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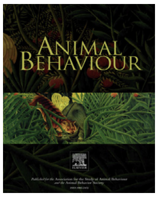

Voice parameters predict sex-specific body morphology in men and women

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Studies of several mammalian species confirm that formant frequencies (vocal tract resonances) predict height and weight better than does fundamental frequency (F0, perceived as pitch) in same-sex adults due to differential anatomical constraints. However, our recent meta-analysis (Pisanski et al., 2014, *Animal Behaviour, 95*, 89–99) indicated that formants and F0 could explain no more than 10% and 2% of the variance in human height, respectively, controlling for sex and age. Here, we examined whether other voice parameters, many of which are affected by sex hormones, can indicate additional variance in human body size or shape, and whether these relationships differ between the sexes. Using a cross-cultural sample of 700 men and women, we examined relationships among 19 voice parameters (minimum–maximum F0, mean F0, F0 variability, formant-based vocal tract length estimates, shimmer, jitter, harmonics-to-noise ratio) and eight indices of body size or shape (height, weight, body mass index, hip, waist and chest circumferences, waist-to-hip ratio, chest-to-hip ratio). Our results confirm that formant measures explain the most variance in heights and weights of men and women, whereas shimmer, jitter and harmonics-to-noise ratio do not indicate height, weight or body mass index in either sex. In contrast, these perturbation and noise parameters, in addition to F0 range and variability, explained more variance in body shape than did formants or mean F0, particularly among men. Shimmer or jitter explained the most variance in men's hip circumferences (12%) and chest-to-hip ratios (6%), whereas harmonics-to-noise ratio and formants explained the most variance in women's waist-to-hip ratios (11%), and significantly more than in men's waist-to-hip ratios. Our study represents the most comprehensive analysis of vocal indicators of human body size to date and offers a foundation for future research examining the hormonal mechanisms of voice production in humans and perceptual playback experiments.

Many animals use vocalizations to communicate in social contexts. Vocalizations may communicate an animal's motivational state (Morton, 1977) but can also function as indexical cues to identity, sex and various physical traits (Ghazanfar & Rendall, 2008; Owren, 2011). Bioacoustic analyses suggest that the vocalizations of mammals contain reliable and perpetually salient information about a vocalizer's body size and mass (Ey, Pfefferle, & Fischer, 2007; Pisanski, Fraccaro, Tigue, O'Connor, Röder, et al., 2014; Taylor & Reby, 2010), and playback experiments suggest that both human and nonhuman listeners may use vocalizations to gauge the body size of conspecifics (e.g. humans, *Homo sapiens*: Charlton, Taylor, & Reby, 2013; Pisanski, Fraccaro, Tigue, O'Connor, & Feinberg, 2014; Rendall, Vokey, & Nemeth, 2007; Smith & Patterson, 2005; red deer, *Cervus elaphus*: Charlton, Reby, & McComb, 2007; koalas, *Phascolarctos cinereus*: Charlton, Whisson, & Reby, 2013; rhesus macques, *Macaca mulatta*: Fitch & Fritz, 2006; dogs, *Canis lupus familiaris*: Taylor, Reby, & McComb, 2010).

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Known Vocal Indicators of Body Size

Following the source-filter theory of speech production (Fant, 1960), researchers attempting to uncover which voice parameters may reliably indicate body size in humans and other mammals have focused on two largely independent features of the voice: mean fundamental frequency (F0, produced by vocal fold vibration and perceived as voice pitch) and formant frequencies (produced by filtering of the supralaryngeal vocal tract; Titze, 1994). Among humans, our recent meta-analysis showed that formants predict height and weight more reliably than does F0 when sex and age are controlled for (Pisanski, Fraccaro, Tigue, O'Connor, Röder, et al., 2014). This finding supports the prediction that mammalian formants are more anatomically constrained than is F0 (Fitch, 1994, 2000) and corroborates findings from several other mammalian species (reviewed in Kreiman & Sidtis, 2011). However, the meta-analysis also highlighted that formants could explain no more than 10% of the variance in men's heights, whereas mean F0 explained less than 2%. Formants accounted for even less of the variance in women's heights (6%), whereas mean F0 was not significantly correlated with height among women (Pisanski, Fraccaro, Tigue, O'Connor, Röder, et al., 2014). Because of the limited number of studies investigating other kinds of voice–body relationships, the meta-analysis did not test whether vocal features other than mean F0 or formants could explain additional variance in human body size, and did not examine relationships between the voice and body shape, such as circumference parameters.

Fundamental Frequency Range and Variability

A growing literature suggests that several voice parameters, in addition to formants and mean F0, may indicate body size and shape in one sex or the other. These voice parameters include non-mean-based measures of fundamental frequency such as minimum F0, maximum F0 and F0 variability (the standard deviation of F0, F0 SD) that are sexually dimorphic (Puts, Apicella, & Cardenas, 2012). These source measures indicate the upper and lower range of an individual's voice pitch and the degree to which voice pitch deviates from baseline across an utterance. The standard deviation of men's F0 appears to be a particularly reliable indicator of status, correlating negatively with self-reported dominance, reproductive success and testosterone level (Hodges-Simeon, Gaulin, & Puts, 2010, 2011). In a cross-cultural study, Puts, Apicella, et al. (2012) found that F0 SD predicted self-reported physical aggression in American men, and was marginally negatively related to arm strength among American but not Hadza men. In that study, however, formants reliably predicted height in both samples of men, whereas F0 SD did not.

Vocal Perturbation and Noise

Vocal frequency perturbation (jitter), amplitude perturbation (shimmer) and noise (harmonics-to-noise ratio) parameters may also correlate with body size or shape as they relate to the mass and oscillating properties of the vocal folds. Jitter and shimmer measure the mean deviation in voice pitch or amplitude between adjacent cycles, whereas harmonics-to-noise ratio measures the relative degree of periodicity to aperiodicity in the voice. A relatively high degree of jitter or shimmer or a low harmonics-to-noise ratio can indicate irregular vocal fold vibration, often caused by laryngeal asymmetry in mass or tension, which can result in vocal breathiness and hoarseness (Buder, 2000). Traditionally, these measures have been used by clinicians to assess voice quality in pathological voices (Maryn, Roy, De Bodt, Van Cauwenberge, & Corthals, 2009), however, several researchers have criticized the validity of jitter and shimmer as reliable indices of voice quality (Hillenbrand, 1987; Kreiman & Gerratt, 2005; Maryn et al., 2009).

