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Phonological Universals: Trilling, Voicing, and Frication

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1. Introduction. This paper addresses the issue of why certain combinations of features, phonological patterns, and segment contrasts, are statistically preferred over others in the languages of the world. The principles that determine such universal preferences have been recognized as deriving from the physical and auditory properties of speech features (Ohala 1974, 1983; Lindblom 1983, 1990; Westbury and Keating 1986). In this view, the sound patterns which are more likely to be used in the world's languages are those reflecting the physical constraints of the speech production mechanism (and, consequently, not involving extra adjustments and increased articulatory cost), and having efficient acoustic consequences (*i.e.*, resulting in auditorily salient and distinct signals); or those representing an optimal balance between competing demands of perception and articulation.

The constraints of the speech production and perception mechanisms underlie the notions of 'gestural economy' and 'auditory distinctiveness' which define the combination of features into possible speech segments and their likelihood. For example, the feature values [+nasal] and [+fricative] do not co-occur due to *physical* constraints; a sufficient velo-pharyngeal port opening to create the percept of nasality would bleed the volume velocity of airflow required to create friction (Ohala, Solé and Ying 1997). Poor *auditory* result (as measured from confusion coefficients or dephonologization) can be evoked to account for the relatively low incidence of voiceless nasals, where the amplitude modulation for nasals is impaired by voicelessness. Conversely, some combination of features enhance the acoustic/auditory image, *e.g.*, the combined action of [+back] and [+rounded] heighten F2 lowering (Perkell *et al.* 1993), which is in line with the universal preference to round back vowels.

In this paper, we address the co-occurrence of tongue tip trilling with voicing, frication and nasalization. Exploring the physical and auditory properties of trills will allow us to account for their possibilities of combination with other features. The present study attempts (1) to characterize the aerodynamic conditions required for the production of lingual trills, specifically, the range of allowable variation in pharyngeal pressure to initiate and sustain trilling, and (2) to account for the combination of trilling with other speech events in terms of its aerodynamic and perceptual requirements. We address the questions of whether it is more 'natural' for trills to be voiced, why trilling tends to alternate with frication across languages, and why there is a lack of nasal trills.

This study is in line with the notion that in the search for universal patterns it is necessary to characterize a set of parameters -- physiological, aerodynamic, and acoustic/auditory -- their range of variation, and a set of categorial values along these parameters which exhibit stable relations in the articulatory and auditory domains. These categories or 'optimal settings' are the more likely seat of segments which are common cross-linguistically (Stevens 1989, Lindblom 1986, Ohala 1983). 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), are not present in the babbling or 'vocal play' stage in infant vocal production when they are exploring the possibilities of the vocal tract (Stark 1980)[1], and present difficulties to second language learners and also to native speakers, *i.e.*, some speakers never succeed in rolling their [r]s, which suggests that they are sounds involving a complex production mechanism requiring positioning of the articulators, stiffness conditions, and aerodynamic requirements. Yet they are not uncommon sounds in phonological systems, half (47.5%) of the r-sounds in the languages of the world are trills, overwhelmingly dental/alveolar trills (Maddieson 1984). Ruhlen (1975) reports lingual trills in 79.5% of languages with an r-sound (78.3% of the sample).

The mechanics of tongue-tip vibration have been described by Catford (1977), Ladefoged and Maddieson (1996), Spajic, Ladefoged and Bhaskararao (1996), Barry (forthcoming), 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 lingual trilling involve (i) muscle contraction of the tongue to assume the position, shape and elasticity requirements, and (ii) a sufficient pressure difference across the lingual constriction. Once trilling is initiated, tongue-tip vibration is maintained as a self-sustaining vibratory system. 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. 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 and Pallarès, in press). Unfortunately, the aerodynamic forces in trills have received little attention (but see McGowan 1992). 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 are necessary for trill production[2]. 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 non-trilled variants (*e.g.*, in Spanish, Italian, Toda). In addition, trills alternate historically, dialectally and allophonically with taps, approximants and fricatives.

The main aim of this paper is to characterize the aerodynamic requirements for trills and their range of variation, and how they account for some common patterns in trills. In section 2 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 3 we provide an account for some phonological universals in the patterning of trills: the preference for voiced trills, the alternation between trills and fricatives, and the lack of nasal trills. Section 4 presents the conclusions.

