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RESEARCH PAPER

Voice change as a new measure of male pubertal timing: A study among Bolivian adolescents

Carolyn R. Hodges-Simeon[1], Michael Gurven[1], Rodrigo A. Cárdenas[2] & Steven J. C. Gaulin[1]

[1]*Department of Anthropology, University of California, Santa Barbara, CA 93106, USA, and* [2]*Department of Psychology, Pennsylvania State University, University Park, PA 16802, USA*

***Background*: Age at menarche is often used to measure maturational tempo in girls. Unfortunately, no parallel marker exists for boys. It is suggested that voice change has a number of advantages as a marker of the timing and degree of male pubertal development.**
***Aim*: Traditional auxological methods are applied to voice change in order to compare differential development both *between* (males vs females; Tsimane vs North American; better vs worse condition) and *within* (voice vs height; fundamental frequency vs formant structure) populations.**
***Subjects and methods*: Fundamental and formant frequencies, as well as height and weight, were measured for 172 Tsimane males and females, aged 8–23. Participants were assigned to 'better' or 'worse' condition based on a median split of height-for-age and weight-for-age *z*-scores.**
***Results*: Results support dramatic vocal changes in males. Peak voice change among Tsimane male adolescents occurs ~ 1 year later than in an age-matched North American sample. Achieved adult male voices are also higher in the Tsimane. Tsimane males in worse condition experience voice change more than 1 year later than Tsimane males in better condition.**
***Conclusion*: Voice change has a number of attractive features as a marker of male pubertal timing including its methodological and technical simplicity as well as its social salience to group members.**

Keywords: Puberty, adolescence, voice, fundamental frequency, formants, formant dispersion, peak height velocity, pitch

INTRODUCTION

From a life-history perspective, sexual maturation marks a strategic shift involving a re-allocation of resources away from growth and towards reproduction (Stearns 1992; Hill 1993; Kaplan et al. 2000). Phenotypic (e.g. endocrine, somatic) changes accompany dramatic alterations in social, economic and reproductive roles and relationships. Differential timing of the onset and duration of these changes is thought to occur in response to variation in social and ecological inputs (Wyshak and Frisch 1982; Susanne 1985; Eveleth and Tanner 1990; Belsky et al. 2007; Bogin 1999; Cole 2003; Parent et al. 2003; Walker et al. 2006; Cameron 2007). As the study of development progressively incorporates this theoretical perspective, hypothesis testing about both evolutionary and proximate (internal and external) environmental triggers will depend on multiple reliable measures of this important biosocial transition.

The primary measure of the timing and pace of reproductive maturation has been the age at menarche (Wyshak and Frisch 1982; Bogin 1999; Fredriks et al. 2000; Cole 2003; Herman-Giddens 2006; Walker et al. 2006; McDowell et al. 2007). This defining event has been occurring earlier for at least the past century (Wyshak and Frisch 1982) and continues to show declines of ~ 1 month per decade in the US and Western Europe (Fredriks et al. 2000; Herman-Giddens 2006; Ong et al. 2006; McDowell et al. 2007). Compared with more developed countries, less developed countries have a later age at menarche (Bogin 1999; Walker et al. 2006), which often falls as living conditions improve (Hoshi and Kouchi 1981; Bogin 1999; Parent et al. 2003). Studies of menarcheal age have provided important breakthroughs in understanding the impact of social and environmental factors on reproductive development (e.g. Belsky et al. 2007; Walker et al. 2006). Unfortunately, parallel investigations into male pubertal timing have been more difficult because no equivalent marker of masculine pubertal development has been identified.

Because the pubertal period differs so markedly for the sexes (Tanner 1981), markers of male reproductive development are needed. Compared to females, males reach puberty later (Tanner 1981; Bogin 1999), develop divergent

Correspondence: Carolyn R. Hodges-Simeon, Department of Anthropology, University of California, Santa Barbara, CA 93106, USA.
Tel: 540-588-4639. E-mail: crhodges@umail.ucsb.edu

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primary and secondary sexual characteristics (Tanner 1981) and employ different life history and reproductive strategies (Trivers 1972; Kaplan et al. 2000). In addition, growth and development among males may be more sensitive to environmental hardship (Stinson 1985; Cole 2000), such that supportive or adverse conditions impact their development more strongly than for females (Kuh et al. 1991). The timing of reproductive landmarks also differs: females develop secondary sexual characteristics prior to adult reproductive functioning, whereas, for males, the opposite pattern prevails (Bogin 1999).

Given the growing focus on sexual maturation as a major life-history transition, more precise markers of male reproductive development could support theory formulation and testing. Conventional measures include the age at peak height velocity (Eveleth and Tanner 1990; Bogin 1999), testicular volume (Harries et al. 1997; Campbell et al. 2004), Tanner stages of genital and pubic hair development (Harries et al. 1997; Bogin 1999) and endocrine biomarkers (e.g. DHEA-S and testosterone; Halpern et al. 1998; Ellis and Essex 2007). Unfortunately none of these measures is ideal. Although height itself has relatively high reliability, peak height velocity can sometimes be difficult to detect in cross-sectional or energetically stressed samples (Bogin 1999). Tanner stages are widely used but are somewhat subjective; as such, measures collected by different researchers may be incomparable (Brooks-Gunn and Warren 1985; Herman-Giddens 2006) and provide a poor basis for population comparisons. Both Tanner stages and testicular volume often require the presence of a physician or trained health professional, making them sub-optimal measures for sensitive or reticent populations or for studies with limited funding (Coleman and Coleman 2002). Endocrine biomarkers provide a desirable level of objectivity and reliability (McDade et al. 2007), but the expense and difficulty associated with storage, transport and analysis discourages their widespread adoption, especially by field researchers.

