

1 A house of cards: Bias in perception of body size mediates the relationship between  
2 voice pitch and perceptions of dominance

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22 ABSTRACT

23           *Theories of the evolution of low voice pitch in men are based on the idea that*  
24 *voice pitch is an honest indicator of physical dominance, but relationships among pitch,*  
25 *physical body size and strength among same sex adults voice are weak and unstable.*  
26 *Nevertheless, judgements of body size based on voice pitch are the result of perceptual*  
27 *bias that low frequencies sound large. If dominance judgements are based in part on*  
28 *perception of size, then dominance perception could also be the result of perceptual*  
29 *bias. Thus, we tested if the relationship between voice pitch and judgements of height*  
30 *mediated the relationship between voice pitch and dominance judgements. The*  
31 *relationship between voice pitch and perceived height fully mediated the relationship*  
32 *between voice pitch and dominance. This was driven by the portion of variance that was*  
33 *inaccurate in height perception (i.e. residual error), and not conditional upon actual*  
34 *height, or perceptions thereof. Collectively our results demonstrate that the relationship*  
35 *between voice pitch and perceived dominance is not based on observation of real world*  
36 *relationships between physical size and voice pitch, but rather based on a bias to*  
37 *perceive low pitched voices as large people. Hence, the relationship between*  
38 *dominance and voice pitch is coincidental rather than causal. Thus, since the*  
39 *relationship between physical dominance and voice pitch is conditional upon the*  
40 *relationship between a biased perception of body size, voice pitch is not an honest*  
41 *indicator of physical dominance. Consequently, the evolution of low pitch in men's*  
42 *voices cannot be explained by selection for accurate dominance cues.*

43

44

## 45 INTRODUCTION

46 It is an evolutionary stable strategy for animals to display secondary sexual  
47 characteristics in competitive scenarios to indicate dominance in such a way as to  
48 reduce costs associated with physical fights over access to resources (Maynard Smith  
49 & Price, 1973). One category of such displays is vocalizations. Vocal indicators of  
50 dominance are used in hundreds of species across the animal kingdom (Andersson,  
51 1994), including among humans (Borkowska & Pawlowski, 2011; Cowan, Watkins,  
52 Fraccaro, Feinberg, & Little, 2015; Doll et al., 2014; Feinberg et al., 2006; Feinberg,  
53 2008; Han et al., 2017; Jones, Feinberg, DeBruine, Little, & Vukovic, 2010; Puts,  
54 Hodges, Cárdenas, & Gaulin, 2007; Puts, Gaulin, & Verdolini, 2006; Vukovic et al.,  
55 2011). Voice pitch (the perception of fundamental frequency and its harmonics), and/or  
56 formant frequencies (the resonant frequencies of the supralaryngeal vocal tract) are  
57 used by many species to indicate body size (Bowling et al., 2017), the primary indicator  
58 of physical dominance (Darwin, 2004; Trivers, 1976). Voice pitch and formant  
59 frequencies are used as indicators of dominance, but do they relate to physical  
60 measures of the primary indicators of physical dominance: body size and strength? The  
61 aim of our study was to test if the relationship between voice pitch and dominance  
62 perceptions is based on the false perception that tall people have low pitched voices.

### 63 Pitch

64 A physical property of sound is that larger objects produce sounds that have  
65 longer wavelengths, and hence lower frequencies (Titze, 1994). However, this  
66 phenomenon does not de facto translate to bioacoustics because most terrestrial  
67 mammals, including humans, produce sound by vocal fold vibrations. The vocal folds