2. Aerodynamic Characteristics of Trills. Aerodynamic conditions play a critical role in the production of trills, and their pathologically (*e.g.*, cleft palate), contextually (coarticulation, speaking rate, etc), or artificially (*e.g.*, experiments) induced modification may seriously affect the production of these sounds. The experiment reported here was designed to provide information on the allowable range of aerodynamic variation and compensatory articulatory maneuvers to sustain voiced and voiceless trilling, and their acoustic result. The results may throw light on the role played by aerodynamic factors in some universal tendencies in the patterning of trills.

2.1. Experimental Method. In order to identify the aerodynamic conditions required for trilling, intraoral pressure (Po) and airflow were recorded simultaneously in two trained phoneticians producing steady state and intervocalic voiced and voiceless alveolar trills, as well as sustained trills with maximum exhalatory effort. Uvular trills and taps were also recorded for comparison. Po was sampled via a catheter inserted into the pharynx through the nose and connected to a pressure transducer. Airflow was collected with a Rothenberg mask and a pneumotachograph. The oral pressure and airflow signals were low-pass filtered at 50 Hz. The aerodynamic and acoustic data were digitized and sampled at 16 kHz. Oral pressure during trills and taps was intermittently bled with catheters of varying cross-sectional areas (7.9, 17.8, 31.6 and 49.5 mm^2), all 25 cm long, inserted into the speaker's mouth via the buccal sulcus and the gap behind the back molars. The impedance (*i.e.*, resistance to exiting air) of the catheters for the range of flow used in voiced and voiceless trills was calculated, as well as the vocal tract impedance during the production of trills for each speaker. The catheters venting the Po were intended to simulate variations in oral pressure present in speech due to contextual and prosodic factors, *e.g.*, coarticulation with sounds of varying impedance, adjacent nasals, stress, speaking rate, phrasal position, etc. Po and airflow were measured for the different conditions and the variation, impairment or extinction of trilling as a function of varying intraoral pressure was analyzed acoustically.

Masking noise was placed on the speaker through earphones to minimize auditory feedback. Kinaesthetic feedback could not be eliminated and measurements were made during the first 60ms after Po was varied.

2.2. Results

2.2.1. Aerodynamic Features of Voiced and Voiceless Trills. Voiceless trills differ from voiced trills in the nature and rate of airflow which 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. The laryngeal vibrations reduce the amount of air flowing into the oral cavity.

The higher rate of transglottal flow through the open glottis for voiceless trills, vis-à-vis voiced trills, resulted in the following differences: (1) Voiceless trills show a *higher Po* than voiced trills as illustrated in Fig. 1, which shows peak intra-oral pressure for steady state and intervocalic voiced and voiceless trills for the two speakers (the difference in absolute values in the two speakers may stem from the net differences in the overall size of the vocal tract). Since there is no other narrow constriction downstream, the pressure difference across the lingual constriction for trills is equal to Po ($\Delta P_{supraglott}$ = Po - Pa, where atmospheric pressure, Pa = 0). The pressure drop between the oral cavity and the atmosphere, which is larger for voiceless than for voiced trills, determines a *larger rate of flow* across the lingual constriction (0.66 and 1.34 lit/sec for voiceless trills *vs* 0.22 and 0.56 lit/sec for voiced trills for speakers MJ and JJ, respectively). The larger flowrate results in a higher particle velocity and the generation of turbulence or friction noise across the lingual constriction for voiceless trills. Fig. 1 also shows that the Po required to sustain tongue tip vibration is lower than that required to initiate it. Coarticulatory effects can also be observed; trills in the /i/ context exhibit a higher Po (due to a smaller cavity volume for the vowel) than in the /a/ context.

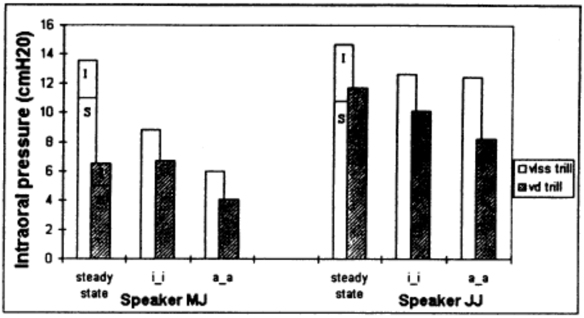

FIGURE 1. Mean peak oral pressure (ΔP across lingual constriction), in cmH20, for voiced (grey bars) and voiceless (white bars) steady state and intervocalic trills for speakers MJ and JJ. In the steady state trills the difference in Po needed to initiate (I) and sustain (S) a trill is indicated. Each bar represents an average of approximately 30 observations.

