a higher rate of flow through the lingual constriction for voiceless as opposed to voiced trills for both speakers and for trills between high front vowels as opposed to low vowels for speaker JJ.

The larger translingual flow for voiceless trills results in a higher particle velocity ($v$) (velocity being directly proportional to flowrate, for a given aperture, $v=U/A$) and the generation of friction noise across the lingual constriction for voiceless trills, as can be observed in the audio signal in Figs. 3 and 6.

### 3.1.3. Opening and closing phases

The repeated opening and closing movements in tongue-tip vibration show a larger open to closed phase ratio for voiceless as opposed to voiced trills (1.94 vs. 1.34). Fig. 6 illustrates the shorter closure phase (indicated by a rising $P_o$ in the middle pressure trace) for voiceless than for voiced trills—most likely due to the higher oropharyngeal pressure which overcomes the resistance of the tongue-tip in a shorter amount of time—whereas the opening phase is comparable in both. The mean duration of the open and the closed phase of tongue-tip vibration for voiced and voiceless trills is presented in Fig. 7. (The difference in overall duration of the vibratory cycle results in a higher rate of tongue-tip vibration for voiceless trills, as observed in the next section.)

Two-factor ANOVAs with voicing in trills (voiced vs. voiceless) and phase (open vs. closed) as independent variables, and duration of phase as the dependent variable, were performed for each individual speaker. The results for the ANOVAs, shown in Table I(c), revealed a significant main effect for voicing, a significant main effect for phase, and a significant interaction between voicing and phase for both speakers. Because the interaction was significant, the differences between voiced and voiceless trills for the open and closed phase were examined separately. One-factor ANOVAs showed that voiced and voiceless trills did not show significant differences for the open phase (speaker MJ, $F(1, 56)= 1.11$, ns; speaker JJ, $F(1, 60)= 7.20$, ns),
but there were significant differences for the closed phase (speaker MJ, $F(1, 56)=168.02$, $p<0.0001$; speaker JJ, $F(1, 60)=240.01$, $p<0.0001$), which was approximately 30% shorter for voiceless than for voiced trills for both speakers combined.

The shorter apical contact in voiceless trills results in proportionally longer periods of released (turbulent) energy, *vis-à-vis* voiced trills. Voiceless trills also tend to show some turbulent noise during the closure (as shown in the waveform in Fig. 6). Thus, noise seems to be constantly present in voiceless trills.

Figure 6. Unfiltered $P_o$, low-pass filtered $P_o$, and audio signal for sustained voiced and voiceless trills. The tongue-tip contact phase, showing a rise in $P_o$, is indicated between the first cursor and the vertical line in the filtered $P_o$ trace (a small phase shift is present between the filtered and the unfiltered $P_o$ traces). The tongue-tip release phase is indicated between the vertical line and the second cursor.

Figure 7. Mean duration of the open and closed phase of tongue-tip vibration for voiced and voiceless trills for speaker MJ.
3.1.4. Rate of tongue-tip vibration

Voiceless trills exhibit a higher rate of tongue-tip vibration than voiced trills (29.3 Hz, range 28–33 Hz vs. 28.1 Hz, range 26–29 Hz). One-factor ANOVAs showed that the difference was significant for both speakers (speaker MJ, $F(1, 38)=35.36$, $p<0.0001$, speaker JJ, $F(1, 38)=94.19$, $p<0.0001$). Rate of tongue-tip vibration is a function of tongue-tip tension and mass, and translingual flow. The larger pressure drop and rate of flow across the lingual constriction for voiceless trills, vis-à-vis voiced trills, is consistent with a higher frequency of apical vibration. These results are in contrast with Lindau’s (1985, p. 161) finding that voiceless trills in Edo show a lower rate of vibration than voiced trills (22.5 vs. 25 Hz).

3.1.5. Trill duration

Fig. 3 shows that voiceless trills are longer than their voiced counterparts (patterning like voiced and voiceless obstruents) and exhibit more linguo-palatal contacts. In addition, trills in the [i] context are shorter and exhibit fewer contacts than in the [a] context. Two-factor ANOVAs with voicing in trills (voiced vs. voiced) and vowel context ([a] vs. [i]) as independent variables, and trill duration as the dependent variable, were performed for each individual speaker. The ANOVA results revealed a significant main effect of trill voicing with voiceless trills being longer than voiced trills, a significant effect of bordering vowels, with shorter trills for [i’ri] than for [a’ra]—and non-significant interaction effects for both speakers (Table I(d)).

Not only did trills in the [i] context proved to be significantly shorter than those in the [a] context, but also a higher rate of failing trills was found in [i’ri] than in [a’ra] sequences. This might be due to the fact that palatal vowels involve active raising of the tongue predorsum which is in conflict with predorsum lowering and postdorsum retraction required for [r] (Recasens & Pallarès, 1999). In addition, palatal vowels involve a more massive and tenser tongue-tip and blade (due to coupling effects with the active tongue predorsum) offering a higher resistance to trilling (McGowan, 1992). Shorter trills and failing trills in the [i] context have been reported by a variety of investigators (Barry, 1997; Recasens & Pallarès, 1999; Kavitskaya, 1997).