Voice frequency, which changes dramatically during adolescence (Hollien et al. 1994; Harries et al. 1997, 1998; Huber et al. 1999), is an under-utilized male pubertal marker. With digital means of collection, storage and analysis (e.g. Boersma and Weenik 2010), acoustic samples can be easily gathered in a wide variety of settings, without extensive technical training. For these pragmatic reasons, male vocal characteristics could be useful in studies of within- and between-population comparisons of peri-pubertal timing and a candidate marker for the examination of secular trends or epidemiological factors in male puberty (Pedersen et al. 1986; Juul et al. 2007). Voice frequency would be an especially useful marker of male pubertal development if male vocal changes were relative precipitous compared to other developmental transitions.

Like height, the voice is a socially and economically significant characteristic, particularly for males. Research indicates that a lower voice impacts social perceptions, including assessments of age (Collins 2000; Feinberg et al. 2005), size (Collins 2000; Feinberg et al. 2005), physical and social dominance (Puts et al. 2006, 2007; Wolff and Puts 2010) and attractiveness to women (Collins 2000; Feinberg et al. 2005; Puts 2005). Men with lower voices had greater mating success in a US sample (Puts 2005; Hodges-Simeon et al. 2011) and greater reproductive success in a sample of Hadza hunter-gatherers (Apicella et al. 2007). Thus, unlike pubertal indicators such as testicular volume, manifest changes in males' voices are likely to coincide with social and economic changes in adolescents' lives—a transition that would be of interest to those studying biocultural dimensions of human puberty and adolescence.

Although male voice change from 'high' to 'low' is self-evident to listeners, acoustic dimensions must be measured objectively and precisely in order to be useful to researchers. The perceptual experience of a 'low' voice is the psychophysical product of two acoustic components: fundamental frequency (a perceptual correlate of 'pitch'; F_0) and formant structure (Puts et al. 2007; Feinberg et al. 2011). F_0 is a product of the length, tension and cross-sectional area of the vocal folds, such that larger vocal folds produce lower F_0 (Williams and Eccles 1990; Harries et al. 1998). Speakers can vary F_0 to some extent by changing the tension of the vocal folds and they often do so for prosodic purposes. However, stable individual differences exist in the baseline F_0 as a result of the length and cross-sectional area of the folds (Titze 1994).

Formant dispersion (D_f; Fitch 1997) and formant position (P_f; Puts et al. 2012) are measures of the spacing of the formants—energy peaks in the harmonic spectrum (Fitch 1997). Lower and more closely spaced formants give a more 'resonant' quality to the voice—analogous to the fuller and deeper resonance of a middle C played on a cello vs a violin. Formant structure is a function of the length and shape of the vocal tract (or the depth of the larynx in the throat), which jointly define the region that sound waves traverse from the vocal folds through the oral cavity (Baken 1987; Titze 1994). Thus, differences in acoustic dimensions reflect differences in the biology of the vocal tract. See Figure 1 for a visual representation of formant frequencies in a pre- and post-pubertal male. A longer vocal tract in the older male generates lower and more closely spaced formants; thus, post-pubertal formants are lower. In the present study, we report two measures of formant structure: D_f and P_f (Puts et al. 2012).

In both sexes, F_0 drops steadily throughout childhood as the growth of the vocal folds scales with overall body growth (Vuorenkoski et al. 1978). However, working through androgen receptors on the larynx (Newman et al. 2000), testosterone lengthens and thickens the vocal folds in males (Kahane 1978; Jenkins 1998), causing a rapid drop in F_0 during Tanner stages 3 and 4, usually around 12–15 years old (Hollien et al. 1994; Harries et al. 1997, 1998; Huber et al. 1999). Male F_0 continues to lower more gradually throughout the 20s and 30s, but rises again in old age (Baken 1987). Similarly, vocal tract length scales with body size growth, with little sexual dimorphism prior to puberty (Vorperian et al. 2005). At puberty, however, males' larynges begin to descend further than females (Titze 1994).

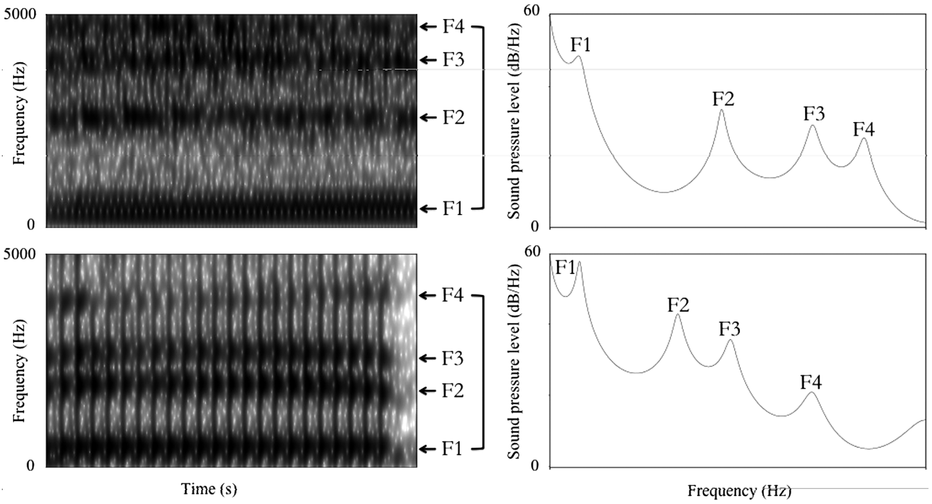

Figure 1. Comparison of formant frequencies in a pre-pubertal (top) and post-pubertal (bottom) male. *Note:* Images show Images show spectrograms (left) and smoothed sound pressure level peaks generated using long-term average spectrum (right; Hodges-Simeon et al., 2010). F1–F4 correspond to the first four formants. Note the lower formants and more compressed spacing in the post-pubertal male. (spectrogram settings: window length: 0.2 s, Fourier method, Gaussian window shape, frequency steps: 250, time steps: 1000, dynamic range: 70 dB).