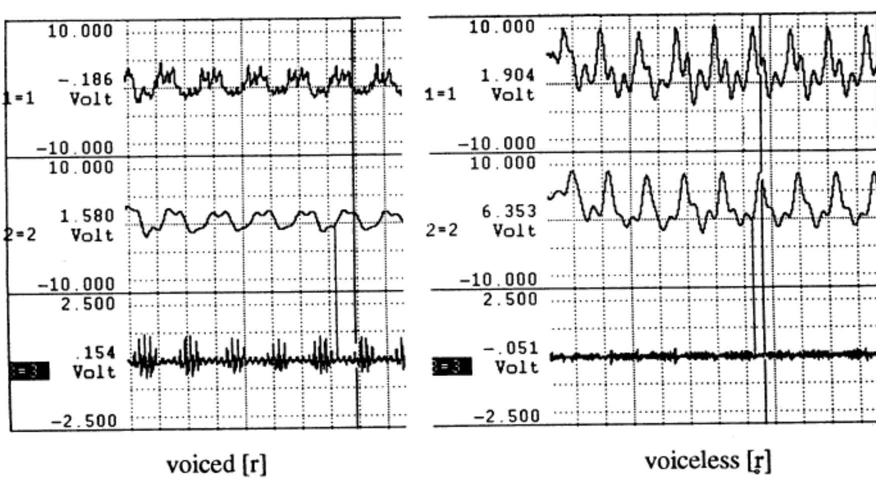

FIGURE 2. Unfiltered Po (channel 1), low-pass filtered Po (channel 2) and audio signal (channel 3), in volts, for sustained voiced and voiceless trills. The tongue tip contact period, showing a rise in Po, is indicated between lines in the filtered Po trace (a small phase shift is present between the filtered and unfiltered Po traces). Voiceless trills exhibit a shorter closure period than voiced trills.

(2) A *larger open to closed period ratio* in tongue tip vibration was found for voiceless as opposed to voiced trills (1.96 *vs* 1.29). Fig. 2 illustrates the shorter closure period (indicated by a rising Po) for voiceless than for voiced trills -- most

likely due to the higher oral pressure which overcomes the resistance of the tongue-tip in a shorter amount of time -- whereas the opening period is comparable in both. The proportionally longer open period in voiceless trills results in a lower impedance at the lingual constriction and longer periods of released (turbulent) energy, vis-à-vis voiced trills. As shown in the waveform in Fig. 2, voiceless trills also show frication during the closure, reflecting an imperfect palato-lingual closure.

(3) Voiceless trills exhibit a slightly *higher rate of vibration* than voiced trills (29.3 Hz, range 28-31.5 Hz *vs* 28.1 Hz, range 26-29 Hz) due to the larger pressure drop across the lingual constriction for the former. These results contrast with Lindau's (1985:161) finding that voiceless trills in Edo show a slower rate of vibration than voiced trills (22.5 Hz *vs* 25 Hz).

Voiced trills involve very precise aerodynamic conditions in order to maintain trilling and voicing. Po needs to be high enough to produce tongue tip vibration and low enough not to impair the transglottal flow required for voicing. Thus, the range of Po variation is bounded by the requirements for translingual flow needed for trilling and those for transglottal flow needed for voicing.

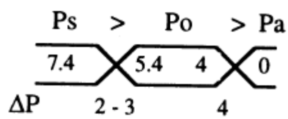

FIGURE 3. Estimated Po range for voiced trills for speaker MJ.