In summary, the unimpeded flow of air through the glottis in voiceless trills, vis-à-vis voiced trills, results in a higher oropharyngeal pressure and a higher volume velocity through the lingual constriction which results in the generation of friction noise. In addition, voiceless trills exhibit a longer duration and a slightly higher rate of tongue-tip vibration as opposed to voiced trills. Coarticulatory effects result in trills exhibiting a higher $P_o$ and flowrate in contact with high front vowels, vis-à-vis low vowels, as well as fewer apical contacts.

3.2. Variations in oropharyngeal pressure during trill production

In order to determine the range of allowable variation in oropharyngeal pressure in the production of trills, the backpressure during trills was intermittently bled with catheters of different cross-sectional area (as described in Section 2.1), and the articulatory and acoustic consequences were analyzed. Fig. 8 illustrates the effects of the reduction in $P_o$ associated with a 17.8 mm$^2$ vent (onset of venting is marked
Figure 8. Unfiltered $P_{io}$, low-pass filtered $P_{io}$, and audio signal during the production of sustained voiced (a) and voiceless (b) trills. The unblocking and blocking of the catheter (area 17.8 mm$^2$) are indicated by arrows.
Sustained voiced trilling (top panel) is extinguished on vent, resulting in a nonsibilant postalveolar fricative, as determined from auditory and spectrographic analysis, whereas voiceless trilling (bottom panel) is maintained, with peak $P_o$ noticeably reduced and the amplitude of the acoustic energy greatly diminished as can be observed on the waveform. Thus, for a given vent, trilling was extinguished earlier in voiced trills than in voiceless trills. Tongue-tip vibration was extinguished into a fricative/approximant as the reduction in $P_o$ diminished the rate of flow through the oral constriction and the magnitude of the Bernoulli effect, which was not sufficient to suck back the tongue-tip to the contact position. Fig. 8 shows that blocking of the tube (marked by the rightmost arrow) restores the original pressure conditions and associated acoustic effects in voiceless trills, but trilling fails to reinitiate in voiced segments.

Fig. 9 displays an intervocalic trill under normal pressure conditions (left), and with a vent area of 7.9 mm$^2$ (right), where the reduced $P_o$ impairs tongue-tip vibration resulting in a nonsibilant voiced postalveolar fricative. Intervocalic trills seemed to be more resistant to pressure changes between open vowels than between high front vowels. A one-factor ANOVA with vowel context ([i] vs. [a]) as independent variable and number of failing voiced trills (i.e., fricative/approximant realizations) when vented with tubes 1 and 2 (tubes 3 and 4 extinguished intervocalic trills irrespective of vowel context) as the dependent variable were performed for each individual speaker. The results showed that trills in the [i] context were extinguished significantly more often than in the [a] context for speaker JJ ($F(1, 18)=36, p<0.0001$), but not for speaker MJ ($F(1, 20)=0.16$, ns). The lesser robustness of trills in the [i] context for speaker JJ is most likely due to increased tension and mass of the tongue-tip due to coarticulation with the high front vowel, rather than to intrinsic differences in $P_o$ of trills in different vowel contexts (which would
in fact predict a smaller percentage pressure change in the [i] context, due to the higher $P_o$).

The reduction in $P_o$ associated with venting the backpressure with catheters of different areas is presented in Fig. 10. The extinction of trilling is indicated by a dashed line. When $P_o$ dropped below a certain threshold, trills were extinguished resulting in a fricative (a nonsibilant voiced postalveolar fricative in the case of voiced trills, and a [h] sound for voiceless trills) or an approximant with catheters of larger areas ($\geq 31.6 \text{ mm}^2$). The threshold for trilling was determined empirically by measuring the pressure values at which tongue-tip vibration ceased on vent. Thus, for example, Fig. 10 shows that for speaker MJ a vent of 7.9 mm$^2$ reduced the $P_o$ in voiced trills below 4 cm H$_2$O and extinguished sustained voiced trilling. The same vent aperture did not extinguish voiced trilling for speaker JJ who exhibited higher pressure values. A vent of 17.8 mm$^2$ extinguished voiced trilling in both speakers. It is not possible to report absolute pressure values at which trilling was impaired, since the minimum oropharyngeal pressure required for tongue-tip vibration varies depending on initial conditions (articulator tension, mass, cavity volume, articulatory position, compliance of the supraglottal walls, etc., McGowan, 1992). It was found that a pressure drop of 2.5–3.5 cm H$_2$O impaired sustained trilling in voiced segments. A larger pressure drop, 5 cm H$_2$O, was needed to impair voiceless trills. Thus, voiceless trills are more resistant to variations in $P_o$ due to a higher $P_o$ which allows a larger reduction in pressure before reaching the minimum pressure drop across the lingual constriction required for trilling. The fact that during voiceless trills the glottis is open and thus there is less resistance to air flowing from the lungs to the oral cavity, vis-à-vis voiced trills (i.e., the air vented may be more readily

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure10.png}
\caption{Intraoral pressure in sustained voiced (gray lines) and voiceless (black line) trills for speakers MJ and JJ, when vented with catheters of different cross-sectional areas. The threshold at which trilling is sustained is indicated by a dashed line. The “unvented” condition shows the mean of 15 observations. The number of observations for each of the “vented” conditions varies between 3 and 8 (mode = 5).}
\end{figure}
resupplied from the pulmonic air reservoir), may contribute to venting not having as much effect on the lingual pressure drop in voiceless trills.