The general goals of the present study are to highlight voice change as an important aspect of adolescent male biology and to suggest ways that change in F_0 and formant structure can be useful as an additional measure of the peri-pubertal life-history shift from growth to reproduction. In addition to age-specific means and standard deviations, we use traditional auxological tools to capture the 'spurt' in adolescent voice change: distance, velocity and acceleration curves and their attendant features, age at peak velocity, minimal velocity (or age at take-off velocity), maximal acceleration and deceleration (Bogin 1999; Cameron 2004). We then use these measures to make several comparisons of voice change among adolescent males and females in an energetically stressed population, the Tsimane of Bolivia. Several studies have previously described aspects of adolescent voice change (Hollien et al. 1994; Harries et al. 1997, 1998; Huber et al. 1999); however, this is the first study to examine voice change: (a) using auxological tools and (b) in a non-westernized population living under considerable immune and energetic stress, where growth and development are often adversely affected (Susanne 1985; Eveleth and Tanner 1990; Bogin 1999; Cole 2003).

Within the framework of these general goals we have five specific objectives:

- First, both male and female F_0 and formant structure are modelled in order to highlight the pronounced difference between male and female voice change and to identify the ages at which the sexes diverge on these vocal parameters.
- Second, we compare the age of peak F_0 change between Tsimane and US adolescent boys, where the latter estimate derives from published North American data (Huber et al. 1999). Other indicators of pubertal timing (i.e. age at menarche, age at peak height velocity) suggest delayed development in our Bolivian population (Walker et al. 2006); therefore, we predict that Tsimane development will be delayed on the vocal dimension as well.
- Third, male voice change is modelled separately for boys in better vs worse condition, as defined by weight-for-age and height-for-age *z*-scores (Kuczmarski et al. 2000). Within the Tsimane, variation is present in access to food, healthcare, clean water and other variables that affect development (Gurven et al. 2007). We hypothesize that peak voice change will occur later for males in worse condition than for males in better condition.
- Fourth, post-pubertal values of F_0 and D_f are compared to published averages from the US and Europe. Just as a slower rate of linear growth is associated with shorter stature among those in relatively worse condition (Walker et al. 2006; Godoy et al. 2010), we predict that a later age at peak F_0 and D_f velocity combined with a slower rate of change at all ages will result in higher voices among post-pubertal Tsimane males.
- Finally, we compare our measures of F_0 and formant structure change with another widely used pubertal marker—the linear growth spurt in height. Here we address two related questions. First, are vocal and stature changes temporally correlated? Second, is the pace of change in each similarly dispersed across adolescence or is one more temporally compressed than the other? This is important because the more 'instantaneous' the change (e.g. menarche), the more precise a measure of reproductive timing it can provide.

MATERIALS AND METHODS

Population

The Tsimane are South American forager-horticulturalists living in the Amazonian lowland forests of the Beni region of Bolivia. Villages are settled along the banks of the Maniqui River, between market towns San Borja and San Ignacio de Mojos. Several different villages were sampled for the present study. Tacuaral del Mato (population was ~553 in 2010, $n = 74$) and Campo Bello (pop. 328, $n = 56$)

are ~ 1 hour from San Borja. Jamanchi Uno (pop. 221, $n = 42$) is a smaller, less-acculturated village 2 hours from San Borja. The Tsimane participate in a broad, NIH/NIA-funded project (Tsimane' Health and Life History Project [THLHP]; Co-PIs: Michael Gurven and Hillard Kaplan).

In this population, the average male adolescent growth spurt in stature lasts from age 13–18 years; the age at peak height velocity is 14 (age 12 for females). The overall rate of child–juvenile growth velocity is 5.2 cm/year (4.9 for females) until an adult size of 163 cm (149 cm for females) is reached. The average age at menarche is 13.9 according to one estimate from a mixed cohort sample (Walker et al. 2006); however, girls in the most recent cohort—especially those in more acculturated villages—may experience menarche earlier (McAllister et al. 2012). Self-reported age at menarche for the current sample of post-menarche girls was 13.0. Tsimane children and young adults experience high rates of endemic infections—primarily respiratory and gastrointestinal—and intestinal parasitism (Gurven et al. 2008). These infections likely account for the low height-for-age profiles of children and young adults (McDade et al. 2005). Life expectancy at age 15 is 43 additional years (Gurven et al. 2007).

Participants

Eighty-one females, aged 8–20, and 91 males, aged 8–23, participated in this IRB-approved study. The distribution across ages can be found in Table I.

Ages were obtained using two sources of information. First, each participant was asked his or her age and date of birth. Many participants (mostly under the age of 12; $n = 69$) did not know their exact birth date. One participant did not know his age or birth date. Second, stated age was compared with the THLHP census (see Gurven et al. 2007 for detailed age methods). This census information was primarily obtained from demographic interviews conducted over the past 10 years. Census ages are most accurate for younger ages (vs middle and older ages) because interviews were conducted with parents when their child was young. In addition, parents of the current participants are more likely to keep records of their child's birth than earlier generations. Therefore, the census age was used when it was in conflict with stated age. When participants neither knew their birth date nor could be found in the census ($n = 8$), they were assigned their stated whole number age plus 0.5. Omitting these individuals did not alter any of the results reported here and so are included in the sample.

Acoustic recording

Voices were recorded using a Sony PCM-M10 digital audio recorder and an Audio-Technica lavalier microphone. The microphone was mounted on an adjustable headset in order to standardize the distance from the lips and reduce background noise. Due to differing head sizes, the headset was adjusted for each person so that the microphone was ~ 5 centimetres from the lips. Voice samples were recorded in mono using a sampling rate of 44.1 kHz and 16-bit quantization. Each recording was saved as a high-quality uncompressed linear PCM.wav file.

Participants were shown five photographs representing easily recognized objects in Tsimane life (cat, dog, plantains, soccer ball and frog) and asked to name each object. These particular words were chosen because they terminate in five different vowel sounds (míshi: 'ee', açhuj: 'oo', pe're: 'ä', perota: 'ah' and ococo: 'oh').