A pressure drop across the oral constriction of at least 4 cmH20 (depending upon tongue tip tension and mass) was found to be needed to sustain trilling, and the liminal volume velocity was about 0.175 lit/sec. Transglottal flow for voicing requires a minimum pressure drop of 2-3 cmH2O, and a minimum volume velocity of 0.050 lit/sec (Catford 1977: 98). To estimate the allowable range of Po variation, the peak intraoral pressure during voiceless trills was used as an estimate of subglottal pressure (Ps). Subject MJ had a peak, sustained Po of approximately 7.4 cmH20 for intervocalic voiceless trills (vowel contexts pooled), which can be assumed to be the value for Ps. If transglottal flow requires a pressure drop across the glottis (Ps-Po) of at least 2-3 cmH20, that leaves a Po of at most 5.4 cmH20, as schematically shown in Fig. 3. Trilling requires a minimum pressure drop of 4 cmH20 across the oral constriction, which means that Po may vary between a rather narrow range of 5.4 - 4 cmH20 in order to sustain voicing and trilling (the actual average Po value for speaker MJ was 5.39 cmH20). The estimation of the range of Po variation for speaker JJ was between 8 - 11 cmH20. Thus, the Po range for voiced trills is very narrow and unforgiving, and small pressure variations may lead to devoicing or cessation of trilling (a similar argument has been made by Ohala (1983) to account for the difficulty in maintaining voicing and frication). Ladefoged and Maddieson (1996:221) suggest that the rapid *increases* in Po during tongue tip contact in trills may impair the sufficient pressure drop for voicing, and be responsible for the tendency to devoice trills during the closure interval in a number of languages. Similarly, *decreased* Po may lead to devoicing: A lowered Po (due to decreasing subglottal pressure in utterance final position) endangers trilling, and active abduction of the vocal folds may be present to directly access the air reservoir and thus preserve trilling (see section 2.2.3), resulting in the commonly observed tendency to devoice final trills, *e.g.*, South American Spanish (Quilis 1981, Canfield 1981), Farsi (Ladefoged and Maddieson 1996). As for the cessation of trilling, non-trilled allophones of trills have been reported in a number of languages (see section 3.2).

2.2.2. Variations in Oral Pressure. In order to determine the range of allowable variation in intraoral pressure in the production of trills, the backpressure during trills was intermittently bled with catheters of different cross-sectional area, and the articulatory and acoustic consequences were analyzed. Fig. 4 illustrates the effects of the reduction in Po associated with a 17.8 mm^2 vent. Sustained voiced trilling is extinguished on vent, resulting in a fricative, whereas voiceless trilling is maintained, with peak oral Po noticeably reduced and the amplitude of the acoustic energy diminished as can be observed on the waveform. Thus, for a given vent trilling was extinguished earlier in voiced than in voiceless trills. Tongue tip vibration was extinguished into a fricative/approximant as the reduction in Po 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. 4 shows that blocking the tube restores the original pressure conditions and associated acoustic effects in voiceless trills, but trilling fails to reinitiate in voiced segments. Fig. 5 displays an intervocalic voiced trill in normal pressure conditions (right), and with a vent area of 7.9 mm^2 (left), where the reduced Po impairs tongue tip vibration, resulting in a fricative. Intervocalic trills proved to be more resistant to pressure changes between open vowels than between high front vowels. The lesser robustness of trills in the /i/ context is due to increased tension and mass of the tongue tip due to coarticulation with the high front vowel, rather than to intrinsic differences in the Po of trills in different vowel contexts.

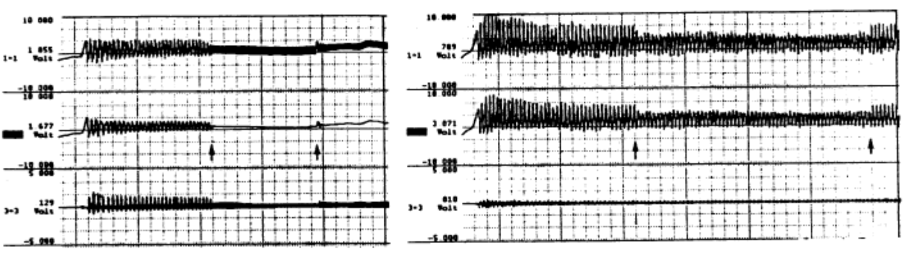

FIGURE 4. (1) Unfiltered Po, (2) filtered Po and (3) audio signal during the production of steady state voiced (left) and voiceless (right) trills. The unblocking and blocking of the catheter (area 17.8 mm^2) is indicated by arrows.

The reduction in oral pressure associated with venting the backpressure with catheters of different areas is presented in Fig. 6. When the Po dropped below a certain threshold, trills were extinguished resulting in a fricative (a non-sibilant voiced alveolar fricative in the case of voiced trills, and a [h] sound for voiceless trills) or an approximant with catheters of larger areas (≥ 31.6 mm^2). It is not possible to report absolute pressure values at which trilling was impaired, since depending on initial conditions (articulator tension, mass, cavity volume, articulatory position, compliance of the supraglottal walls, etc.) and speaker, the minimum oral pressure required for tongue tip vibration varied. A pressure drop of 2.5-3.5 cmH20 impaired sustained trilling in voiced segments. A larger pressure drop, 5 cmH20, was needed to impair voiceless trills. Thus, voiceless trills are more resistant to variations in Po due to (1) a higher Po which allows a larger reduction in pressure before reaching the minimum pressure drop across the lingual constriction required for trilling, (2) direct access to Ps to replace vented airflow, and (3) a smaller Po reduction for the same vent aperture (because impedance is higher at higher flow rates).