Fig. 11 exhibits the values for impedance (i.e., resistance to exiting airflow) at the oral constriction (dashed lines) for voiced and voiceless trills. It also shows the impedance of the catheters at the lower and upper flowrates found in trills (i.e., the rates of flow used in the production of intervocalic trills ranged from 0.206 to 0.581 l/s, the impedance of the catheters at these two extremes of flowrate was calculated and the values are shown in the bars). Comparison of Figs 10 and 11 shows that venting voiceless trills with catheters with a higher impedance (7.9 and 17.8 mm² area catheters, Fig. 11) than that at the oral constriction did not affect trilling (Fig. 10) since airflow exited through the lingual aperture, with lower impedance, and translingual flow was not noticeably affected. Catheters with values for impedance similar (31.6 mm² area) to those at the oral constriction extinguished voiceless tongue-tip trilling in speaker MJ but not in speaker JJ, who showed higher $P_0$ values. Larger area catheters ($\geq 49.5$ mm²), with a lower impedance than that in the vocal tract, extinguished voiceless trilling, since airflow exited through the aperture with lower impedance, thus reducing the required pressure drop across the oral constriction for tongue-tip vibration.

**Voiced trills** were adversely affected for a smaller vent diameter than voiceless trills. Voiced tongue-tip trilling was extinguished not only when vented with catheters with values for impedance similar to or lower than impedance at the oral constriction (catheter areas $\geq 31.6$ mm²), as for voiceless trills, but also when vented with catheters with substantially higher impedance (areas 7.9 and 17.8 mm²), most probably due to bleeding of $P_0$ below the threshold necessary for trilling. Thus, voiced trills allow a narrower range of $P_0$ variation and have more highly constrained aerodynamic requirements than voiceless trills.

**Figure 11.** Impedance of catheters of different cross-sectional areas calculated at the minimum and maximum flowrates used in trill production for speaker MJ. The impedance of the vocal tract for voiced and voiceless trills, averaged over all the repetitions, is shown by the horizontal dotted lines.
Other aerodynamic properties of vented and unvented trills were analyzed, specifically, effects of variations in translingual and transglottal flow. A reduction in $P_o$ due to venting with the catheters was expected to result in a reduced translingual flow and a lower rate of tongue-tip vibration on vent. The differences in rate of apical vibration between vented and unvented trills, however, were not found to differ significantly for any of the two speakers. Occasionally, however, when trilling was imperilled due to venting, the frequency of tongue-tip vibration increased, most probably reflecting the vibration of a smaller portion (or just one side) of the tongue-tip/blade. Similarly, since changes in $P_o$ affect the rate of flow through the glottis, it was expected that a reduction in $P_o$ due to venting would result in a larger pressure difference across the glottis and an increased rate of laryngeal vibration ($f_0$) when trills were vented. The differences in $f_0$ between vented and unvented trills, however, did not reach significance.

3.3. Range of aerodynamic variation in voiced trills

The results in the preceding section show that voiced trills are more severely affected by changes in oropharyngeal pressure than voiceless trills, that is, they allow a narrower range of $P_o$ variation. Indeed voiced trills involve very precise aerodynamic conditions in order to maintain trilling and voicing. They require a high oropharyngeal pressure and a pressure difference across the oral constriction sufficient to set the tongue-tip into vibration. A high oropharyngeal pressure, however, tends to impair the transglottal flow required for voicing. Thus, the range of $P_o$ variation for voiced trills is bounded by the requirements for translingual flow needed for trilling and those for transglottal flow needed for voicing.