Linders, Massa, Boersma, and Dejonckere (1995) suggested that jitter and body size may be negatively related to the extent that larger, more massive vocal folds may result in a mechanical dampening of vocal fold oscillation, producing a steadier voice pitch (see also Lieberman, 1963; Titze, 1988). However, vocal fold mass is more closely related to sex hormone levels than to height, where for example pubertal increases in testosterone masculinize and enlarge the vocal folds causing F0 to drop (Hollien, Green, & Massey, 1994; Prelevic, 2013). Indeed, researchers have long proposed that sex hormones may influence voice perturbation and noise parameters, either by affecting the mass of the vocal folds, or the motor and sensory processes involved in laryngeal control (e.g. Higgins & Saxman, 1989; Silverman & Zimmer, 1978; for more recent work see Gugatschka et al., 2010; Prelevic, 2013). It follows that jitter, shimmer and harmonics-to-noise ratio may relate to body size and in particular body shape via the shared influence of sex hormones on these vocal properties and on the development and distribution of fat and muscle on the body.

Relationships between perturbation or noise parameters and the human body have been examined in only a small number of studies with mixed results. González (2007) found that jitter correlated positively with women's body mass, such that heavier women showed more irregularities in their voice pitch, whereas shimmer and harmonics-to-noise ratio were relatively poor indicators of women's, and even less so of men's, heights and weights. In contrast, Linders et al. (1995) reported a negative correlation between jitter and height in prepubescent girls and boys independent of gender, suggesting that before puberty, shorter children show more irregularities in their voice pitch than do taller children. Finally, Hamdan et al. (2012) failed to find relationships between body size and jitter or harmonics-to-noise ratio, but reported weak positive relationships between shimmer and trunk fat or muscle mass in men. The largest same-sex sample among these studies included only 81 individuals (González, 2007), which may be too few to detect various voice–body relationships.

Vocal Indicators of Body Shape?

There is some evidence that information about body shape, not only height and weight, may be present in the human voice. The principal mechanism linking voice to body shape may be hormonal (Hughes & Gallup, 2008). In addition to affecting voice F0 and formants, and possibly also perturbation parameters (Abitbol, Abitbol, & Abitbol, 1999; Dabbs & Mallinger, 1999; Lieberman, McCarthy, Hiiemae, & Palmer, 2001), oestrogens and androgens affect the circumferences of the waist, hips and chest and the ratios among them (waist-to-hip ratio, chest-to-hip ratio), as well as an individual's body mass index (Blouin, Boivin, & Tchernof, 2008; Derby, Zilber, Brambilla, Morales, & McKinlay, 2006; Evans, Hoffmann, Kalkhoff, & Kissebah, 1983). These indices of body shape are sexually dimorphic and can vary independently of one another within the same individual. Moreover, the distribution of fat and muscle mass on the body that determines body shape is largely independent of the amount of fat and muscle on the body that determines body mass (Singh & Singh, 2011).

Similar to physical height, indices of body shape such as waist-to-hip ratio and chest-to-hip ratio can provide socially relevant information about an individual (Hughes & Gallup, 2008). For instance, body shape predicts a wide range of health-related factors in both sexes, controlling for body mass (Blouin et al., 2008; Larsson et al., 1984; Seidell, 2009). Among women, waist-to-hip ratio and the body mass index are robust predictors of fecundity and correlate with ratings of women's physical attractiveness from photographs (Kaye, Folsom, Prineas, Potter, & Gapstur, 1990; Singh, 1993; Zaadstra et al., 1993). Women with lower waist-to-hip ratios are also rated as having more attractive voices (Hughes, Dispenza, & Gallup, 2004), and listeners are able to gauge women's waist-to-hip ratios from their voices alone (Hughes, Harrison, & Gallup, 2009). Among men, chest-to-hip ratio and height positively predict physical attractiveness and reproductive success (Pawlowski, Dunbar, & Lipowicz, 2000; Swami et al., 2007). Like body size, body shape influences mate preferences across a range of human cultures (Pisanski & Feinberg, 2013) and is likely to be important for both mate selection and intersexual competition.

Few studies have examined vocal indicators of body shape compared to body size, and again the results of this work are mixed. Early studies examined relationships between principal components of voice and body shape (i.e. factor scores) in small samples of men or women ($N = 26$–34), making interpretation of results difficult. In these studies, Collins (2000) and Bruckert, Liénard, Lacroix, Kreutzer, and Leboucher (2006) failed to find relationships between voice and body shape components among men, whereas Collins and Missing (2003) reported that women with higher harmonics (integer multiples of F0) had lower scores on a body component comprising body mass index, weight, waist and hip circumference. Evans, Neave, and Wakelin (2006) reported negative relationships between men's mean F0 and their shoulder and chest circumferences or shoulder-to-hip ratios, but no relationship between men's F0 and shoulder-to-waist or waist-to-hip ratios. More recently, in a sample of 109 women, Vukovic, Feinberg, DeBruine, Smith, and Jones (2010) reported negative relationships between women's mean F0s and their body mass indices and hip circumferences, but not waist circumferences or waist-to-hip ratios.