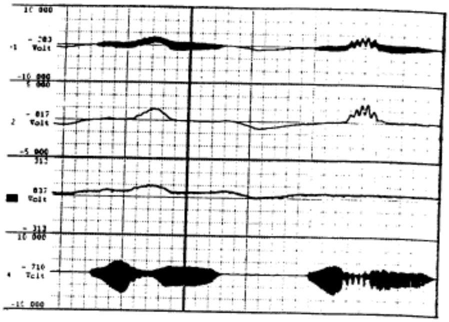

FIGURE 5. (1) Unfiltered and (2) filtered Po, (3) airflow escaping through the catheter when unblocked, (4) audio signal for vented and unvented [i'ri].

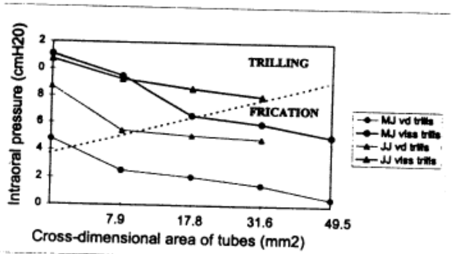

FIGURE 6. Reduction in intraoral pressure (y axis) per tube cross-sectional area (x axis) for steady state voiced (grey line) and voiceless (black line) trills produced by speakers MJ and JJ. The threshold of trilling is indicated by a hatched line. Each value represents an average of betwen 3 and 8 observations (mode 5). The number of vented tokens in each condition varied since intermittent venting had a random pattern.

2.2.3. Trill Extinction and Reinitiation. It was found that once trilling was extinguished, in the majority of cases it did not reinitiate when the initial pressure conditions were restored (by blocking the catheter, as shown in Fig. 4), suggesting that the pressure difference required to initiate tongue tip vibration is higher than that required to sustain it, in accordance with our measurements (Fig. 1) and with the reported differences in pressure drops necessary to initiate and maintain vocal fold vibration (Westbury et al. 1986). Alternatively, failure to reinitiate trilling may reflect differences in the initial tongue tip positioning for trills and fricatives.

The role played by initial pressure and articulatory conditions in trill production is illustrated in Fig. 7, which exhibits the initiation of trilling on vent (a), and the failure to sustain trilling in comparable pressure conditions (c) or to reinitiate trilling with increased Po (d). The physiological adjustments (in cavity volume, mass and/or tension of the vibrating articulator, vocal tract compliance) to compensate for initial pressure conditions in (a), are most likely relaxed when Po is reestablished in (b). When Po is further reduced in (c), trilling cannot be sustained with the existing articulatory conditions. Similarly, trilling cannot be reinitiated when Po is reestablished in (d). This illustrates once more the finely tuned aerodynamic and articulatory requirements to initiate and sustain trilling.

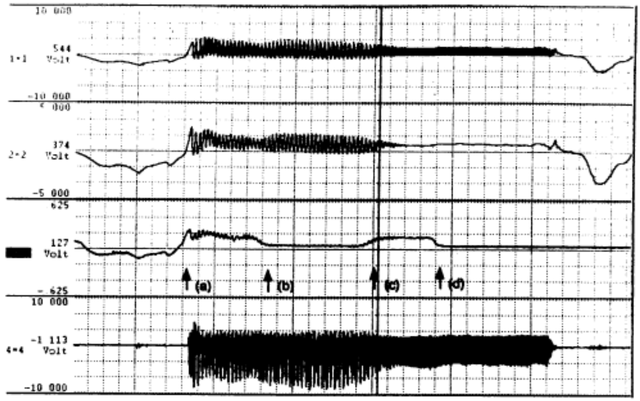

FIGURE 7. (1) Unfiltered Po, (2) filtered Po, (3) catheter vent, and (4) audio signal for a sustained voiced trill. (a) Trilling is initiated on vent (vent area 17.8 mm^2); (b) the catheter is blocked, Po and amplitude of the signal increase; (c) extinction of trilling on vent; (d) failure to reinitiate trilling when the pressure conditions are reestablished by blocking the catheter.

In the cases when 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 Po and in volume velocity before the Bernoulli force 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.