68 are soft tissue and can grow independently of the rest of skeletal structure (Fitch, 1997)  
69 and sound is determined by the size and thickness of the vocal folds. Across species,  
70 larger animals produce lower-pitched sounds (Bowling et al., 2017; Hauser, 1993;  
71 Martin, Tucker, & Rogers, 2017). Within the same species, pitch is related to body size,  
72 and used in dominance assessments, among Humboldt penguins (*Spheniscus*  
73 *humboldti*) and Magellanic penguins (*Spheniscus magellanicus*) (Favaro, Gamba, Gili,  
74 & Pessani, 2017), common toads (*Bufo bufo*) (Davies & Halliday, 1978), as well as  
75 many other species. Voice pitch is perceived to scale allometrically with height in same  
76 sex adults (Feinberg, Jones, Little, Burt, & Perrett, 2005; Pisanski & Rendall, 2011;  
77 Rendall, Vokey, & Nemeth, 2007; Smith & Patterson, 2005), but meta-analyses of  
78 human height and voice pitch show that there is no relationship between voice pitch and  
79 height or weight among same-sex human adults (Pisanski et al., 2014b; Pisanski et al.,  
80 2015).

81 In humans, voice pitch is linked to pubertal testosterone levels (Harries, Hawkins,  
82 Hacking, & Hughes, 1998), and this relationship remains stable throughout adulthood  
83 (Fouquet, Pisanski, Mathevon, & Reby, 2016). While testosterone is not a proxy for  
84 height (Tremblay et al., 1998) or strength (Fahey, Rolph, Moungmee, Nagel, & Mortara,  
85 1976), it builds muscle by increasing the rate of protein synthesis (Griggs et al., 1989).  
86 While body size is the primary indicator of physical dominance, physical strength is also  
87 very important, especially when individuals are closely matched in size, as the purpose  
88 of signalling size and strength is to minimize the costs of direct aggression (Maynard  
89 Smith & Price, 1973). Several studies have tried to find a link between voice pitch and  
90 physical strength, but the results are weak and do not typically replicate. Three

91 independent lab groups were unable to find any link between voice pitch and physical  
92 strength measures among adults (Han et al., 2017; Sell et al., 2010; Smith, Olkhov,  
93 Puts, & Apicella, 2017). Out of several published samples on adults, only one reports  
94 that voice pitch is negatively related to physical strength (Puts, Apicella, & Cárdenas,  
95 2012), however, these results were weak and only significant when not controlling for  
96 multiple comparisons (Bakker, Hartgerink, Wicherts, & van der Maas, 2016). Thus,  
97 there is no evidence to support the idea that voice pitch indicates physical strength  
98 among same-sex adults.

99

## 100 Formants

101 Formant frequencies are the resonant frequencies of the supralaryngeal vocal  
102 tract (henceforth: vocal-tract) (Titze, 1994). Formants are thought to relate to body size  
103 because larger individuals typically have longer vocal tracts (Fitch & Giedd, 1999; Sulter  
104 et al., 1992). Among humans, estimates of vocal tract length from formant frequencies  
105 at best explain 10-15% of the variance in human body size among same-sex adults  
106 (Pisanski et al., 2014b; Pisanski et al., 2015). About 75% of the explanatory power in  
107 height is lost when vocal-tract length is estimated from formant frequencies as opposed  
108 to measured in MRI. Even more of this explanatory power is lost when these formants  
109 translate into size assessments because of the interaction between fundamental and  
110 formant frequencies on size perception (Smith & Patterson, 2005), and other biases in  
111 height perception such as the “low is large” heuristic (Pisanski, Isenstein, Montano,  
112 O’Connor, & Feinberg, 2017), whereby playing low pitched voices closer to the ground  
113 makes them sound larger than when played from higher up in spatial location.

114

115 Subjective vs. Objective Measures of Dominance

116           Studies have shown that in natural voices, voice pitch and formant frequencies  
117 are negatively tied to both perceptions of body size and dominance (Doll et al., 2014;  
118 Han et al., 2017; Hodges-Simeon, Gaulin, & Puts, 2011; Jones et al., 2010; Puts et al.,  
119 2007; Vukovic et al., 2011).