Acoustic analysis

For all participants' recordings, mean F_0 and formant structure (D_f and P_f), all measured in Hertz (Hz), were determined using Praat voice analysis software (Version 5.1.37; Boersma and Weenik 2010).

Formants were obtained using methods described by Puts et al. (2012); however, formant ceilings were adjusted for different developmental groups. Participants completed the Pubertal Development Scale (PDS; Petersen et al. 1988), which has been shown to be a reliable approximation of the Tanner stages (Brooks-Gunn & Warren 1985; Petersen et al. 1988; Coleman and Coleman 2002). Males and females in stages 1 and 2 (mean age = 10.9 ± 1.6) were measured using a formant ceiling of 7000 Hz. Females in stages 3, 4 and 5 (mean age = 15.4 ± 2.7) and males in stage 3 (mean age = 15 ± 1.5) were measured using a formant ceiling of 6000 Hz. Males in stages 4 and 5 (mean age = 18.2 ± 2.3) were measured with a formant ceiling of 5000 Hz.

F_1 through F_4 were measured at each glottal pulse, targeting voiced speech only and then averaged for analyses (mean number of glottal pulses per file = 527 ± 273). In order to calculate P_f, the first four formants were standardized using between-sex means and standard deviations (Puts et al. 2012). The median was used for analyses. D_f was calculated by taking the average of the distances between the first four formants (Fitch 1997). Because within-sample means are used to calculate standardized formants for P_f, it does not provide an optimal measure for between-study comparisons of formant frequencies. Therefore, we retain the more conventional D_f as our primary measure of formant structure.

Height, weight and nutritional condition

Standard anthropometric procedures were used to collect height and weight (Lohman et al. 1988); participants were measured without shoes and in light clothing. Sex-specific weight-for-age (WAZ) and height-for-age (HAZ) *z*-scores were computed using CDC (2000) reference curves in EpiInfo (version 3.5.3). WAZ and HAZ were averaged to create a composite condition variable. Participants were assigned to either 'better' ($M = -0.5$) or 'worse' ($M = -1.8$) condition based on a median split of this condition variable.

RESULTS

Exploration of male and female F_0 and formant structure (P_f and D_f) at different ages

See Table I for mean values of F_0 (Hz; $M = 219.3$, SD = 50.2, Range: 106.8–353.4), D_f (Hz; $M = 1356$, SD = 142, Range: 947–1664) and P_f ($M = 1.17$, SD = 1.06, Range: − 1.12

Table I. Mean and standard deviation of fundamental frequency (F_0), individual formants (F_1–F_4) and formant structure (formant dispersion [D_f] and formant position [P_f]) across adolescent ages.

		Age									
		≤ 10 ($n = 48$)	11 ($n = 17$)	12 ($n = 18$)	13 ($n = 15$)	14 ($n = 20$)	15 ($n = 12$)	16 ($n = 9$)	17 ($n = 11$)	18 ($n = 10$)	≥ 19
F_0	Males	243 ± 29	227 ± 27	242 ± 29	182 ± 30	166 ± 44	133 ± 14	123 ± 5	140 ± 5	125 ± 26	141 ± 33
	Females	259 ± 38	244 ± 28	252 ± 40	227 ± 8	235 ± 18	219 ± 31	258 ± 46	221 ± 14	231 ± 27	242 ± 25
	U	176	20	34.0	1**	9**	0**	0†	0*	0*	0**
D_f	Males	1474 ± 78	1492 ± 60	1387 ± 96	1354 ± 31	1304 ± 218	1251 ± 84	1199 ± 124	1226 ± 113	1119 ± 98	1083 ± 80
	Females	1470 ± 97	1414 ± 96	1379 ± 109	1309 ± 94	1270 ± 51	1270 ± 69	1228 ± 67	1274 ± 66	1302 ± 54	1337 ± 41
	U	237	22	33	16	44	13	4	6	0†	0**
P_f	Males	2.09 ± 0.43	2.06 ± 0.21	1.51 ± 0.76	0.99 ± 0.51	0.55 ± 1.05	−0.10 ± 0.53	0.22 ± 0.88	−0.29 ± 0.56	−0.62 ± 0.71	−0.48 ± 0.65
	Females	2.33 ± 0.75	1.79 ± 0.56	0.94 ± 0.83	0.99 ± 0.55	0.45 ± 0.31	0.50 ± 0.46	0.16 ± 0.88	0.54 ± 0.50	0.91 ± 0.32	0.44 ± 0.43
	U	190	25	20	22	44	6†	4	2†	0†	5†
F_1	Males	472 ± 43	493 ± 48	463 ± 68	428 ± 82	433 ± 27	362 ± 24	427 ± 54	403 ± 19	390 ± 29	439 ± 45
	Females	486 ± 60	488 ± 50	412 ± 74	445 ± 38	424 ± 48	429 ± 25	415 ± 50	417 ± 59	459 ± 55	380 ± 85
	U	185	31	23	20	46	1**	3	7	2	7
F_2	Males	2261 ± 149	2148 ± 163	2124 ± 228	2021 ± 216	1874 ± 260	1897 ± 134	1883 ± 277	1684 ± 249	1715 ± 114	1655 ± 75
	Females	2349 ± 195	2141 ± 224	2010 ± 169	1984 ± 230	1858 ± 114	1883 ± 174	1822 ± 313	1898 ± 132	1964 ± 158	1985 ± 51
	U	171	30	23	19	46	14	2	5	0†	0**
F_3	Males	3677 ± 170	3613 ± 170	3471 ± 139	3322 ± 127	3106 ± 341	2921 ± 187	3007 ± 216	2788 ± 195	2713 ± 230	2732 ± 182
	Females	3746 ± 232	3738 ± 207	3317 ± 201	3370 ± 281	3159 ± 192	3142 ± 168	3040 ± 88	3244 ± 108	3237 ± 227	3092 ± 80
	U	197	28	19†	19	43	7†	3	0*	1	0**
F_4	Males	4894 ± 237	4969 ± 142	4622 ± 329	4489 ± 121	4344 ± 663	4115 ± 266	4023 ± 385	4081 ± 345	3748 ± 322	3688 ± 238
	Females	4895 ± 316	4731 ± 270	4549 ± 360	4371 ± 267	4233 ± 141	4240 ± 211	4099 ± 251	4241 ± 177	4364 ± 135	4389 ± 99
	U	247	20	32	15	42	12	4	6	0	0**