Key Research Questions

In the present study, we address three key research questions. (1) Do voice parameters other than formants and mean F0 explain additional variance in men's and women's heights and weights (i.e. body size)? (2) Does any voice parameter explain variance in the circumferences and circumference ratios of the waist, hips and chest (i.e. body shape)? (3) Do voice parameters explain more variance in the body size or shape of one sex than the other? To answer these questions we examined relationships among 19 voice parameters and eight indices of body size or shape in a large cross-cultural sample of adult men and women. To our knowledge, our study is the first to examine relationships between body shape and any of the following vocal parameters: minimum F0, maximum F0, F0 variability, jitter, shimmer and harmonics-to-noise ratio. Although the voice–body relationships investigated in this study were chosen on the basis of the theoretical and empirical work reviewed above, the study is exploratory in nature. The principal aim of the study is to offer a comprehensive account of vocal correlates of body size and shape in humans that may help researchers to generate novel testable hypotheses concerning the mechanisms and functions of these relationships, and ultimately allow for a meta-analysis of less commonly studied voice–body relationships.

METHODS

Sample Characteristics

Voice recordings and body measures derived from a total of 700 adults from Canada ($N = 118$ women, 185 men), Scotland ($N = 235$ women, 111 men) and Germany ($N = 85$ women). Age data were available for the Canadian (mean ± SE: men: 18.7 ± 1.5, women: 19 ± 2.3, range 17–30 years) and German (23.1 ± 2.2, range 19–30 years) samples. Voice recordings and body measures were initially collected for other research; as a result, age data were unavailable for the Scottish sample and only female participants were included in the German sample. All participants were students at local universities who provided written informed consent to participate in the study, and all procedures were approved by the research ethics review board.

Voice Recording

Participants were recorded in a sound-attenuated chamber using a professional condenser microphone with a cardioid pick-up pattern and at an approximate distance of 5–10 cm. All participants were recorded speaking five vowel sounds. For the Canadian and German samples, the five vowels were /ɑ/, /i/, /ɛ/, /o/ and /u/ (International Phonetic Alphabetic notation). For the Scottish sample, the vowels were /eɪ/, /i/, /aɪ/, /o/ and /ju/.

Voice Measurement and Analysis

Voice measurements and analyses were performed in Praat (Boersma & Weenink, 2013). For each vocalizer we analysed 19 voice parameters including minimum and maximum F0, mean F0, the standard deviation of F0 (F0 SD), three perturbation or noise parameters (shimmer, jitter and harmonics-to-noise ratio), the first to fourth formants (F1–F4) and several amalgamated formant-based parameters, henceforth termed vocal tract length (VTL) estimates, as follows: average formant frequency, F_n (Pisanski & Rendall, 2011); formant dispersion, D_f (Fitch, 1997); formant position, P_f (Puts, Apicella, et al., 2012); formant spacing and apparent vocal tract length derived from formant spacing, ΔF and $VTL(\Delta F)$ (Reby & McComb, 2003); apparent vocal tract length derived from mean formants, $VTL(F_i)$ (adapted from Fitch, 1997; see also Titze, 1994); geometric mean formant frequency, MFF (Smith & Patterson, 2005); and factor scores from a confirmatory factor analysis, CFA (Turner, Walters, Monaghan, & Patterson, 2009). The algorithms used to compute VTL estimates are provided in Pisanski, Fraccaro, Tigue, O'Connor, Röder, et al. (2014). All mean voice measurements were taken from the steady-state portion of each of five isolated vowels per vocalizer, averaged within vocalizers, and then within sex to obtain mean values.

We measured all F0 parameters using Praat's autocorrelation algorithm with a search range set to 65–300 Hz for men and 100–600 Hz for women and measured formants F1–F4 using Praat's Burg linear predictive coding algorithm with the initial settings of maximum formant set to 5000 Hz for men and 5500 Hz for women. Formants were first overlaid on a spectrogram and formant number was manually adjusted until the best visual fit of predicted onto observed formants was obtained (Boersma & Weenink, 2013; see Praat user manual, www.praat.org). The fundamental frequency and formant measures we obtained (see Table 1) agree well with weighted population-level averages (Pisanski, Fraccaro, Tigue, O'Connor, Röder, et al., 2014). From the mean F1–F4 values we computed eight different VTL estimates (F_n, D_f, P_f, ΔF, $VTL(\Delta F)$, $VTL(F_i)$, MFF and CFA; see Table 1 for descriptive statistics, and Pisanski, Fraccaro, Tigue, O'Connor, Röder, et al. (2014) for additional details and algorithms used to compute VTL estimates).

We measured one noise parameter (harmonics-to-noise ratio), five frequency perturbation or jitter parameters (local, local absolute, rap, ppq5, ddp) and six amplitude perturbation or shimmer parameters (local, local dB, apq3, apq5, apq11, dda) using Praat's cross-correlation algorithm (Table 1; see also Baken & Orlikoff, 2000). The five jitter measures correlated significantly with one

Table 1
Mean values ± SD for vocal parameters and indices of body size or shape in men and women

Parameter	Men	Women
Voice[a]		
F0 mean (Hz)	114.16±17.01	210.52±21.58
F0 min (Hz)	90.03±17.78	162.76±40.20
F0 max (Hz)	179.19±65.14	370.67±146.33
F0 SD (Hz)	14.85±11.16	33.53±24.19
F1 (Hz)	466.61±45.92	516±79
F2 (Hz)	1520.45±140.33	1848±200
F3 (Hz)	2592.49±132.29	3020±199
F4 (Hz)	3493.87±187.54	4100±217
F_n (Hz)	2015.99±93.32	2293.55±247.80
Df (Hz)	1008.84±62.40	1194.79±69.34
P_f (Z(Hz)	-0.58±0.63	0.30±0.47
ΔF (Hz)	1010.66±46.09	1187.16±66.21
VTL(F_i) (cm)	18.75±2.10	15.61±1.63
VTL(ΔF) (cm)	17.35±0.79	14.79±0.84
MFF (Hz)	1589.07±71.37	1847.59±133.57
Jitter local (%)	0.0958±0.037	0.0911±0.05
Jitter local absolute (s)	0.00013±0.00007	0.00006±0.00003
Jitter rap (%)	0.0066±0.004	0.0072±0.004
Jitter ppq5 (%)	0.0067±0.004	0.0070±0.004
Jitter ddp (%)	0.0199±0.011	0.2146±0.013
Shimmer local (%)	0.0958±0.037	0.0911±0.054
Shimmer local (dB)	0.9438±0.315	0.8690±0.454
Shimmer apq3 (%)	0.0416±0.018	0.0425±0.026
Shimmer apq5 (%)	0.0587±0.028	0.0615±0.044
Shimmer apq11 (%)	0.0868±0.039	0.0920±0.076
Shimmer dda (%)	0.1249±0.055	0.1285±0.076
HNR (dB)	14.15±3.21	14.73±4.62
Body		
Height (cm)	179.34±7.16	166.37±6.93
Weight (kg)	74.96±12.44	63.28±10.77
BMI	23.27±3.26	22.87±3.64
Hip circ. (cm)	99.55±7.87	99.20±7.69
Waist circ. (cm)	83.81±8.12	74.54±7.97
Chest circ. (cm)	95.87±8.57	88.67±7.34
WHR	0.84±0.06	0.75±0.05
CHR	0.96±0.07	0.90±0.05