In prolonged trills, tongue tip vibration was sustained as long as sufficient airflow was available. When Ps (and consequently Po) diminished thus endangering trilling, two possible acoustic outcomes were observed: frication and/or devoicing. In the great majority of cases the trill decayed into a fricative as airflow through the lingual constriction dropped due to diminished Ps. In a few cases, the trill or the resulting fricative were further devoiced. Devoicing can be seen as a maneuver to directly access Ps by removing the resistance at the glottis and thus to prolong trilling.

In opposition to trills, which extinguish when oral pressure is vented by approximately 2.5-3.5 cmH20, taps continue to exist on vent, which illustrates that the two sound types involve different primary energy forces: aerodynamic *vs.* muscular.

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.

3. Phonological Patterns.

3.1. Preference for Voiced Trills. We now address the issue of trilling co-occurring with voicing almost exclusively. The statistical preference for voiced over voiceless trills is evidenced in phonological inventories and diachronic variation. Trills are mostly voiced in the languages of the world; only 1.5% of the trills are voiceless (Maddieson 1994, Ruhlen 1975). This is a lower percentage than for other voiceless sonorants (3.17% for nasals, approximants and liquids).

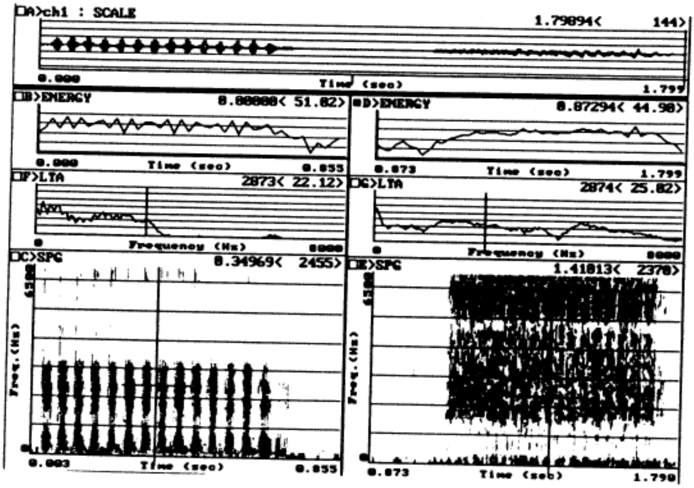

FIGURE 8. Waveform, energy plot, long term average spectrum and spectrogram of steady state voiced (left) and voiceless (right) trills produced by speaker MJ.

Fig. 9 shows contrastive voiced and voiceless trills for Lai-chin and Icelandic (the spectrograms show from 0 to 9 kHz). In voiceless trills the continuous high frequency component dominates the spectrum. Voiced trills show one clear contact followed by a burst of energy and subsequent decreases in intensity due to the vibration of the tongue tip approaching a closure.

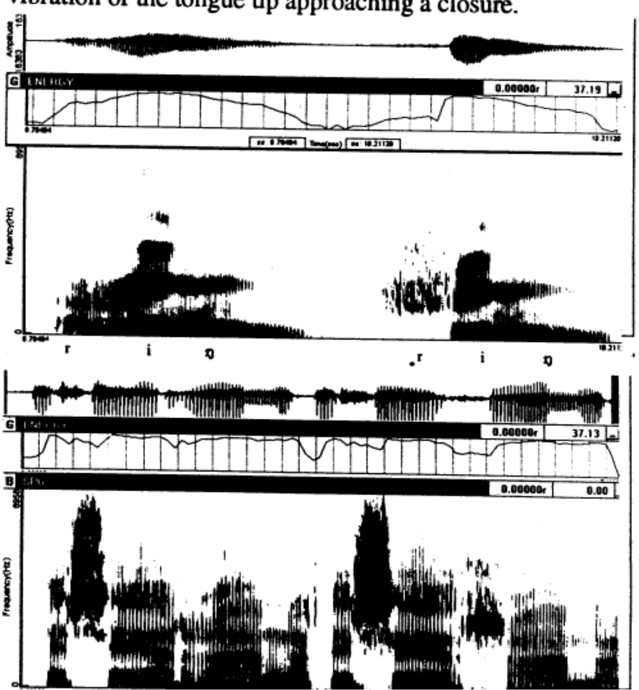

FIGURE 9. Voiced and voiceless trills in Lai-chin, [ri¯] 'loud' and [hri¯] 'green' (top), and Icelandic ([Teir 'seija 'ra:nar] 'they say trunks', [Teir 'seija 'hra:nar] 'they say boors' (bottom). Waveform, energy plot and spectrogram (0-9KHz).