Note:‘ ≤ 10’ includes ages 8–10. ‘ ≥ 19’ includes ages 19–22. Whole number categories (e.g. ‘11’) include all individuals with that whole number age (e.g. 11.00–11.99). Mann-Whitney U-test (two-tailed) represented by the U-value; $^{\dagger}p \leq 0.10$, * $p < 0.05$, ** $p < 0.01$.

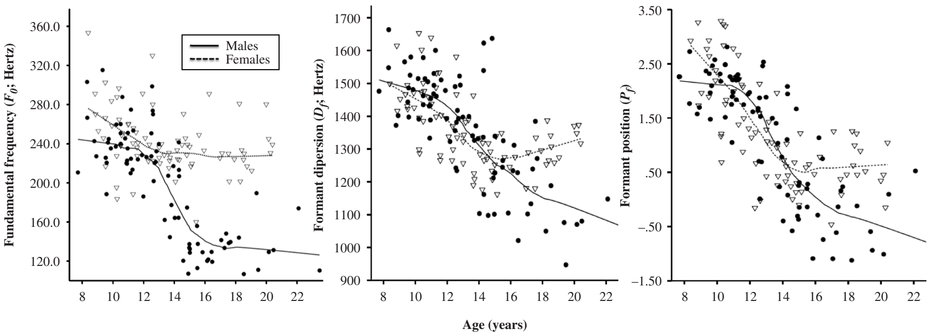

Figure 2. Fundamental frequency (F_0), formant dispersion (D_f) and formant position (P_f) as a function of age and sex. *Note:* Solid lines indicate LOWESS curves fit to 50% of the data using SPSS 19. An Epanechnikov kernel was used.

to 3.29) for males and females at each age category. See also Figure 2 for a scatter plot of F_0, D_f and P_f values. In order to determine the age when male and female F_0 and formant structure diverges, a two-tailed Mann-Whitney U-test was applied to each age category. For F_0, males and females were significantly different by age 13 (U = 1.0, $p < 0.01$). The difference between male and female formants was not definitive; male and female P_f was marginally significantly different at age 15 (U = 6, $p = 0.08$), while D_f did not show a significant difference until the oldest age group (U = 0, $p < 0.01$). Low sample sizes at several of the older ages may explain why statistical significance was not achieved for all post-pubertal age categories.

In Figure 2, locally weighted scatter plot smoothing (LOWESS)—a method that models small sections of the data around each point to construct a best-fit curve—was applied to the data in order to explore age-related patterns in F_0, D_f and P_f for both males and females. An identifiable pattern is apparent from the LOWESS curves. Males' F_0 decreases relatively slowly until ~ 12–13 years of age, then rapidly falls until age 17 when the descent levels off. For females, the curve depicts a linear decline that flattens out around age 13.5. Males' formant structure (D_f and P_f) shows a similar pattern: slow descent until age 12, followed by a more rapid drop that tapers off at age ~ 17.5. Females show a decline of formant structure until age ~ 15. Due to the relative similarity in age-related change between each formant structure measure, we report only D_f in the following models. Although P_f may show greater sexual dimorphism than D_f (Puts et al. 2012), it uses within-sample means to standardize formant position and, therefore, hampers comparisons across populations and samples.

Modeling F_0 and D_f as a function of age for males and females

Curve Expert Version 1.5.0 was used to determine a best-fit algorithm for patterns of age-related change in F_0 and D_f. Goodness-of-fit was assessed using the coefficient of determination (R^2). Male voice change and female D_f were best described using a Weibull model, a sigmoid growth function (1), where *a*, *b*, *c*, *d* and *e* represent constants (see Table II). Female F_0 change was better represented by an MMF function, also a sigmoid function (2).

$$f(x) = a - be^{-cx^d} \tag{1}$$

$$f(x) = \frac{ab + cx^d}{b + x^d} \tag{2}$$

Variance between individuals in rates of growth prevents a perfect fit to the data. Nevertheless, R^2 values indicate that the functions fit the pattern of data well (explaining 72% of the variation in male F_0 and 59% of the variation in D_f). R^2 values for females are considerably lower (24% of variance explained for F_0 and 46% for D_f). Model parameters are listed in Table II. See also Figure 3 for a visual representation of F_0 distance and velocity curves.

Table II. Model parameters for F_0 and D_f.

	a	b	c	d	SE	R^2	APVV
Males							
F_0^a	2.43E + 02	1.23E + 02	4.60E + 10	− 9.46E + 00	29.9	0.72	13.3
D_f^a	1.48E + 03	4.50E + 02	2.49E + 05	− 4.70E + 00	108	0.59	13.5
Females							
F_0^b	2.34E + 02	2.90E − 08	1.18E + 03	− 9.22E + 00	27.9	0.24	n/a
D_f^a	1.48E + 03	2.08E + 02	4.82E + 08	− 8.18E + 00	86	0.46	n/a
$F_0^{a,c}$							
Better condition	2.51E + 02	1.66E + 02	3.97E + 08	− 7.64E + 00	32.1	0.75	13.1
Worse condition	2.38E + 02	1.30E + 02	5.21E + 09	− 8.36E + 00	22.9	0.82	14.4
$D_f^{a,c}$							
Better condition	1.51E + 03	4.24E + 02	2.39E + 05	− 4.85E + 00	116	0.53	12.4
Worse condition	1.46E + 03	4.23E + 02	3.38E + 07	− 6.35E + 00	101	0.67	14.9

[a] Weibull function; [b] MMF function; [c] Males only.
APVV, age at peak voice velocity.