The allowable range of aerodynamic variation for voiced trills can be estimated from aerodynamic data. A pressure drop across the oral constriction of at least 4 cm H$_2$O (depending upon tongue-tip tension and mass) and a minimum volume velocity of about 0.200 l/s were found to be needed to sustain trilling. Transglottal flow for voicing requires a minimum pressure drop of 2–3 cm H$_2$O, and a minimum volume velocity of 0.050 l/s (Catford, 1977, p. 98). To estimate the allowable range of $P_o$ variation, the peak oropharyngeal pressure during voiceless trills was used as an estimate of subglottal pressure ($P_s$). Subject MJ had a peak $P_o$ of approximately 7.4 cm H$_2$O for intervocalic voiceless trills (vowel contexts pooled), which we will assume to be the average value of $P_s$. If transglottal flow for voicing requires a pressure drop across the glottis ($P_s - P_o$) of at least 2–3 cm H$_2$O, that leaves a $P_o$ of at most 5.4 cm H$_2$O, as schematically shown in Fig. 12. Trilling requires a minimum pressure drop of 4 cm H$_2$O across the oral constriction to sustain tongue-tip vibration (and a larger pressure drop to initiate it), which means that $P_o$ may vary between a rather narrow range of 5.4–4 cm H$_2$O in order to sustain voicing and trilling (the actual average $P_o$ value for speaker MJ was 5.39 cm H$_2$O). The estimation of the range of $P_o$ variation for speaker JJ was between 11 and 8 cm H$_2$O. Thus, the $P_o$ range to sustain voicing and trilling is very narrow, and small pressure variations may lead to devoicing or cessation of trilling, as attested in a number of languages (Ladefoged & Maddieson, 1996, Sections 4.3 and 4.4 below). (A similar argument has been made by Ohala (1983) to account for the difficulty in maintaining voicing and frication.) Such severe aerodynamic constraints are not present in voiceless trills.
The conditions for initiating tongue-tip trilling involve (i) muscle contraction of the tongue to assume the position, shape and elasticity requirements, and (ii) a pressure difference ($D_P$) across the oral constriction sufficient to overcome the resistance of the tongue-tip and to set it into vibration. Once trilling is initiated by muscle action and aerodynamic forces (McGowan, 1992), tongue-tip vibration is maintained as a self-sustaining vibratory system. The pressure values reported in Fig. 4 show that the pressure difference required to initiate tongue-tip trilling is approximately 2 cm H$_2$O higher than that required to sustain it (similar to reported differences in pressure drops necessary to initiate and maintain vocal fold vibration (Westbury & Keating, 1986)). Once the tongue-tip starts vibrating, it continues vibrating as long as there is a pressure difference of 4 cm H$_2$O across the lingual constriction. However, a higher pressure difference (approximately 6 cm H$_2$O) is needed to initiate tongue-tip vibration, due to the need to overcome inertial effects. Thus, there is a narrow region of values of the aerodynamic parameters where tongue-tip vibration cannot be initiated, but once started, can be maintained. The higher $P_o$ needed to initiate tongue-tip vibration than to sustain it, may explain the significantly longer duration of the first contact for the trill (to allow higher pressure build-up as air continues to flow through the glottis) than of subsequent contacts found by Blecua (1999). The first closure period for the trill also involves more alveolar contact than subsequent contacts (Recasens & Pallarès, 1999), reflecting the muscular activation and positioning of the tongue to initiate a trill, as opposed to the exclusive aerodynamic forces involved in sustaining a trill. Thus, initiating a trill involves greater targeting of tongue contact and release which is not just the result of aerodynamic and muscular forces.

It was found that when sustained trilling was extinguished into a fricative or an approximant, due to venting the backpressure with the catheters, in the majority of cases tongue-tip trilling did not reinitiate when the aerodynamic conditions for sustaining trills were restored (by blocking the catheter). This is consistent with the finding that the pressure difference required to initiate tongue-tip trilling is higher

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**Figure 12.** Estimated range of oropharyngeal pressure ($P_o$) in cm H$_2$O for voiced trills for speaker MJ. Subglottal pressure ($P_s$), atmospheric pressure ($P_a$), and the minimum pressure difference ($\Delta P$) across the glottis and across the lingual constriction, required for voicing and trilling, respectively, are indicated.
than that required to sustain it. Alternatively, failure to reinitiate trilling may reflect
differences in the initial tongue positioning or bracing for trills and fricatives.

The role played by initial pressure and articulatory conditions in trill production
is illustrated in Fig. 13, which exhibits initiation of trilling on vent (a), and failure to
sustain trilling in comparable pressure conditions (c) or to reinitiate trilling with
increased $P_o$ (d). The physiological adjustments (in cavity volume, mass and/or
tension of the vibrating articulator, vocal tract compliance) to compensate for the
initial pressure conditions (on vent) in (a), are most likely relaxed when $P_o$ is
reestablished in (b). When $P_o$ is further reduced in (c), trilling cannot be sustained
with the existing articulatory conditions. Similarly, trilling cannot be reinitiated
when $P_o$ is reestablished in (d). This illustrates the trade-off between pressure and
articulatory conditions in initiating and sustaining a trill. The likely dropping of
subglottal pressure through the time of the signals shown may contribute to the
difficulty in restarting the trill; however, the difficulty to reinitiate trilling was found
with all venting patterns, regardless of time factors.

In the cases where lingual vibration did reinitiate (usually when the venting period
was very short) it generally did so through a transitional fricative, most likely
reflecting the increase in $P_o$ and in volume velocity before the Bernoulli force and
the muscular tension in the tongue closed the alveolar channel. The extinction and
reinitiation of trills into a fricative suggests that the aerodynamic range of variation
for trills is narrower than for fricatives.