120           In natural voices, ratings of size correlate negatively with both pitch and formant  
121 frequencies (Collins, 2000; Rendall et al., 2007). Although the two frequency  
122 components interact when people make size and attractiveness judgements (Feinberg  
123 et al., 2011; Smith & Patterson, 2005), even when controlling for pitch in natural voices,  
124 formants still negatively predict perceived body size (Rendall et al., 2007). Furthermore,  
125 lowering both pitch and formants together and independently increases perceived size  
126 in men's voices (Feinberg et al., 2005; Smith & Patterson, 2005). The focus of most of  
127 these studies has been men's voices, and little data exist on the relationship between  
128 voice frequencies and *perceived* body size in women's voices. In these studies  
129 (Pisanski, Mishra, & Rendall, 2012; Pisanski & Rendall, 2011; Rendall et al., 2007),  
130 formants are perceived similarly among women's and men's voices with respect to  
131 dominance and size.

132           In addition to altering perceived body size, lowering pitch and formant  
133 frequencies together and independently also increases perceived physical and social  
134 dominance (Feinberg et al., 2006; Jones et al., 2010; Puts et al., 2006). Men will lower  
135 the pitch of their voice in response to a competitive scenario, although formants were

136 not studied in this context (Puts et al., 2006). Across cultures, people also lower their  
137 pitch and formants when volitionally trying to sound larger (Pisanski et al., 2016).

138         Although there is no link between voice pitch and physical dominance indicators,  
139 voice pitch may still predict objective measures of social dominance. Both men and  
140 women with lower pitched voices are perceived to be better political candidates, and are  
141 more likely to actually win political elections (Gregory Jr & Gallagher, 2002; Klofstad,  
142 2016; C. A. Klofstad, Anderson, & Peters, 2012; Pavela Banai, Banai, & Bovan, 2017;  
143 Tigue, Borak, O'Connor, Schandl, & Feinberg, 2012). Furthermore, men and women  
144 with lower pitched voices tend to have higher paying, more prestigious jobs with  
145 leadership roles (Klofstad et al., 2012; Mayew, Parsons, & Venkatachalam, 2013).

146         Despite the weak link between voice pitch and physical markers of formidability,  
147 dominance, and the likelihood of winning dominance bouts, there is a growing body of  
148 literature suggesting the idea that sex difference in voice pitch evolved via male-male  
149 competition, because voice pitch has a very strong effect on dominance ratings (Doll et  
150 al., 2014; Hodges-Simeon et al., 2011; Puts, 2016; Puts, 2010; Puts et al., 2012; Puts et  
151 al., 2006; Puts et al., 2016; Puts et al., 2007). Given the lack of relationship between  
152 objective physical markers of dominance and voice pitch, we tested if perceived height,  
153 measured height, and the residuals of perceived and measured height (i.e. residual  
154 error in height perception) mediated the relationship between putative vocal indicators  
155 of size and dominance (i.e. pitch and formant frequencies), and dominance perception.  
156 Following previous work (Puts et al., 2006), we separated dominance into physical and  
157 social categories and asked both men and women to rate men and women's voices for  
158 dominance (physical and social) and height. We then tested whether body size

159 (perceived, measured, and residual error in perceived height) were mediators of the  
160 relationship between pitch and dominance, and formants and dominance,  
161 independently. Since the aforementioned work shows that the links among voice pitch,  
162 formants, and perceived body size are much stronger than the links among these voice  
163 qualities and physical size measurements, we predict that the discrepancy in size  
164 perception versus physical size could affect perceptions that depend on body size  
165 perception, such as dominance. We predict that perceived size, and residual error in  
166 size attribution will mediate the relationship between voice frequency (pitch/formants)  
167 and body size (perceived, residual error, and measured). Here measured height serves  
168 as an ideal observer control condition, meaning that if people were 100% accurate in  
169 height perception from the voice, their data would be statistically identical to measured  
170 height. If measured height has little to do with perceived body size from the voice, then  
171 we do not expect measured height to mediate the relationship between pitch and  
172 formants, and dominance.