F0: fundamental frequency; F1–F4: first to fourth formant; F_n: average formant frequency; MFF: geometric mean formant frequency; D_f: formant dispersion; P_f: formant position; ΔF: formant spacing; VTL(F_i): apparent vocal tract length derived from mean formants; VTL(ΔF): apparent vocal tract length derived from formant spacing; HNR: harmonics-to-noise-ratio; BMI: body mass index; WHR: waist-to-hip ratio; CHR: chest-to-hip ratio; circ.: circumference.

[a] See Baken and Orlikoff (2000) for a detailed description and comparison of different jitter and shimmer measures.

another (all $r > 0.43$, all $P < 0.001$), and the five shimmer measures correlated significantly with one another (all $r > 0.88$, all $P < 0.001$). Hence, using principal component analyses, we reduced each set of measures to a single dimension (henceforth termed 'jitter' and 'shimmer') for which 78% and 94% of the variance was explained, respectively.

Body Size and Shape Measurement

We assessed a total of eight body size and shape measures including height, weight, body mass index, hip circumference, waist circumference, chest circumference, waist-to-hip ratio and chest-to-hip ratio (see Table 1). Height was measured using a stadiometer or metric tape affixed to the wall, and weight was measured using an electronic scale. Participant's body mass index was computed as weight (kg)/height (m)^2 (where 18.5 to 24.9 indicates normal weight as defined by the World Health Organization, http://www.who.int/mediacentre/factsheets/fs311/en/). Circumference measures were taken using metric tape following previous work (i.e. waist circumference was taken at the narrowest point between the rib cage and iliac crest; hip circumference was taken at the widest point between the waist and thigh; chest circumference was taken at the widest point with the tape measure placed under the arm pits and, for women, above the breasts; Evans et al., 2006; Hughes, Dispenza, & Gallup, 2004; Singh, 1993; Vukovic et al., 2010). Participant's waist-to-hip ratios were computed as the ratio of the waist circumference to the hip circumference and chest-to-hip ratios were computed as the ratio of the chest circumference to the hip circumference.

Statistical Analysis

Shapiro–Wilk tests of normality indicated that many individual voice or body parameters were non-normally distributed. Hence, we examined relationships between the 19 individual voice parameters and the eight individual body size or shape parameters using nonparametric Spearman rank correlations (r_S). We then tested whether the strength of various voice–body relationships differed significantly for samples of men and women by transforming correlation coefficients using Fisher's r-to-z transformations and running a series of independent-samples inference tests (Myers & Sirois, 2006). As our goal was to examine predictive utility differences in the strength of relationships between sexes, we used the more conservative approach of comparing absolute r_S values (i.e. ignoring the sign of the correlation, which in some cases would have inflated the apparent sex difference). Effect sizes for sex differences in $|r_S|$ are given as Cohen's q (Cohen, 1988). All analyses were conducted for each sex separately and all statistical tests were two tailed with an alpha of 0.05.

RESULTS

Relationships Between Individual Voice and Body Parameters

Correlations between individual voice parameters and indices of body size and shape are reported in Table 2.

Vocal tract length estimates

Compared to all other voice parameters, VTL estimates most strongly predicted height and weight within each sex, explaining upwards of 7.3% and 6.7% of the variance in men's heights and weights, respectively, and 6.7% and 6.3% of the variance in women's heights and weights, respectively. The VTL estimates correlated with men's and women's heights and weights more strongly than did mean F0 (barring F1 and F2), replicating the findings of Pisanski, Fraccaro, Tigue, O'Connor, Röder, et al. (2014). Although several VTL estimates correlated significantly with men's and women's body mass indices, these relationships were weaker than for height or weight alone.

Among women, most VTL estimates also correlated significantly with women's hip, chest and waist circumferences. The VTL estimates were also good predictor's of women's waist-to-hip ratios, wherein F_n explained 9% of the variance in waist-to-hip ratios among women. Despite our large sample size ($N = 297$), power analysis (alpha = 0.05, power = 0.80) indicated that a sample size of only 85 is required for F_n to reliably predict women's waist-to-hip ratios. Among the VTL estimates, only F_n correlated significantly with women's chest-to-hip ratios, but explained a mere 1.4% of the variance. Compared to women, VTL estimates were relatively poor predictors of men's body shapes. Only F1, F3, P_f and MFF correlated significantly with men's hip and chest circumferences, only P_f and CFA correlated with men's waist-to-hip ratios, and no VTL estimate correlated with men's waist circumferences or chest-to-hip ratios.