Figure 13. Unfiltered $P_o$, filtered $P_o$, airflow through the venting tube, and
audio signal for a sustained voiced trill for speaker MJ. (a) Trilling is initiated
on vent (vent area 17.8 mm$^2$); (b) the catheter is blocked; (c) extinction of
trilling on vent; (d) the catheter is blocked.
In prolonged trills, tongue-tip vibration was sustained as long as sufficient airflow was available. When $P_s$ (and consequently $P_o$) diminished, thus endangering trilling, two possible outcomes were found: extinction of trilling into a fricative and/or devoicing (obviously, the devoicing option was only available for the voiced trill). In the great majority of cases, the trill decayed into a fricative as airflow through the lingual constriction dropped, due to diminished $P_s$. In a few cases, the voiced trill or the resulting fricative were further devoiced. Devoicing can be considered a maneuver to directly access $P_s$ by removing the resistance at the glottis in order to prolong trilling. Fig. 14 illustrates a prolonged trill which is extinguished into a fricative on vent, time (a), and is further devoiced, time (b), when $P_s$ and $P_o$ are lower (the diminished $P_o$ can be observed in channel 2).

In contrast to trills, which were extinguished when $P_o$ was vented by approximately 2.5–3.5 cm H$_2$O, taps continued to exist on vent. Fig. 15 illustrates a series of taps in normal pressure conditions and vented with catheters of different cross-sectional areas. When taps are vented in (a), airflow escapes through the catheters affecting the $P_o$ build-up during the closure, but taps continue to exist as can be observed in the waveform. The only noticeable feature of vented taps is the increased amplitude of the signal during the closure phase, which can be observed on the waveform, resulting from pseudo-nasal leakage through the catheter. The original pressure and acoustic conditions are restored when the catheter is blocked at time (b). The fact that taps are not crucially affected by changing pressure conditions whereas trills are, illustrates that the two sounds involve different primary energy forces: aerodynamic vs. muscular.

4. Phonological patterns

The behavior of trills in varying aerodynamic conditions parallels common processes and alternations found in languages (e.g., trill devoicing, detrilling, trill frication) and can account for observed phonological patterns.

4.1. Absence of nasal trills

A phonological universal involving trills is the absence of nasal trills (Maddieson, 1984). The non co-occurrence of trilling and nasality is dictated by aerodynamic reasons. An open velopharyngeal port for nasality would bleed the intraoral pressure required to make a relaxed oscillator vibrate for trills, as shown in the experiment where trilling ceased when $P_o$ was vented with catheters that simulated nasal leakage (Section 3.2). It has been shown that lingual trills require a high intraoral pressure ($\geq 4$ cm H$_2$O) to sustain tongue-tip vibration (and even higher values to initiate it), and that trilling was extinguished when the oropharyngeal pressure was reduced by 2.5 cm H$_2$O. Thus, trilling cannot combine with an open velopharyngeal port that reduces the $P_o$ by 2.5 cm H$_2$O or more (vent areas $\geq 7.9$ or $17.8 \text{mm}^2$, depending on absolute $P_o$ values). The small velopharyngeal openings

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1Given the greater length of the catheters (25 cm), and consequently their higher impedance, vis-à-vis the nasal passage through which nasally vented air would pass naturally (11–13 cm), a given catheter cross-sectional area may correspond to a smaller velopharyngeal opening.
which do not impair trilling (<7.9 mm²) would most likely be insufficient to create a percept of nasalization. A greater coupling between the oral and the nasal cavity is needed for vowels and sonorants to be perceived as nasalized. Work by Maeda (1993) suggests that a robust percept of nasalization requires an opening of 40 mm² or more for vowels. Consequently, if impedance at the velopharyngeal port is high

Figure 14. Unfiltered $P_o$, filtered $P_o$, audio signal, energy plot, and spectrogram for a prolonged voiced trill. (a) and (b) are the times of venting (at which trilling is extinguished) and devoicing, respectively.
enough not to affect tongue-tip trilling, the trill will not sound nasalized. Thus, aerodynamic factors explain the lack of nasal trills.

Nasal taps (as in American English 'winter') are, however, possible due to their ballistic muscular contraction being compatible with velopharyngeal opening.
Similarly, the sound change /n/ → /ɾ/ in Middle Indo-Aryan (Skt. *manah > dial. MIAr. mano [maño] (Hock, 1986, p. 82)), and /n/ → /ɾ/ in Rumanian, presumably through [ɾ] (Rosetti, 1978; Sampson, 1999), results from a rapid and short ballistic apical contact for /n/ and illustrates the compatibility between taps and nasality.

4.2. Preference for voiced trills

The statistical preference for voiced over voiceless trills is evidenced in phonological inventories and the tendency of voiceless trills to disappear historically. Trills are mostly voiced in the languages of the world; only 1.5% of the trills are voiceless (Maddieson, 1984; Ruhlen, 1975). This is a lower percentage than for other voiceless sonorants (3.17% for nasals, approximants and liquids). Voiceless trills tend to disappear historically, merging with /ɾ/s or fricatives, mostly /h/. An example is Proto-Tai *hr-, a voiceless tongue-tip trill, which developed into /ɾ/ in Northern dialects (e.g., Wu-ming rek ‘cauldron’), and into /h/ in Central and South Western dialects (Lungchow heek, Nung hek). Voiceless /ɾ/ has only been preserved in the SW dialect Lü as a literary pronunciation for common h- in ordinary speech (Li, 1977, 142, 148ff).