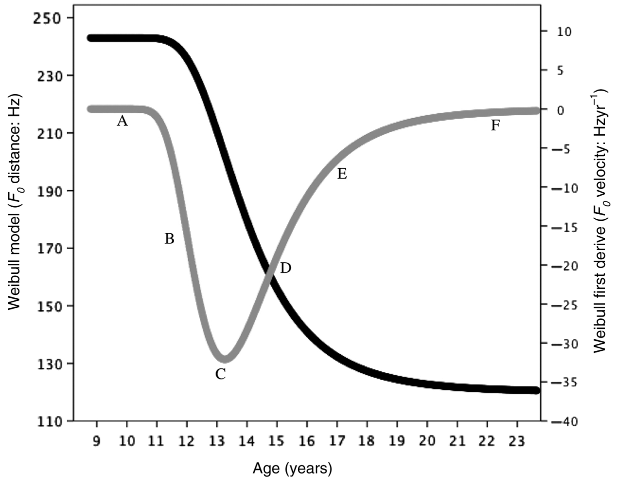

Figure 3. Representation of F_0 distance and velocity using the Weibull model and its derivative. *Note:* A = Minimium velocity, B = Maximal acceleration, C = Peak velocity, D = Maximal deceleration, E = 90% of adult value, F = Adult value. Numerical values for each of these milestones for F_0, D_f, and height can be found in Table III.

Growth is often described by auxologists as a distance 'travelled' by the individual (Bogin 1999; Cameron 2004; Molinari and Gasser 2004). The derivative of the 'distance' curve (the 'velocity' curve) is the rate of change in growth at different ages, while the rate of change in velocity ('acceleration') is specified by the second derivative. The derivative of the Weibull (3) models was used to understand variance in velocity at different ages for males. Parallel analyses were not performed for females because there was no clear and analogous 'spurt' in female voice change (see Figure 1).

$$f'(x) = bcdx^{d-1}e^{-cx^{d}} \qquad (3)$$

Using this function and its derivative, male voice change in this population can be defined more precisely (Bogin 1999; Cameron 2004; Molinari and Gasser 2004). We treat voice change here similarly to height change in order to increase comparability; that is, although F_0 and D_f are decreasing over time rather than increasing, we use terms such as 'peak' velocity, even though 'trough' velocity might be strictly more accurate. Age at minimal velocity (or 'takeoff', when acceleration is zero) is 11.1 for F_0 (at 243 Hz) and 10.1 for D_f (at 1485 Hz). This measure is used to mark the beginning of the linear growth spurt and can be treated similarly here. Maximal acceleration (the inflection point in the velocity curve leading to peak velocity) is at 12.0 for F_0 (at 213.8 Hz) and 11.1 for D_f (at 1467 Hz). Peak F_0 velocity occurs at age 13.3, at $-$ 32.1 Hz/year, when F_0 is 201 Hz. Peak D_f velocity occurs at age 13.5, at $-$ 56.6 Hz/year, when D_f is 1354 Hz. Adult values (at age 23) are 121 Hz for F_0 and 1075 Hz for D_f (see Table III).

In this model, F_0 'travels' from 243 Hz at age 11.1 to 121 Hz at age 23. Ninety per cent of this distance (to 133.2 Hz) is completed by age 16.9. D_f reaches 1075 Hz at age 23, beginning at 1485 Hz at age 10.1. Ninety per cent of this distance is reached at age 20, when D_f is 1116 Hz. Thus, change in F_0 occurs in a narrower window of time than change in D_f: 5.8 vs 9.9 years. In addition, F_0 makes a more dramatic change than D_f: Peak F_0 velocity is -32.1 Hz per year, which is 16% of F_0 at that age (201 Hz). Peak D_f velocity is -56.6 Hz per year, which is 4.2% of the D_f at that age (1354 Hz). Between the ages of maximal acceleration and maximal deceleration, which is often used to assess the intensity of a growth spurt (Molinari and Gasser 2004), F_0 'loses' 46.7 Hz—23.2% of F_0 at peak velocity—while D_f drops by 17.3%.

Comparison of change in F_0 of Tsimane adolescents with North American adolescents (males only)

In order to compare Tsimane vocal development with that of a more developed country, we applied the Weibull model to published age-specific F_0 averages from a North American sample (Huber et al. 1999). Model fit was excellent ($R^2 = 0.99$, SE = 6.9). Age at minimal velocity is 8.2 (at 248 Hz). Peak F_0 velocity occurs at age 12.0, at -23.1 Hz/year, when F_0 is 199 Hz. Maximal acceleration is at age 9.8 (at 241 Hz) and maximal deceleration is at 14.2 (at 153 Hz).

In order to offer a stricter age-matched comparison, we applied a Weibull model to equivalent age categories for the present sample of Tsimane adolescents ($R^2 = 0.93$, SE = 23.5). All landmarks occur $\sim$ 1 year later in the Tsimane: age at minimal velocity is 9.8 (at 248.5 Hz). Peak F_0 velocity occurs at age 12.9, at -23.1 Hz/year, when F_0 is 204 Hz. Maximal acceleration is at age 11.0 (at 240.9 Hz) and maximal deceleration is at 14.8 (at 164.2 Hz).

Comparison of F_0 change in Tsimane males in better vs worse condition

A similar analysis was used to compare voice change between males in better vs worse condition. For males in

Table III. Age and frequency for F_0 and D_f growth milestones based on Weibull model.