Table 2

Relationships between individual voice parameters and individual indices of body size or shape in men and women

Parameter	Men								Women							
	Height $N=262$	Weight $N=259$	BMI $N=259$	Hip circ. $N=100$	Waist circ. $N=100$	Chest circ. $N=100$	WHR $N=100$	CHR $N=100$	Height $N=438$	Weight $N=436$	BMI $N=436$	Hip circ. $N=297$	Waist circ. $N=297$	Chest circ. $N=297$	WHR $N=297$	CHR $N=297$
F0 mean	**−0.17****	−0.09	−0.01	−0.10	−0.08	−0.09	0.09	0.03	**−0.10***	**−0.20****	**−0.16****	**−0.14***	**−0.16****	**−0.20****	−0.09	−0.11
F0 min	−0.11†	**−0.13***	−0.08	0.06	−0.06	−0.11	−0.11	**−0.20***	0.04	−0.03	−0.05	0.03	0.01	−0.03	−0.04	−0.09
F0 max	−0.15*	**−0.19***	**−0.13***	**−0.33****	−0.18†	**−0.21***	0.10	0.09	−0.07	**−0.16****	**−0.14****	−0.09†	**−0.19****	**−0.16****	−0.14*	**−0.10***
F0 SD	−0.06	−0.11†	−0.09	**−0.31****	−0.13	−0.13	0.14	0.15	−0.07	**−0.15****	**−0.12***	**−0.13***	**−0.22****	**−0.19****	**−0.15***	−0.09
Shimmer	0.03	0.01	−0.01	**−0.33****	−0.12	−0.10	0.14	**0.24***	−0.05	−0.08†	−0.06	−0.01	**−0.22****	−0.08	**−0.27****	−0.10
Jitter	−0.01	−0.05	−0.06	**−0.34****	−0.15	−0.15	0.13	0.15	−0.04	−0.08	−0.06	−0.02	**−0.22****	**−0.11***	**−0.27****	**−0.12***
HNR[a]	−0.08	−0.10	−0.07	−0.01	−0.01	−0.17	−0.07	**−0.21***	**−0.11***	−0.08	−0.05	**−0.21****	0.08	−0.11	**0.33****	0.14†
F1	**−0.15***	**−0.26****	**−0.21***	**−0.24****	−0.12	**−0.18***	0.13	0.06	**−0.15****	**−0.18****	**−0.11***	**−0.18****	0.06	**−0.14***	**0.26****	0.06
F2	−0.09	−0.02	0.04	−0.14	−0.05	−0.14	0.16	0.06	**−0.15****	−0.07	−0.01	**−0.17****	−0.09	**−0.14***	0.08	0.06
F3	**−0.21****	**−0.18****	−0.08	**−0.22***	−0.10	**−0.23***	0.17†	0.01	**−0.18****	**−0.15****	−0.07	**−0.18****	**−0.16****	**−0.17****	−0.02	0.01
F4	**−0.25****	**−0.19****	−0.08	−0.03	−0.02	−0.07	0.10	−0.06	**−0.26****	**−0.25****	**−0.14****	**−0.27****	**−0.13***	**−0.22****	0.10†	0.09
F_n	**−0.26****	**−0.18***	−0.06	−0.14	0.04	−0.15	0.15	−0.01	**−0.22****	**−0.19****	**−0.10***	**−0.25****	−0.01	**−0.18****	**0.30****	**0.12***
D_f	**−0.21****	**−0.13***	−0.02	0.04	−0.03	−0.01	0.07	−0.08	**−0.23****	**−0.22****	**−0.12***	**−0.24****	**−0.16****	**−0.20****	0.03	0.08
P_f	**−0.13***	**−0.20****	**−0.15***	**−0.33****	−0.14	**−0.25***	**0.24***	0.11	**−0.24****	**−0.24****	**−0.13****	**−0.24****	−0.07	**−0.20****	**0.17****	0.08
ΔF	**−0.25****	**−0.18****	−0.06	−0.09	0.03	−0.13	0.15	−0.05	**−0.24****	**−0.22****	**−0.11***	**−0.26****	**−0.15****	**−0.22****	0.08	0.07
VTL(F_i)	**0.18****	**0.12***	0.04	−0.01	0.02	0.06	−0.03	0.07	**0.16****	**0.18****	**0.11***	**0.17****	−0.06	0.09†	**−0.27****	−0.11†
VTL(ΔF)	**0.25****	**0.18****	0.05	0.09	0.03	0.13	−0.14	0.05	**0.25****	**0.22****	**0.11***	**0.26****	**0.15****	**0.22****	−0.08	−0.07
MFF	**−0.23****	**−0.23****	**−0.13***	**−0.23***	−0.11	**−0.22***	0.17†	0.04	**−0.23****	**−0.21****	**−0.11***	**−0.23****	−0.06	**−0.18****	**0.18****	0.07
CFA[b]	**0.27****	**0.21****	0.09	0.18†	0.07	0.17†	**−0.20***	−0.05	**−0.24****	**−0.22****	**−0.11***	**−0.26****	−0.04	**−0.22***	**0.20****	0.05

F0: fundamental frequency; F1−F4: first to fourth formant; F_n: average formant frequency; MFF: geometric mean formant frequency; D_f: formant dispersion; P_f: formant position; ΔF: formant spacing; VTL(F_i): apparent vocal tract length derived from mean formants; VTL(ΔF): apparent vocal tract length derived from formant spacing; CFA: confirmatory factor analysis (factor scores); HNR: harmonics-to-noise-ratio; BMI: body mass index; WHR: waist-to-hip ratio; CHR: chest-to-hip ratio; circ.: circumference.

Statistical significance of bivariate Spearman correlation (r_S) is based on a two-tailed t test ($^{\dagger}P < 0.10$; $^{*}P < 0.05$; $^{**}P < 0.01$). Significant correlations ($P < 0.05$) are shown in bold.

[a] Sample size for women's HNRs = 185.

[b] Sample sizes for women's CFA scores = 326 (height), 324 (weight, BMI) and 100 (circumference measures, WHR, CHR).