173

## 174 METHODS

175 All protocols were approved by the McMaster University Research Ethics Board.

### 176 Stimuli

177 From a larger database of peer-aged voices recorded at McMaster University,  
178 Hamilton, Ontario, Canada (Pisanski et al., 2014b), we used recordings of 108 women  
179 ages 17 to 30 and 74 men ages 17 to 30. Six people opted to not report their age. Each  
180 speaker was recording saying the English monophthong vowels /a/, /ɛ/, /i/, /o/, and /u/.

181 Recordings were made in an anechoic sound-controlled booth (WhisperRoom Inc. SE  
182 2000 Series Sound Isolation Enclosure), with speakers standing approximately 5-10 cm  
183 from the Sennheiser MKH 800 studio condenser microphone with a cardioid pick-up  
184 pattern. An M-Audio Fast Track Ultra interface was used to digitally encode the audio at  
185 a 96 kHz sampling rate and 32-bit amplitude quantization. Files were stored onto a  
186 computer as PCM WAV files using Adobe Soundbooth CS5 version 3.0. We used the  
187 root mean squared method to normalize voices to 70dB SPL. Vowels for each voice  
188 were presented in a consistent order, separated by 350 ms of silence. The voices used  
189 in this experiment were selected on the criteria that they were the largest available set  
190 of voices for which we had physical measurements of their height and weight (as  
191 opposed to self-report), and were recorded under the same conditions with the same  
192 equipment, speaking the same sounds. This sample size is larger than some studies  
193 (Collins, 2000; Collins & Missing, 2003), and comparable to others (Puts et al., 2006).

#### 194 Height/Ideal Observer Measurement

195 As noted in Pisanski et al., 2014b, speakers' heights were measured in cm with  
196 metric tape affixed to a wall. Women ranged from 151.5 to 183 cm tall (mean=164.7cm,  
197 SD=7.11 cm), and men ranged from 167 to 191 cm tall (mean=177.7 cm, SD=6.50 cm).

#### 198 Voice Measures

199 The voices used in this experiment were previously analysed for voice pitch and  
200 apparent vocal tract length (Pisanski et al, 2014b). Briefly, we used the autocorrection  
201 algorithm in Praat software (Boersma & Weenink, 2013) with a range of 65 Hz–300 Hz  
202 for male voices and 100 Hz–600 Hz for female voices to determine the average

203 fundamental frequency (the physical correlate of pitch) of each voice. The first four  
204 formant frequencies (F1–F4) were measured using the Burg Linear Predictive Coding  
205 (LPC) algorithm in Praat (Boermsa & Weenink 2013) with a maximum formant setting of  
206 5000 Hz for male voices and 5500 Hz for female voices. The formants were  
207 superimposed on a spectrogram and then the formant number was manually adjusted  
208 to achieve the best visual match of predicted and observed formants. The mean values  
209 for F1–F4 were used to calculate the apparent vocal tract length (henceforth VTL)  
210 (Reby & McComb, 2003), which has previously been shown be a relatively accurate  
211 method of estimating vocal-tract length in men’s voices (Pisanski et al., 2014b).

212

### 213 Procedure

214 Participants listened to a series of voices played on Sennheiser HD 280 Pro  
215 over-ear headphones, played at a consistent volume set prior to the experiment. We  
216 used PsychoPy (Peirce, 2007) to present stimuli and record responses. Male and  
217 female voices were presented in separate blocks. In each male block, participants rated  
218 each of the 74 voices, and in each female voice block, participants rated each of the  
219 108 voices. The order of voices within each block, as well as the rating attribute for each  
220 block, was randomized. Participants chose to complete 1, 2, or 3 blocks of ratings. Most  
221 participants completed 3 blocks. Our design contains a mix of within and between-  
222 subjects data. Voices were rated for one of the following attributes: height (1=very short;  
223 7=very tall) social dominance, defined as “A socially dominant person tells other people  
224 what to do, is respected, influential, and often a leader; whereas submissive people are  
225 not influential or assertive and are usually directed by others.” (1=very submissive;