	F_0		D_f		Height	
	Age (years)	Frequency (Hz)	Age (years)	Frequency (Hz)	Age (years)	Height (cm)
Minimum velocity (A)	11.1	243.0	10.1	1485	7.5	121.6
Maximal acceleration (B)	12.0	213.8	11.1	1467	10.1	127.6
Peak velocity (C)	13.3	201.0	13.5	1354	12.4	141.0
Maximal deceleration (D)	14.5	167.1	15.9	1232	14.7	154.8
Length of spurt (D–B)	2.5	46.7	4.8	− 235	4.6	27.2
90% of adult value (E)	16.9	133.2	20.0	1116	17.2	162.6
Length of 90% change (E–A)	5.8	109.8	9.9	− 369	9.7	41.0
Adult value (F)	23.0	121.0	23.0	1075	23.0	167.1

Note: See Figure 3 for a visual guide to milestones A–F.

better condition, peak F_0 velocity occurs at age 13.1, at -35.3 Hz/year, when F_0 is 198 Hz. For males in worse condition, F_0 change occurs over 1 year later at a reduced velocity; peak F_0 velocity is at age 14.4, at -27.8 Hz/year, when F_0 is 195 Hz. Comparing across conditions, for D_f, peak velocity occurs at age 12.4 for those in good condition (vs 14.9 for those in poor), at -59.8 Hz/year (vs -65 Hz/year), when D_f is 1387 Hz (vs 1328 Hz). See Table II for model parameters.

Comparison of voice and height change in this sample

In order to illustrate the magnitude of change in vocal parameters relative to other changes in the pubertal phenotype, we compared F_0 and D_f with another widely used pubertal marker—height—using similar metrics. Because of the narrow range of ages in the present sample, the growth curves designed to fit the entire growth period (e.g. JPPS) were not appropriate. The best fit was offered by a MMF model (2), which explained 85% of the variance (SE = 6.8). The first derivative (4) was used to determine velocities.

$$f'(x) = \frac{(bc - ab)dx^d}{x^{2d+1} + 2bx^{d+1} + b^2x} \tag{4}$$

In this model, height increases from 121.6 cm at age 7.5 (at minimum velocity) to 167.1 cm at age 23. Ninety per cent of this distance (to 162.6 cm) is completed by age 17.2. Thus, the bulk of change in height (as dictated by this model) occurs over 9.7 years. Peak height velocity is 6.8 cm per year (at age 12.5 in this model), which is 2% of height at that age (141 cm). Between the ages of maximal acceleration (age 10.1) and maximal deceleration (age 14.7), height gains 27.2 cm—19.3% of height at peak height velocity (see Table III).

Several comparisons of the magnitude and intensity of change in height compared to F_0 and D_f were made for the peri-pubertal ages in this sample. First, voice change occurs over fewer numbers of years: 5.8 for F_0 and 9.9 for D_f vs 9.7 for height. Second, peak voice velocity (particularly F_0) may be thought of as more temporally compressed: the rate of change in F_0 is 16% of F_0 at peak velocity (4.2% for D_f) vs 2% of height at peak velocity (6.8 cm per year at 141 cm). Third, during the period between maximal acceleration and maximal deceleration, F_0 drops slightly more in frequency (23.2% of F_0 at peak velocity) in slightly more than half the time (2.5 years) than height does in centimetres (19.3% of height at peak velocity over 4.6 years).

DISCUSSION

To our knowledge this is the first attempt to explore voice change using auxological markers. Modelling the ‘growth’ curve of voice change facilitates quantification of the ages at peak voice velocity, minimum acceleration (i.e. ‘takeoff’ velocity), maximal acceleration and maximal deceleration in F_0 and D_f. Here we show that these parameters can be used to compare reproductive maturation of boys within and between populations and, therefore, can be utilized as a complement to existing pubertal markers.

Several advantages come with using voice characteristics to characterize the timing of the peri-pubertal shift from growth to reproduction. First, sampling a voice does not require an invasive interview or examination or the presence or participation of a parent or physician. Second, voice recordings are relatively simple and inexpensive to collect, store, transport and analyse. Voice analysis—particularly of F_0—is accessible to researchers of varying backgrounds and in different research settings. Third, frequencies are analysed digitally and expressed with an objective number, facilitating cross-sample comparison and limiting inter-researcher error, subjectivity and bias. Fourth, the voice is a socially significant characteristic and is likely to coincide with social and economic changes in males’ roles. Finally, the ‘growth spurt’ in F_0 is so pronounced that it can be easily detected and modelled in cross-sectional datasets. The growth spurt in height, by contrast, is sometimes difficult to model in cross-sectional analyses, especially if sample sizes are small or if growth is stunted (Bogin 1999).

Sex differences in F_0 and formant structure development during adolescence

Tsimane adolescent males show strikingly different F_0 and formant structure development from adolescent females. While female F_0 decreases linearly throughout development, male F_0 gradually lowers until around age 12–13, when it drops precipitously and significant sex differences emerge. Male formant structure slowly decreases until age 12, followed by a more rapid drop that diverges from females at age 15. Similar patterns of age-related change in male F_0 have been observed in several US and European samples (Baken 1987; Hollien et al. 1994; Titze 1994); however, no previous studies have examined voice change in a developing, energetically stressed population where growth and development are often adversely affected (Eveleth and Tanner 1990; Bogin 1999).

Comparison of F_0 change in Tsimane and North American males

An age-matched comparison of Tsimane and North American adolescents revealed that Tsimane voice change (as indicated by the age at peak F_0 velocity) occurs ~ 1 year later, but at the same F_0 and rate of change in F_0. A delay in puberty among males in this population accords with observed differences in Tsimane female reproductive timing; Tsimane age at menarche is ~ 13.0 (the current sample) to 13.9 (Walker et al. 2006), whereas the US age at menarche is ~ 12.4–12.6 (Bogin 1999; Herman-Giddens 2006; McDowell et al. 2007). Tsimane youth experience greater energetic stress than typical North American and Western European adolescents, with higher workloads, rates of parasitic infection (Tanner et al. 2009; Vasunilashorn et al. 2010; Blackwell et al. 2011), respiratory and gastrointestinal disease (Gurven et al. 2008) and anaemia (Vasunilashoren et al. 2010). According to life history theory, children and juveniles must trade-off between the competing energy demands of survivorship and growth. When survival-related energetic demands are high, individuals must delay the onset of pubertal maturation until energy stores are great enough to bear the demands of reproduction (Stearns 1992; Hill 1993; Bogin 1999; Kaplan et al. 2000). Although voices are not directly involved in reproduction, we show that voice change is also delayed in energetically stressed adolescents.