Fundamental frequency parameters

Although mean F0 explained some variance in height within each sex (2.6% among men and 1.9% among women) and in women's weights, body mass indices and circumference measures (up to 4%), mean F0 did not significantly indicate waist-to-hip ratio or chest-to-hip ratio in either sex. Rather, F0 range and variability were better predictor's of body shape than was mean F0. Among these F0 parameters, minimum and maximum F0 significantly predicted men's and women's chest-to-hip ratios, respectively, and maximum F0 and F0 SD predicted women's waist-to-hip ratios. Maximum F0 and F0 SD also correlated significantly with circumference measures in each sex. Compared to mean F0, which did not indicate body shape among men, maximum F0 and F0 SD explained a noteworthy 11% of the variance in men's hip circumferences.

Vocal perturbation and noise parameters

Shimmer and jitter were not correlated with height, weight or body mass index in either sex. Harmonics-to-noise ratio also was not correlated with height or body mass index in either sex, but it did explain a significant yet small (1.2%) amount of the variance in women's heights. In contrast to indices of body size, each of these parameters significantly predicted one or more indices of body shape including circumference measures, waist-to-hip ratios and chest-to-hip ratios. Compared to all other voice parameters, shimmer explained the most variance in men's chest-to-hip ratios (5.7%), followed by harmonics-to-noise ratio (4.4%), whereas harmonics-to-noise ratio explained the most variance in women's waist-to-hip ratios (10.8%), followed by F_n (9%), VTL(F_i), jitter and shimmer (each 7.3%).

Sex differences

Following Fisher's *r*-to-*z* transformations controlling for sample size, we tested whether the 19 individual voice parameters reported in Table 1 indicated body size or shape significantly better in one sex than the other. Our results indicated that harmonics-to-noise ratio and VTL(F_i) predicted women's waist-to-hip ratios better than men's waist-to-hip ratios, and the VTL estimates F4 and D_f predicted women's hip circumferences better than men's hip circumferences. In contrast, maximum F0, shimmer and jitter each predicted men's hip circumferences better than women's (see Table 3). Several nonsignificant patterns emerged, namely: VTL estimates generally explained more variance in men's than in women's heights; noise and perturbation parameters explained more variance in men's than in women's chest-to-hip ratios; and mean F0 explained more variance in women's than in men's weights, body mass indices and circumference measures.

Table 3

Significant sex differences in relationships between the voice and body shape

Body shape parameter	Voice measure	*Z*	*P*	Cohen's *q*
Stronger relationships in men:				
Hip circumference	Shimmer	2.84	<0.01	0.33
	Jitter	2.85	<0.01	0.33
	F0 max	2.16	0.03	0.25
Stronger relationships in women:				
WHR	HNR	2.33	0.02	0.27
	VTL(F_i)	2.11	0.03	0.25
Hip circumference	F4	2.11	0.03	0.25
	Df	2.43	0.01	0.29

F0: fundamental frequency; WHR: waist-to-hip ratio; HNR: harmonics-to-noise-ratio; VTL(F_i): apparent vocal tract length derived from mean formants; F4: fourth formant; Df: formant dispersion.

Statistical significance is based on a two-tailed test comparing correlation coefficients following Fisher's *r*-to-*z* transformations. Only significant relationships ($P < 0.05$) are shown in this table. Effect sizes for differences in correlation strength between sexes are given as Cohen's *q* (note that all reported effect sizes fell around the lower threshold of a medium effect size (0.30)).

DISCUSSION

Our findings demonstrate that the human voice can indicate both body size and shape among adult men and women. We extend the findings of a recent meta-analysis (Pisanski, Fraccaro, Tigue, O'Connor, Röder, et al., 2014) and show that, in addition to formant frequencies, several other voice parameters including minimum and maximum F0, F0 variability, jitter, shimmer and harmonics-to-noise ratio may communicate meaningful information about body size or shape. We emphasize, however, that these voice parameters could explain only a small amount of the variation in various indices of human body size and shape controlling for sex and age, and in some cases, the strength of voice—body relationships varied between men and women. Our key findings are discussed in detail below.

Vocal Tract Length Estimates

Formants are constrained by the length and dimensions of the mammalian vocal tract, which in turn is positively related to skull size and height between and within sexes (Fitch, 2000; Fitch & Giedd, 1999). Thus, formants predict vocal tract length in many mammals including humans (Fitch & Hauser, 2003; Taylor & Reby, 2010). In men, formants also appear to predict circulating levels of testosterone (Bruckert et al., 2006; Cartei, Bond, & Reby, 2014; Evans, Neave, Wakelin, & Hamilton, 2008), which can affect muscularity and the distribution of fat on men's bodies (Blouin et al., 2008), but it remains unknown whether sex hormones affect the formant frequencies of women's voices. Our results indicate that formant-based VTL estimates correlate with men's and women's heights and weights more reliably than any other voice parameter investigated in this study. In addition, our study shows that VTL estimates correlate with one or more indices of body shape in each sex, including hip, waist and chest circumferences, waist-to-hip ratios and chest-to-hip ratios.

Formants were particularly robust indicators of body shape among women. One previous study tested but failed to find significant relationships between women's voice parameters (principal components representing F0 and formants) and body shape. This may be because the authors used factor scores in their regression analyses and a sample of only 30 women (Collins & Missing, 2003). Thus, our study presents the first evidence that formants can explain variation in women's body shapes given an adequate sample size (here, $N = 297$, but power analysis suggested that a sample of $N = 85$ would suffice). Moreover, many individual VTL estimates explained several times more variance in circumference measures and waist-to-hip ratios of women than of men. Indeed, only four formant measures (F1, F3, P_f and MFF) significantly predicted variation in men's hip circumferences and chest circumferences, and only one (CFA) predicted variation in men's waist-to-hip ratios, whereas no voice parameter predicted men's waist circumferences. Theoretically, the finding that women's voices may carry information about their waist-to-hip ratios is in line with a growing body of literature implicating the 'hour-glass' shape of a woman's body as a key indicator of her age, fertility status and health (Pisanski & Feinberg, 2013; Singh & Singh, 2011). As an important determinant of her physical attractiveness and desirability as a potential mate, a woman's body shape may be advertised through various modalities, including her voice. However, on a proximate level, the mechanism linking formants to women's waist-to-hip ratios remains unclear and will require a more comprehensive understanding of the relative roles of androgens and oestrogens on formant production (particularly among women) and on regional fat distribution.