226 7=very dominant) (adapted from Mazur, Halpern, & Udry, 1994); physical dominance,  
227 defined for male voices as “A physically dominant person is someone who if they were  
228 in a fist fight with an average undergraduate male, they would probably win.” and  
229 similarly for female voices as “A physically dominant person is someone who if they  
230 were in a fist fight with an average undergraduate female, they would probably win.”  
231 (1=very submissive; 7=very dominant) (adapted from Puts et al., 2006).

232 Gender was self-reported. We assessed gender by asking participants to:  
233 “Please indicate your gender by typing the number that corresponds to your gender. 0 =  
234 female, 1 = male, 2 = transgender, 3 = other, s = skip”. No participants reported they  
235 were transgender or other gender, thus we assumed our sample was cisgender.

236

### 237 Participants

238 We recruited students using McMaster University’s online Research Participation  
239 System. Participants provided informed consent and were compensated with either  
240 course credit or \$10 Canadian per hour, *pro rata*. Table 1 shows the breakdown of  
241 number of raters and their ages per condition.

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245 Table 1 around here

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248 Statistical Analyses

249 All statistical analyses were conducted in R statistical analysis software.

250 Although each block had different numbers of participants, there was very high  
251 agreement between raters (All Chronbach's alpha calculated separately for each sex  
252 and rating > 0.9).

253 First, using linear mixed effects modelling, we tested whether the association  
254 between voice pitch and dominance ratings (physical and social) decreased when  
255 adding one of the three height measurements (perceived height, measured height, and  
256 inaccurate height) into the model. Linear mixed effects models were conducted using  
257 the '*lme4*' (Bates, Mächler, Bolker & Walker, 2015) and '*lmerTest*' (Kuznetsova,  
258 Brockhoff & Christensen, 2015) packages for the R statistical software. Separate  
259 models were conducted for physical and social dominance ratings, and for each height  
260 measurement, and also repeated using VTL as a predictor instead of voice pitch,  
261 resulting in 12 separate models. For each model, random intercepts were specified for  
262 each audio stimulus and for each participant to control for non-independence of ratings  
263 of the same stimulus and from the same participant respectively. Random slopes were  
264 specified maximally as suggested in Barr et al. (2013) and Barr (2013). Models where  
265 introducing height as a predictor reduced the predictive power of voice pitch indicate  
266 that there is a potential mediating effect of height; therefore, this was further  
267 investigated via mediation analysis using the '*mediation*' package in R (Tingley,  
268 Yamamoto, Hirose, Keele & Imai (2014). Due to limitations in the R 'Mediation'  
269 package, we were unable to include both random effects groups specified in a multilevel  
270 mediation analysis above. Therefore we only included random effects group of

271 participant in the mediation analyses. For all analyses above, we z-scored each variable  
272 at the appropriate group level (i.e. voice identity for perceived and false height, voice  
273 pitch, VTL, and measured height). We effect-coded participant sex (-0.5 for cis-  
274 gendered females and 0.5 for cis-gendered males). We report fixed effects for models  
275 here. For mediation models, we report only the proportion mediation (PM). Full output,  
276 model specifications, and scripts can be found in supplementary electronic material. We  
277 conducted power analyses on all mediation models and found that in each case, for  
278 voice pitch analyses (our primary interest here), our power approached 1 (Kenny, 2017).

279 To determine how accurately people could assess height from the voice alone,  
280 we created two multilevel models (one for female and one for male voices) with  
281 perceived height as the dependent variable, measured height as the predictor,  
282 participant sex as a fixed effect, and participant identity as a random effects level.