The preference for voiced over voiceless trills cannot be accounted for exclusively in aerodynamic terms. The quantal theory of Stevens (1972, 1989) states that speech sounds and features maintain a balance between stable articulatory gestures and robust auditory properties. Quantal theory implies that the features, and combinations of features, more likely to be used in phonological systems are those where variations in production result in a constant acoustic output. According to the stability of the output criterion, voiceless trills should be preferred since (i) they are more robust to variations in air pressure—venting of $P_o$ and diminished $P_s$—due to their direct access to $P_s$ through the open glottis (Sections 3.2 and 3.4), and (ii) they are not constrained by the aerodynamic requirements to sustain vocal fold vibration (Section 3.3). Auditorily, however, voiceless trills are poorly differentiated from fricatives, as shown in Fig. 16 where contrastive voiced and voiceless trills for Lai-chin (top) and Icelandic (bottom) are shown. The utterances shown in Fig. 16 were recorded by a native speaker of Lai-chin and a native speaker of Icelandic, both graduate students at the University of California, Berkeley, who read sentences containing contrastive voiced and voiceless trills. The acoustic data were recorded in the same conditions as described in the method section. Fig. 16 shows that voiceless trills involve strong turbulent energy at almost all points in time in the mid-high-frequency region (2–6kHz), usually showing a peak around 3kHz. The long-term average spectra in Fig. 16 (top), computed over the length of the voiced and voiceless trill, respectively, show predominance of mid- to high-frequency noise components for the voiceless trill as opposed to low-frequency periodic components for the voiced trill. Thus, voiceless trills are acoustically and auditorily close to fricatives. The observed aerodynamic and articulatory characteristics of voiceless trills, vis-à-vis voiced trills (glottal friction; higher $P_o$ and larger flowrate across the oral constriction; and larger ratio open to closed phase of tongue-tip vibration) contribute to turbulent energy throughout the sound which makes them auditorily fricative-like, as shown in the figures (this is in line with the observation of Ohala (1997) that voiceless sonorants tend to become fricatives).
Figure 16. Waveform, long-term average spectra for the voiced (left) and voiceless (right) trill (derived from averaging 512-point FFTs between the onset and offset of the trill), and spectrogram for the Lai-chin words [ʔna riŋ] “Hna-ring” (name of village) and [saː riŋ] “fresh meat” (above). Waveform, energy contour and spectrogram for Icelandic [þeɪr ‘seɪja ‘rɑːnɑː] ‘they say trunks’ and [þeɪr ‘seɪja ‘rɑːnɑː] ‘they say boors’ (below). The analysis filter for the spectrograms is 300 Hz.
The reduction in transglottal airflow associated with voiced trills makes them less preferable aerodynamically, but contributes to a regular alternation of bursts of periodic energy. Such temporal–spectral discontinuities result in an auditorily distinct signal. In Fig. 16 the voiced trill in Lai-chin (top panel) shows three clear contacts followed by bursts of energy and a subsequent decrease in intensity due to the tongue-tip approaching a closure. The Icelandic voiced trill in ranar “trunks” (bottom panel) exhibits two clear contacts followed by bursts of periodic energy; the temporal modulation of energy for the voiced trill can be clearly observed in the energy plot. Thus, voiced trills exhibit severely constrained aerodynamic requirements and little articulatory stability vis-à-vis voiceless trills, but result in a clearly modulated signal, distinct from other speech segments. The co-occurrence of trilling and voicing can be seen as the natural byproduct of “auditory distinctiveness”.

The preference for voiced trills in phonological systems seems to reflect a trade-off between articulatory stability (i.e., preserving trilling in a narrow range of aerodynamic conditions, as opposed to voiceless trills) and acoustic/auditory saliency (i.e., distinct signal modulation).

4.3. Alternation and co-occurrence of trilling and frication

A common cross-linguistic pattern is the alternation and co-occurrence of trilling and frication. Fricatives and trills tend to alternate synchronically and diachronically (Solé, 1992). Synchronically, apical trills exhibit nontrilled variants, taps, approximants, and fricatives. Fricative (and approximant) allophones of trills result when the vibrating tongue-tip fails to make contact with the palate, or apical vibration fails to occur, which allows the high velocity air to flow continually through the aperture generating friction. Nontrilled fricative variants have been reported in continental Spanish (Navarro Tomás, 1980, p. 117) and American Spanish (Zlotchew, 1974), Toda (Spajić et al., 1996, p. 8), and Standard Swedish (Lindau, 1985, p. 164). Diachronically, trills developed into fricatives in Tai dialects (Li, 1977; pp. 86, 118, 225).