Fundamental Frequency Parameters

Previous studies have shown that when sex and age are controlled, mean fundamental frequency (F0 or voice pitch) is a weak predictor of height in humans (Pisanski, Fraccaro, Tigue, O'Connor, Röder, et al., 2014) and of body size in many other mammals (for reviews, see Ey et al., 2007; Fitch & Hauser, 2003). The length and tension of the vocal folds determine mean F0 (Titze, 1994). However, human vocal folds can develop and grow independently of the rest of the body, as their size appears more closely related to testosterone levels at puberty and into adulthood than to body size (Dabbs & Mallinger, 1999; Harries, Walker, Williams, Hawkins, & Hughes, 1997).

In our study, mean F0 predicted weight, body mass index and body circumferences only among women, and did not predict waist-to-hip ratio or chest-to-hip ratio in either sex. Thus, our results suggest that while mean F0 may indicate women's body masses, it is a relatively poor predictor of body shape in either sex, generally supporting the results of past work (Bruckert et al., 2006; Collins, 2000; but see controlling for age: Evans et al., 2006). Also in line with our results are those of a meta-analysis that showed a negative relationship between mean F0 and weight among women but not among men (Pisanski, Fraccaro, Tigue, O'Connor, Röder, et al., 2014). One other study reported a significant negative correlation between women's mean F0 and factor scores derived from a principal component that included women's weights, body mass indices, percentage body fat, waist and hip circumferences and waist-to-hip ratios (Vukovic et al., 2010), however, it is difficult to ascertain whether this relationship was driven by body mass, body shape, or both. One possible explanation for the apparent negative relationship between women's mean F0 and body mass is that relatively higher levels of androgens and/or lower levels of oestrogens may cause some women to develop both more masculine voices (larger vocal folds and lower F0; Abitbol et al., 1999; Titze, 1994) as well as more masculine bodies (heavier and more muscular; Björntorp, 1991; Blouin et al., 2008). The lack of a relationship between mean F0 and body mass in men suggests that the ratio of oestrogens to androgens may play a key role in driving this relationship.

Although research in other animals indicates that a variety of voice features produced by the vocal source (i.e. the larynx and vocal folds for terrestrial mammals) play a role in acoustic communication (see, e.g. Reby & McComb, 2003; Tyack & Miller, 2002), most human studies examining the indexical functions of voice have focused on mean F0 (for reviews, see Feinberg, 2008; Puts, Jones, et al., 2012). Our results indicate that F0 range and variability are generally better predictors of body shape than is mean F0. In particular, minimum F0 explained several times more variation in men's chest-to-hip ratios, and maximum F0 explained several times more variation in men's circumference measures, than did mean F0. Indeed, physical height and the girth of the chest relative to the lower body are key predictors of men's, but not women's, physical attractiveness and reproductive success (Pawlowski et al., 2000; Swami et al., 2007).

Similar to Puts, Apicella, et al. (2012) whose study samples included men from the northeastern United States and Tanzania, we found that F0 variability was unrelated to height among men (and women) from three additional cultures. However, our results indicated that F0 SD explained 10% of the variance in men's hip circumferences and correlated negatively with women's weights, body mass indices, circumferences measures and waist-to-hip ratios. Thus, in our study, low F0 variability indicated larger body circumferences in both sexes and more masculine (lower) waist-to-hip ratios among women. Other recent work investigating F0 variability in humans suggests that this sexually dimorphic voice parameter may be an important signal of quality. Low F0 variability produces a perceptually monotone voice that is more common among men than women (Puts, Apicella, et al., 2012; Puts, Jones, et al., 2012), is associated with self-reported physical dominance and reproductive success in men (Hodges-Simeon et al., 2010, 2011) and may also predict circulating levels of testosterone and physical strength (Puts, Apicella, et al., 2012; Puts, Jones, et al., 2012).

Vocal Perturbation and Noise Parameters

To our knowledge, no previous study has investigated relationships between perturbation or noise parameters and body shape. We found that jitter, shimmer and harmonics-to-noise ratio each indicated one or more indices of body shape in both men and women. Shimmer and jitter correlated negatively with hip circumferences among men and with waist and chest circumferences among women. Both parameters explained around 12% of the variance in men's hip circumferences, significantly more than in women's hip circumferences.

Among women, shimmer and jitter correlated negatively with waist-to-hip ratio (explaining 7% of the variance) and jitter correlated negatively with chest-to-hip ratio, whereas harmonics-to-noise ratio correlated positively with waist-to-hip ratio and explained more variance in women's waist-to-hip ratios (11%) than did any other voice parameter. Thus, women with relatively low jitter and shimmer (less perturbation) and high harmonics-to-noise ratios (less noise) had relatively more masculine body shapes (higher waist-to-hip ratios or chest-to-hip ratios) than did other women. Some researchers have speculated that relationships between perturbation or noise parameters and body shape may be related to sex hormone levels, particularly among women (Linders et al., 1995; Prelevic, 2013; Silverman & Zimmer, 1978). As the vocal folds have androgen receptors that are sensitive to an influx in circulating testosterone, which increases vocal fold size (Titze, 1994), women with relatively high androgen and/or low oestrogen levels may experience a greater increase in vocal fold mass compared to other women. On the basis that larger vocal folds may oscillate with fewer irregularities than smaller vocal folds (Linders et al., 1995), jitter and shimmer may be lower, and harmonics-to-noise ratio higher, among women with relatively more masculine hormonal profiles and more masculine body shapes. Our results support this prediction for women, but not for men, among whom shimmer correlated positively, and harmonics-to-noise ratio correlated negatively, with chest-to-hip ratio. The possible mechanism linking voice perturbation and noise parameters to men's body shapes is unclear.