## 283 RESULTS

### 284 Measured, Perceived, and Inaccurate Height

285

286 There was an effect of measured height on perceived height (male voices:  
287 estimate=0.323, s.e.=0.0249,  $t_{83}=12.958$ ,  $p<0.0001$ ; female voices: female voices:  
288 estimate=0.10287, s.e.=0.01400,  $t_{88}=7.450$ ,  $p<0.0001$ ). There was a small effect of sex  
289 of participant for male voices (estimate=-0.189, s.e.=0.0848,  $t_{83}=-2.238$ ,  $p<0.0279$ ), but  
290 not female voices. In neither case was there an interaction between sex of participant  
291 and measured height. We saved the residuals from these models and labelled the mean  
292 residuals for each stimulus 'inaccurate height perception' because it represents the

293 residual error in accuracy in height perception across raters. Plots of measured height  
294 vs inaccurate height shows a random distribution of slopes across participants and no  
295 discernible relationship between measured height and the inaccurate height perception  
296 variable, as well as no discernible sex difference in this relationship (see supplementary  
297 online material).

298

## 299 Voice Pitch

### 300 *Voice Pitch and Height*

301 Linear regression demonstrated that there was no significant relationship  
302 between fundamental frequency and measured height for female voices ( $B < 0.001$ ,  
303  $t(106) = -0.010$ ,  $p = 0.992$ ,  $R^2 < 0.001$ ), but there was an association between fundamental  
304 frequency and measured height for male voices ( $B = -0.156$ ,  $t(72) = -3.674$ ,  $p < 0.001$ ,  
305  $R^2 = 0.158$ ). These results are both within the normal distribution of expected effect sizes  
306 given in a recent meta-analysis (Pisanski et al., 2014b). Fundamental frequency  
307 significantly predicted perceived height for both female voices ( $B = -0.022$ ,  $t(106) = -8.911$ ,  
308  $p < 0.001$ ,  $R^2 = 0.428$ ) and male voices ( $B = -0.034$ ,  $t(72) = -13.302$ ,  $p < 0.001$ ,  $R^2 = 0.711$ ).

309

### 310 *Mediation Analysis*

311 Mediation analyses investigated whether height perception mediates the  
312 relationships between voice pitch/formant frequencies and perceived physical/social  
313 dominance. Here our models are 1-1-1 multilevel mediation models, where predictor,

314 mediator, and outcome all occur at level 1. Figure 1 is a graphic description of our  
315 models.

316

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317 Figure 1 around here

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318

319 We performed separate mediation analyses using perceived height, measured  
320 height, and inaccurate height perception as potential mediating variables. Mediation  
321 analyses were conducted using 1000 bootstrap samples and 95% Confidence Intervals.  
322 Full results are found in the Supplementary Information. No differences in confidence  
323 interval significance level were found when using 10,000 vs 1000 bootstraps. We used  
324 1000 bootstraps here due to computation limitations. Here we only report percent  
325 mediation (PM) from mediation analyses from models where including a height variable  
326 decreased the predictive power of voice pitch or vocal-tract length on dominance  
327 perception (either physical or social). In all models we included sex of rater as a fixed  
328 effect.

329 Since other work has found that lower pitch increases accuracy of formant-based  
330 size judgements (Pisanski, Fraccaro, Tigue, O'Connor, & Feinberg, 2014), we also  
331 included either VTL or voice pitch (respectively) as a covariate in the mediation  
332 analyses to control for any potential effects here. Table 2 displays Proportion mediated  
333 and 95% confidence intervals from significant mediation analyses. Full mediation  
334 analyses, outputs, scripts, and models can be found in the supplementary online

335 materials. Proportion mediated results greater than 1 indicate models where  
336 suppression occurred.