Trilling also tends to co-occur with frication, mostly in devoiced trills. Trills with associated frication are most commonly uvular trills (in Southern Swedish, Standard French and Standard German (Lindau, 1985; Ladefoged & Maddieson, 1996)), but apical trills involving frication have been reported in Toda (Spajić et al., 1996, p. 14–15) and Spanish (Blecua, 1999, p. 124). Fig. 17 illustrates trill frication in the intervocalic trill in “correr”, and devoicing of the prepausal /r/, for a Mexican speaker. The intervocalic trill shows frication on the devoiced release of the first two linguo-palatal contacts. The final trill is mostly devoiced, most likely due to utterance-final subglottal pressure reduction, and shows frication throughout.

Our experimental conditions replicated the phonological variation between voiced trills and fricatives. The results in Sections 3.2 and 3.4 show that (i) when oropharyngeal and subglottal pressure were reduced below a certain threshold trilling was extinguished into a fricative (or an approximant with larger pressure drops); (ii) trills may reinitiate as a fricative sound; and (iii) “failing” trills—due to changing aerodynamic conditions, imperfect articulatory positioning or increased tongue-tip tension and mass—result in a fricative. Thus, trills seem to have very similar but more constrained aerodynamic and articulatory requirements than fricatives.
The similarities between fricatives and voiced trills are aerodynamic and muscular. Voiced trills and fricatives show similar pressure and airflow values. In Fig. 18, taken from Stevens (1971), a contour has been added to show the normal region of flows and pressure drops for voiced and voiceless trills. The region for voiced trills overlaps the region for fricatives. The region for voiceless trills shows flow rates similar to those of aspirated sounds. The degree of neuromotoric control and combined muscle contraction for trills is similar to that used in fricatives (Hardcastle, 1976, p. 132). There are three main differences between trills and fricatives: the tongue may be less stiff in trills since otherwise vibration would not be possible; in order to provide sufficient room for the vertical vibration of the tongue-tip there is greater predorsum lowering and postdorsum retraction in trills than in alveolar fricatives (Recasens & Pallarès, 1999); and, as indicated in Section 3.4, there are differences in tongue-tip positioning and bracing.

The perceptual similarity between trills and fricatives is evidenced by the same sound being reported as a trill or a fricative by different investigators (Ladefoged & Maddieson, 1996, p. 241), and by the substitutions for the lingual trill by infants and adult native Spanish speakers who cannot make a trill—intended lingual trills are rendered as a voiced postalveolar nonsibilant fricative or approximant [ɾ], a uvular fricative [ʁ], or a dento-alveolar fricative [ɹ] (Miras Martinez, 1992), but not [w].

In short, the results from the experiment (along with sound substitutions) show that trills may become fricatives if the finely controlled articulatory or aerodynamic requirements for trills are not met, suggesting that fricatives involve a less complex articulation and allow a wider range of $P_o$ variation than trills. The reinterpretation
of fricative variants of trills as the manifestation of phonological fricatives helps to explain the dialectal and diachronic changes in Tai (and in Slavic languages, Section 4.5).

4.4. Trill devoicing

Voiceless allophones of trilled /r/, mainly in utterance final position, have been reported in a number of languages (e.g., for American Spanish: Quilis, 1981, p. 301; Canfield, 1981, p. 7; for Brazilian Portuguese: Silva, 1966; and for Farsi: Ladefoged & Maddieson, 1996). The narrow aerodynamic requirements to sustain tongue-tip trilling and vocal fold vibration (Section 3.3) were seen to result in the cessation of voicing (or cessation of trilling). Decreased subglottal pressure in utterance final position endangers trilling (Section 3.4), and the vocal folds might begin to vibrate inefficiently which would increase the flow of air from the lungs that is required to sustain trilling. Thus, we suggest that devoiced allophones of /r/ utterance finally can be seen as a consequence of sustaining trilling with lowered subglottal pressure by reducing the glottal resistance to the flow of air from the lungs. Similarly, rapid increases in $P_o$ during tongue-tip contact in trills may impair the sufficient pressure drop for voicing, and result in devoicing during the closure interval of trills (Ladefoged & Maddieson, 1996, p. 221). Thus, small variations in $P_o$ may result in devoiced allophones.
The precise articulatory and aerodynamic requirements of lingual trills allow little coproduction and overlap with conflicting neighboring segments if trilling is to be preserved. The antagonistic articulatory and stiffness requirements of apical trills and palatals (observed in Section 3.1.5) are at the origin of the historical depalatalization of palatalized trills, \([r^p]=[r]\), in Belorussian, Slovak, Serbo-Croatian and Macedonian (Carlton, 1991). Alternatively, palatalization may be preserved and tongue-tip trilling may be lost, resulting in a tap or a fricative (e.g., Proto-Slavic *tsarja ‘Czar’ > Czech [taɾa], Polish [tasza] (Carlton, 1991). Nontrilled variants of palatalized trills have been reported in Toda (Spajic et al., 1996) and Bantu languages (Tucker, 1929).