Our results further indicate that although perturbation and noise parameters predicted body shape, these parameters could not reliably predict height, weight or body mass index in either sex. Previous work has also generally failed to find robust relationships between these parameters and adult height (González, 2007; Hamdan et al., 2012; but see in children: Linders et al., 1995), however, two studies reported significant positive relationships between jitter or shimmer and certain indices of body mass including body surface area, trunk fat or muscle mass (González, 2007; Hamdan et al., 2012). As the results of studies to date are mixed, additional studies are needed to determine whether relatively taller or heavier adults show more irregularities in the pitch and amplitude of their voices than do others.

Limitations and Future Directions

Our voices and bodies change throughout the life span, but the most drastic changes occur at puberty and after the age of about 50 (Abitbol et al., 1999; Hollien et al., 1994). Hence, in the present study, we focused our analyses on adults aged 17–30 years to reduce possible age effects on voice–body relationships. Age data were unavailable for one sample (Scotland), however, the sample comprised University students whose ages likely fell within this range. To test whether the strength of voice–body relationships changes across the life span, future work should include samples with a wider age range, including prepubescent children. Moreover, although our study included three large and independent samples of adults from Canada, Scotland and Germany, future replications of this work would also benefit from including multiple other cross-cultural samples, particularly from less industrialized regions of the world.

The voice–body relationships reported in this exploratory study warrant replication, particularly those between perturbation or noise parameters and body shape. Reliable measurement of jitter and shimmer is inherently difficult, particularly with voices in which these parameters are high, as their measurement requires accurate identification of cycle boundaries and may also vary as a function of recording hardware, acoustic analysis software and verbal content (Buder, 2000; Maryn et al., 2009). These parameters can also be difficult to detect and discriminate acoustically (Hillenbrand, 1987; Kreiman & Gerratt, 2005). The average values of jitter, shimmer and harmonics-to-noise ratio in our samples fell within a nonpathological normal range. However, the mechanisms potentially linking these parameters to body size or shape remain unclear. In our study we have speculated about possible hormonal mechanisms linking variation in the human voice to variation in body size and shape, but we did not measure hormone levels. Future studies may focus on further identifying the hormonal mechanisms of voice production in humans and elucidating the proximate causes of the relationships and sex differences in vocal cues to body size and shape reported here.

Unfortunately we cannot infer from our data whether sex differences in vocal cues to body size and shape are the product of sexual selection. It is equally likely, for instance, that men have been selected to exaggerate their body size by lowering the frequencies of their voices (Fitch & Giedd, 1999; Fitch & Reby, 2001; Morton, 1977) and may modulate their formants more than women in ways that reduce the degree to which formants honestly indicate body mass and shape, which are more malleable and variable than is height. At a proximate level, many factors may contribute to sex differences in vocal cues to body size and shape. The vocal tract and resultant formants are sexually dimorphic (Fitch & Giedd, 1999; Titze, 1989). There are also marked sex differences in steroid hormone concentrations and in their effect on vocal anatomy (Abitbol et al., 1999; Lieberman et al., 2001) and on fat distribution (Blouin et al., 2008; Singh, 1993). All or any of these factors may affect the relative degree to which vocal parameters predict variation in body size and shape within and between sexes.

Intimately tied to the question of whether reliable indicators of body size and shape are present in the voice is whether listeners are able to accurately gauge size and shape from the voice and, if so, which vocal parameters listeners use to do so. Perceptual studies of voice have generally focused on listeners' assessments of height and weight (Bruckert et al., 2006; Collins, 2000; Gonzalez, 2006; Krauss, Freyberg, & Morsella, 2002; Pisanski, Fraccaro, Tigue, O'Connor, & Feinberg, 2014; Rendall et al., 2007; Smith & Patterson, 2005). Although accuracy in these tasks is generally low, these studies indicate that listeners can gauge height and weight from the voice above chance, and that accuracy is highest (about 60%) in two-alternative forced-choice paradigms. Compared to height and weight, relatively few studies have examined assessment of body shape from the voice. Hughes et al. (2009) found that listeners were able to gauge women's waist-to-hip ratios (but not shoulder-to-hip ratios) and men's shoulder-to-hip ratios (but not waist-to-hip ratios) from the voice alone. Future studies may test whether the sex of the listener affects the accuracy of body shape assessments, as there is some evidence that men are better than women in voice-based assessments of height (Charlton, Taylor, et al., 2013; but see also Rendall et al., 2007). Moreover, while it is clear that listeners utilize both F0 and formant information to gauge height (Charlton, Taylor, et al., 2013; Pisanski, Fraccaro, Tigue, O'Connor, & Feinberg, 2014; Rendall et al., 2007), it remains unknown whether listeners use jitter, shimmer or harmonics-to-noise ratio to gauge either body size or shape from the voice. Evidence that listeners are generally insensitive to perturbation parameters in the normal range of variation (Kreiman & Gerratt, 2005) suggests that this is unlikely.

Conclusions

We examined relationships among a wide array of voice parameters and indices of both body size and shape in a large cross-cultural sample of men and women. In response to our three research questions outlined in the Introduction, our results revealed the following. (1) Formants predicted height and weight in both men and women better than did any other voice parameter examined, including mean F0 and non-mean-based F0 parameters (F0 range and variability). (2) Various F0, formant, noise and perturbation parameters predicted body shape among men and women. Notably, F0 range and variability were better predictors of body shape than was mean F0 in both sexes; formants could explain a similar amount of variance in women's body shapes and sizes; and jitter, shimmer and harmonics-to-noise ratio were particularly good predictors of body shape, including women's waist-to-hip ratios and men's chest-to-hip ratios. (3) Various VTL estimates predicted women's waist-to-hip ratios and hip circumferences significantly better than men's, but shimmer, jitter and maximum F0 predicted men's hip circumferences better than women's. By informing and guiding future research investigating the mechanisms and functions of vocal communication in humans, these findings may provide further insight into how the human voice and body have been shaped by sexual selection (Puts, Jones, et al., 2012), and may offer practical applications for estimating the body size of vocalizers in criminal profiling and remote medical monitoring of obese or malnourished patients.

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