337 Table 2 around here

338

339 Table 2

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<b>Dominance Type</b>	<b>Sex Of Voice</b>	<b>Height Variable</b>	<b>Voice Quality</b>	<b>Proportion Mediated</b>	<b>Lower CI</b>	<b>Upper CI</b>
Physical	Female	Inaccurate	Pitch	0.582	0.524	0.65
Physical	Female	Measured	Pitch	0.0182	0.0104	0.03
Physical	Female	Perceived	Pitch	0.8440	0.7794	0.92
Physical	Male	Inaccurate	Pitch	0.579	0.520	0.65
Physical	Male	Measured	Pitch	0.01771	0.01063	0.03
Physical	Male	Perceived	Pitch	0.8423	0.7790	0.91
Social	Female	Inaccurate	Pitch	0.526	0.458	0.60
Social	Female	Measured	Pitch	0.0244	0.0134	0.04
Social	Female	Perceived	Pitch	0.0244	0.0134	0.04

Social	Male	Inaccurate	Pitch	0.525	0.464	0.60
Social	Male	Measured	Pitch	0.0243	0.0137	0.04
Social	Male	Perceived	Pitch	0.8421	0.7706	0.92
Physical	Female	Inaccurate	VTL	0.7524	0.6348	0.92
Physical	Female	Measured	VTL	0.3300	0.2554	0.42
Physical	Female	Perceived	VTL	1.4288	1.2061	1.74
Physical	Male	Inaccurate	VTL	0.7484	0.6244	0.91
Physical	Male	Measured	VTL	0.3326	0.2579	0.43
Physical	Male	Perceived	VTL	1.4242	1.2139	1.77

340

341 Physical vs acoustic measures

342 One potential explanation for our results is that they are an artefact of how the variables  
343 were measured (ratings scales show stronger associations whereas non-rating  
344 measures, acoustic and physical measures, show weaker associations). Indeed, the  
345 relationship between voice pitch and social dominance ratings ( $r(74)=0.690$ ) is not  
346 significantly different than the relationship between perceived height and social  
347 dominance ratings ( $r(74)=0.735$ ; Fischer's R to Z,  $z=0.55$ ,  $p=0.582$ ). Therefore, the  
348 aforementioned idea cannot explain our results.

349

## 350 DISCUSSION

351           We found that perceived height fully mediated the relationship between voice  
352 pitch and judgements of dominance. In other words, dominance ratings can be  
353 explained fully by the relationship between voice pitch and our perceptions of body size.  
354 Consistent with other research, we found that perceptions of body size from the voice  
355 were reasonably accurate (Bruckert, Liénard, Lacroix, Kreutzer, & Leboucher, 2006;  
356 Collins, 2000; González, 2003; Pisanski et al., 2014a; Rendall et al., 2007; van  
357 Dommelen & Moxness, 1995). Here we can explain 21% of the variance in body size  
358 from people's ratings of men's voices. However, we determined that for both women's  
359 and men's voices, the residual error or portion of the variance in people's height ratings  
360 that is incorrect (i.e. based on bias) plays a larger role in determining how dominant  
361 people sound than the proportion of variance in perceived height explained by  
362 measured height, or what could be observed. This suggests that judgments of  
363 dominance based on pitch of voice are based on bias rather than observation of the  
364 physical world. If judgements of dominance were based on a physical relationship  
365 between voice pitch and body size, we would have expected data from the ideal  
366 observer to mediate the relationship between voice pitch and height. This did not  
367 happen. Instead, it was the inaccurate portion of the variance in perceived height that  
368 mediated the relationship between dominance and voice pitch. Even though people can  
369 judge body size from the voice to some degree of accuracy in men's voices, this  
370 information is not used when rating the dominance of voices. Instead, our results show

371 that dominance ratings of voices are based on a bias to think that people with low-  
372 pitched voices are tall.