The observed aerodynamic and articulatory characteristics of voiceless trills, vis-à-vis voiced trills (glottal friction; higher Po and larger flowrate across the oral constriction; larger ratio open to closed period of tongue tip vibration; and failure to achieve full palato-lingual closure) contribute to turbulent energy throughout the sound which makes them auditorily fricative-like. This is in line with Ohala's (1997) observation that voiceless sonorants tend to become fricatives. The reduction in airflow associated with voiced trills contributes to a regular alternation in the spectrum of bursts of energy; such temporal-spectral discontinuities result in an auditorily distinct signal. The co-occurrence of trilling and voicing can be seen as a natural byproduct of acoustic and auditory salience.

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).

3.2. 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. Synchronically, apical trills exhibit non-trilled 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. Non-trilled fricative variants have been reported in continental Spanish (Navarro Tomás 1950: 117) and American Spanish (Zlotchew 1971), Toda (Spajic, Ladefoged and Bhaskararao (1996:8), and Standard Swedish (Lindau 1985:164). This is most common in fast speech, and in the environment of high front vowels, where time constraints and muscular contraction for adjacent segments affect the tension of the tongue tip.

Historically, trills developed into fricatives in Tai dialects when voiceless (section 3.1) and devoiced, *e.g.*, *pr, *tr, *kr > ph, (t)h, kh, in Central dialects (Li 1977: 86, 118, 225). Other examples are the spirantization of palatalized trills in dialectal variants of Irish, *e.g.*, *ma:rʲa > [máʐa] 'Maire' or Proto-Slavic, where a palatalized trill developed into a trilled fricative [ř] in Czech, and a palatoveolar fricative [ʒ] in Polish (*e.g.*, Proto-Slavic *tsarja > Czech [tsařa] Polish [tsaʒa], 'Czar'). Palatalization involves active raising of the tongue predorsum which is antagonistic with the tongue shape (concave) and tension (relaxed tongue tip) required for trills (Recasens and Pallarès, in press). In addition, palatalization involves a more massive tongue tip and blade offering a higher resistance to trilling (Kavitskaya 1997).

Trilling tends to *co-occur* with frication. Trills with associated frication are most commonly uvular trills (in Southern Swedish, Standard French and Standard German (Ladefoged et al. 1996, Lindau 1985)), but apical trills involving frication have been reported in Toda and Spanish. Spirant trills [ř] (or assibilated /r/s) are the norm in approximately half of the American Spanish dialects and some dialects of Peninsular Spanish. Approximately half of these spirant trills are devoiced (Quilis 1981:301, Canfield 1981:7). Thus, *la ropa* 'the clothes' and *la sopa* 'the soup' are often confused by outsiders. Utterance and syllable final trills are assibilated in virtually all the American Spanish territory. Fig. 10 illustrates assibilation and devoicing of prepausal /r/ for a Mexican speaker. The intervocalic trill also shows some fricative component. Fricative trills result from imperfect linguopalatal closure or partial vibration of the tongue tip, which allows the high velocity air to flow continually through the aperture generating friction. The concomitance of trill devoicing and frication has been referred to in the previous section.

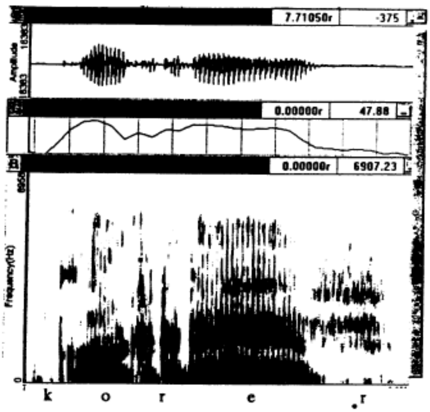

FIGURE 10. Waveform, energy plot and spectrogram of the word *correr* 'to run' uttered by a Mexican speaker. The intervocalic trill, showing three linguo-palatal contacts, is voiced with some frication, and the prepausal trill is assibilated and devoiced during most of its duration.

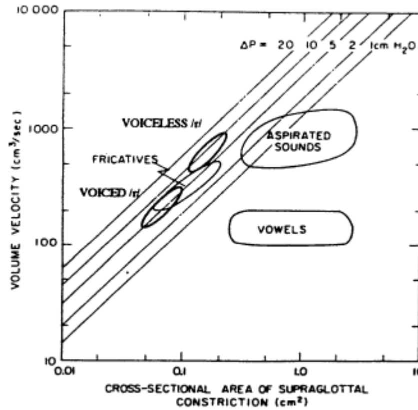

FIGURE 11. Pressure and airflow values for voiced and voicless trills have been added to Steven's (1971) chart.