Comparison of F_0 and D_f change in Tsimane males in better vs worse condition

Differences in voice characteristics between Tsimane adolescents in relatively better vs worse condition provide a further test of the role of energetic burden in the development of male voices. Tsimane males in better condition had an earlier age at peak F_0 velocity (age 13.1) compared with those in worse condition (age 14.4). Similarly, males in better condition experienced peak velocity over 2 years earlier than those in poor condition. Variation within the Tsimane exists in many of the factors that affect life history, such as access to clean water, healthcare and high-quality food (Foster et al. 2005; Gurven et al. 2007).

It is notable that, in all groups (North America, better and worse condition Tsimane), peak F_0 velocity occurred within several Hertz of 200 Hz, despite occurring at variable ages and at disparate velocities in each group. Pedersen et al. (1986) also observed that adolescent F_0 aggregated into pre- and post-200 Hz groups. Using 200 Hz as a discrete milestone in pubertal development may also be of use to researchers.

Comparison of post-pubertal F_0 and D_f in Tsimane males vs other populations

Males in the current sample had a post-pubertal F_0 of 121 Hz. In comparison, Puts et al. (2012) found a mean F_0 of 111.4 Hz in a US college population and a mean of 114.7 in a Tanzanian forager population. Other studies have reported similar adult mean F_0 in US samples (Feinberg et al. 2005; Rendall et al. 2005; Puts et al. 2007). Tsimane adolescent males had a post-pubertal D_f of 1075 Hz. In a sample of 10 college-aged males aged 20–22, Feinberg et al. (2005) reported an average D_f of 1005 Hz, while Puts et al. (2012) reported a D_f of 985 Hz. Listeners attend to both F_0 and D_f (Puts et al. 2007; Feinberg et al. 2011) and on both of these dimensions Tsimane males have higher values—and thus higher voices—than US males.

Among energetically-stressed populations, a later age at peak height velocity and a slower rate of growth is associated with shorter stature in adulthood (Bogin 1999; Walker et al. 2006; Godoy et al. 2010). Here we show that Tsimane adolescents have a later age at peak F_0 velocity as well as a slower rate of F_0 descent and that this is associated with higher voices among post-pubertal Tsimane males.

Comparison of voice and height change in Tsimane males

In order to illustrate the conspicuous and acute nature of male pubertal voice change, we compared the magnitude and timing of F_0 and D_f change with that of height in this sample. Voice frequencies—particularly F_0—shift by a greater relative amount in a shorter window of time. One reason for this difference may be that development of the vocal folds is energetically inexpensive. At 17–26 mm (Titze 1994), the vocal folds require little physiological investment compared to general somatic growth (Gurven and Walker 2006). Similarly, F_0 makes a more dramatic change than Df or even height. D_f is relatively more constrained—by the bony morphology surrounding the vocal tract—than are the small soft-tissue features that determine F_0.

The fact that voice change—like height—manifests a ‘spurt’ is an interesting phenotypic design. According to Bogin (1999), the late male linear growth spurt has an adaptive function: boys can gain most of the reproductive, economic and social capacities of an adult male while outwardly appearing as a sub-adult. At the end of the adolescent period, when boys are ready to take on the costs associated with participation in the adult world of men, characteristics outwardly identified with manhood, such as height, change rapidly. Because a lower voice is associated with characteristics such as age (Collins 2000; Feinberg et al. 2005), size (Collins 2000; Feinberg et al. 2005) and physical and social dominance (Puts et al. 2006, 2007; Wolff and Puts 2010), the developmental pattern of male voice change may likewise follow this adaptive logic. That is, there may be costs to sounding like a man before one is ready to be a man.

Limitations

Several limitations of the present study should be noted. First, growth of all kinds is better described using longitudinal rather than cross-sectional data. Unfortunately, longitudinal data—especially of the kind needed to accurately measure voice change—are difficult to obtain. Second, sample size for our condition groups and for each age category was relatively small, which increases the chance that extreme values influenced the findings.

Like other measures of reproductive timing, the use of voice characteristics as a pubertal marker also has drawbacks. Collecting high-quality voice samples requires a quiet location with minimal background noise. In addition, voice characteristics may sometimes be affected by sickness, nervousness or other emotions and intentional manipulation. Finally, comparison across samples (i.e. between the Tsimane and North America) is confounded by differences in language. However, care was taken to use words with similar vowels as found in the English language and to use both high frequency (e.g. ‘ee’) and low frequency (e.g. ‘oh’ and ‘ah’) vowel sounds. Finally, it is unclear at this point how our measures align with other pubertal indicators and, for this reason, they may not yet be appropriate for identifying specific aspects of pubertal timing, such as the first onset of puberty, until more research is conducted.

CONCLUSIONS

In the present study, we argue that voice is one of the defining features of adolescent biology and can be used as a marker of the timing and degree of pubertal development.

Past under-utilization of the voice is likely due to the absence of accessible digital tools and processing power, rather than the voice's inability to appropriately mark pubertal change. We show that traditional auxological methods can be used to model voice change in adolescents and that this method can be used to compare development both within (i.e. F_0 vs D_f, voice vs height) and between (i.e. males vs females, better condition vs worse condition, Tsimane vs North America) populations. Future research should explore the factors that affect variance in vocal development within and across populations and in relation to other anthropometric, hormonal and psychological markers of growth and development.

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