Along the same lines, trills tend to assimilate conflicting neighboring segments (e.g., /z, s, dz/ + /r/>[r] in Catalan (Recasens, 1993) and Portuguese (Vázquez Cuesta & Mendes de Luz, 1971); /s, θ/ + /r/>[r] in Spanish (Navarro Tomás, 1980)). The early onset of the lingual movements for the trill to attain the constrained positioning, tongue configuration and aerodynamic requirements for tongue-tip vibration affect the articulatory and aerodynamic conditions for generating audible turbulence for the fricative, resulting in fricative to trill assimilation, e.g., Catalan les Rambles “the Ramblas” [laɾəˈmabləs]. Interestingly, if the fricative is not assimilated, the /r/ is not trilled, e.g., [laɾəˈmabləs], suggesting that the two conflicting segments cannot be coproduced (Solé, 1999, 2002).

The rather unique phonological patterning of apical trills reflects the precise production requirements for tongue-tip trilling. In contrast with most other sonorants and rhotics (i.e., taps and uvular trills), apical trills do not combine with other consonants to form consonant clusters. Coproduction of trills with tautosyllabic obstruents would affect the narrowly constrained lingual and aerodynamic requirements for tongue-tip trilling. In addition, apical trills exhibit a limited pattern of contrast with taps. In Spanish, Catalan, Portuguese and Italian, trills only contrast with taps intervocally in syllable onset position (e.g., Catalan and Spanish para/parra ‘stop’/‘vine’, syllabified pa-ra, pa-r-ra, Recasens, 1993; Harris, 1969), where the precise requirements for trilling can optimally be met. Coproduction with adjacent consonants and coda position (which involves larger gestural reduction (Byrd, 1996; Krakow, 1993)) could disrupt the narrowly constrained postural and aerodynamic conditions for trilling and the contrast may be lost.\(^2\) Along the lines of Steriade (1996), it can be suggested that production requirements determine positions of contrast.

\(^2\)The need to maintain perceptual distinctiveness in phonological contrasts is illustrated in Spanish and Catalan word-final rhotics. A coda rhotic may optionally be trilled in rather deliberate speech, because there is no contrast between the trill and the tap word finally, (1) and (2) below for Spanish. Crucially, trilling is not possible before vowel-initial words (Harris, 1983, pp. 70–71), (3) below, to avoid perceptual confusion between contrastive trills and taps in this position. The allophony of final rhotics has been taken as evidence that Spanish coda consonants are resyllabified as onsets when followed by vowel-initial words (Kenstowicz, 1994, p. 281) and thus there is potential contrast between the tap and the trill.

(1) **ser**  
\([\text{ser}]\approx [\text{ser}]\)  
“to be”

(2) **ser feliz**  
\([\text{serfe}ˈliθ]}\approx [\text{serfe}ˈliθ]}\)  
“to be happy”

(3) **ser amigos**  
\([\text{seraˈmivos}]\approx *[\text{seraˈmivos}]\)  
“to be friends”
5. Discussion and conclusions

This study provided empirical evidence on the aerodynamic conditions required for tongue-tip trilling. The results show that voiced trills exhibit highly constrained aerodynamic requirements, in order to preserve tongue-tip vibration and laryngeal vibration, and that small variations lead to cessation of trilling or devoicing. It was found that gradual reductions in $P_o$ extinguished voiced trills earlier than voiceless trills. A pressure drop of 2.5–3.5 cm H$_2$O impaired voiced trilling whereas a larger pressure drop, 5 cm H$_2$O, was needed to impair voiceless trills, which indicates that voiced trills are less robust to variations in $P_o$. Trills extinguished into a fricative and reinitiated (if they did) through a transitional fricative, which indicates that the $P_o$ range of variation for trills is narrower than for fricatives. Tighter aerodynamic requirements (i.e., higher pressure build-up) were found, and more precise targeting of tongue-tip contact (i.e., greater magnitude of linguo-palatal contact and longer duration of the first contact) was inferred from articulatory data, for initiating than for sustaining tongue-tip trilling.

In addition, the phonological patterning of trills has been shown to reflect the constraints imposed by the physics and physiology of the speech production system, or to optimize competing requirements of perception and articulation. Thus, voiced trills have been shown to have narrower aerodynamic requirements and to be less stable articulatorily than voiceless trills, but to exhibit a clearly modulated signal, clearly distinct from other speech segments, whereas voiceless trills are acoustically and auditorily similar to fricatives. The statistical preference for voiced trills in phonological systems thus reflects a trade-off between competing demands of perception and production: preserving maximum auditory distinctiveness in a narrow range of aerodynamic conditions.

The common alternation and co-occurrence of trilling and frication result from similar production characteristics (aerodynamic, muscular and positional), with tongue-tip trilling having more highly constrained requirements which may be easily imbalanced resulting in continuants. Devoicing of utterance final trills can be seen as a consequence of maintaining trilling with lowered subglottal pressure by removing the glottal resistance. Finally, the absence of nasal trills has been shown to be dictated by the incompatibility of maintaining the relatively high oropharyngeal pressure needed for trilling with an open velopharyngeal port required for nasality.

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