A related phenomenon is the *trilling of fricatives* (velar, uvular, and pharyngeal) in Northern Dutch (van den Berg 1958), dialectal German and French, (Ladefoged et al. 1996), !Xóo (Traill 1985), and peninsular Spanish (Quilis 1981). Occasionally presence of uvular/epiglottal trills reinforcing [-anterior] fricatives is found in these languages (mainly in contact with low back vowels).

Our experimental conditions replicated the phonological variation between voiced trills and fricatives. The results in sections 2.2.2 and 2.2.3 show that (i) when pharyngeal 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 aiflow values. In Fig. 11, 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 falls within (and is bounded by) the region for fricatives. The region for voiceless trills show flowrates 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 1976:132). In addition, fricatives and trills involve a highly constrained tongue dorsum and tongue tip to meet the critical positioning required for frication and trilling, resulting in their being very resistant to coarticulatory effects (Recasens et al., in press). The main differences betwen trills and fricatives seem to lie in the tension of the articulator (a stiffer articulator will not be free to vibrate); the configuration of the tongue (predorsum lowering and postdorsum retraction for the trill to make possible the vertical vibration of the tongue tip as opposed to pre- and postdorsum raising and advancement for alveolar fricatives (Recasens et al., in press)), and initial tongue tip positioning (2.2.3).

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 and Maddieson 1996:241), and by the substitutions for the lingual trill by infants and unskilled adult native speakers -- intended lingual trills are rendered as a voiced uvular fricative [ʁ] (or uvular trill [R]), a postalveolar non-sibilant fricative, or a dental fricative [ð] (but not [w]).

In short, the results from the experiment (along with acquisitional and pathological 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 Po variation than trills. The reinterpretation of fricative variants of trills as the manifestation of phonological fricatives helps to explain the dialectal and diachronic change.

3.3. Absence of Nasal Trills. Another phonological universal involving trills is the absence of nasal trills. The non co-occurrence of trilling and nasality is dictated exclusively by aerodynamic reasons. An open velo-pharyngeal 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 the Po was vented with catheters that simulated nasal leakage. It has been shown that lingual trills require a high intraoral pressure (>4cmH20) to sustain tongue tip vibration (and even higher to initiate it), and that trilling was extinguished when the oral pressure was reduced by 2.5 cmH2O. Thus, trilling cannot combine with an open velopharyngeal port that reduces the Po by 2.5 cmH20 or more (vent areas $\geq$ 8 or 17.8 mm^2, depending on absolute Po values, from our estimates). The small velopharyngeal openings which do not impair trilling would most likely be insufficient to create a percept of nasalization. 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.

4. Conclusions. This study provided empirical evidence on the aerodynamic conditions required for trilling and their compatibility with other features in making up speech segments. In addition, the universal principles in the phonological patterning of trills have been shown to reflect the constraints imposed by the physics and physiology of the speech production and perception systems, 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 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 thrown off, 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 oral pressure needed for trilling with an open velopharyngeal port required for nasality.

We have illustrated how aerodynamic factors, in combination with other constraints of production and perception, may determine feature coocurrence restrictions and common phonological patterns. In Darwinian terms, we know that complex phonological structure can emerge from simpler (phonetic) mechanisms; and phonological universals seem to reflect the darwinian drift towards patterns that almost seem designed for their environment -- efficient speech production and perception --, eventually, the result of 'intelligent design'.

NOTES

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[1] Bilabial and (ingressive) uvular trills are reported in children's speech in the vocal play stage (Vihman 1996). The absence of tongue tip trills may be due to (i) the large volume of the tongue in relation to the oral cavity, leaving little room for distinct vertical movements of tongue tip or blade (Stark 1980), (ii) lack of maturity of the intrinsic muscles of the tongue to assume the position, shape and elasticity requirements of trills (Fletcher 1973), and lack of neuromuscular control of the tongue and kinaesthetic sensory information.

[2] The contribution of all these factors to trilling is evidenced by the conditions that have been anecdotally reported to aid trilling: (1) variations in air pressure (easier to trill after a [b], which involves increasing the airpressure downstream of the lingual constriction, or when singing, due to increased respiratory effort and subglottal Ps); (2) positioning (easier to trill when facing down, the gravitational force acting on the oscillator aids to closing the lingual channel; (3) tongue tension and mass (easier to trill between low vowels).

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