### 373 Types of ratings

374 The inaccurate portion (i.e. residual error) of our perception of body size partially  
375 mediated the relationship between voice pitch and dominance. In fact, data from an  
376 ideal observer (i.e. physical height measurements), who would perceive body size from  
377 the voice with 100% accuracy, mediated these relationships even less than did the false  
378 height variable. Thus, the inaccurate perception of size drives perceptions of  
379 dominance, rather than the component of the relationship between perceived and actual  
380 size that is accurate. Therefore, we suggest that ratings of dominance are based on the  
381 bias that low pitch originates from tall people and that this bias is what makes us think  
382 that people with low voices are more dominant. Our findings show no support for the  
383 idea that dominance ratings are causally related to measured physical size (Hodges-  
384 Simeon et al., 2011; Puts et al., 2016; Puts et al., 2007). This has implications for  
385 theories that evolution of low voice pitch in men is due to male-male competition (Puts  
386 et al., 2016), as voice pitch can no longer be thought of as an honest indicator of  
387 physical dominance. Consequently, we suggest that future theories of the evolution of  
388 low voice pitch in men focus on sensory bias, rather than honest or costly signalling.

389 Sensory exploitation theories of sexual selection suggest that males with traits  
390 that effectively stimulate sensory systems are relatively more successful (see  
391 Feinberg, Jones, & Armstrong, in press, for review). Over evolutionary time, selection  
392 ramps up the frequency and size of those traits via female choice (Ryan & Keddy-  
393 Hector, 1992). In the sensory exploitation theory of sexual selection, preferences for

394 traits do not have to be adaptive on their own (Dawkins & Guilford, 1996), but can be  
395 by-products of neural responses that evolved to deal with different evolutionary  
396 pressures (Johnstone, 1995). Almost all hearing species react to low-frequency sounds  
397 as if they are potentially large or threatening (Owings & Morton, 1998). There are no  
398 special circumstances to suggest otherwise for our lineage; therefore, it is reasonable to  
399 suggest that there is a sensory bias that low frequency sounds originate from large  
400 and/or threatening organisms. Cost-benefit analysis suggests that any fights resulting  
401 from misses (i.e. not using a "low is large" heuristic) would be of potentially higher cost  
402 (i.e. death) than any potential gains in reproductive success garnered from additional  
403 mating opportunities secured after combatting an enemy with a lower voice, than the  
404 benefits gained by accurately deriving body size from voice alone (see Feinberg, Jones,  
405 & Armstrong, in press, for review). Humans are a visually-dominant species, and there  
406 is very little selection pressure to very accurately assess the size of other humans from  
407 the voice alone, simply because we can see height better than we can hear it. This  
408 allows sensory exploitation to take control. If men with lower-pitched voices were able to  
409 exploit the sensory bias that low sounds large, threatening, and scary, they would be  
410 able to increase their reproductive success, and over the course of generations, drive  
411 sex differences in human voice pitch (see Feinberg, Jones, & Armstrong, in press, for  
412 review).

413

#### 414 Physical vs social dominance

415 For voice pitch analyses, we found that among men height mediated physical  
416 dominance ratings more than social dominance ratings, whereas for women, mediation

417 rates were relatively equal across dominance rating contexts. While physical dominance  
418 is thought to be tied to height and strength, both of which are not related to voice pitch,  
419 social dominance is additionally influenced by other social factors. For example, voice  
420 pitch predicts several objective social dominance outcomes in women and men such as  
421 political election results (Gregory Jr & Gallagher, 2002; Klofstad, 2016) and job prestige  
422 in highly stereotypically female oriented leadership positions (Anderson & Klofstad,  
423 2012). It is possible that we found stronger mediation among men's voices in the  
424 physical dominance condition than in the social dominance condition because social  
425 dominance judgements predict real-world outcomes such as political elections (Gregory  
426 Jr & Gallagher, 2002; Klofstad, 2016) more than do physical dominance judgements,  
427 which are not related to size (Pisanski et al., 2014b; Pisanski et al., 2015) or strength. In  
428 other words, social dominance judgements of the voice may be based on a kernel of  
429 truth, whereas judgements of physical dominance are driven primarily by bias.  
430 Therefore, social dominance judgements are perhaps under less influence from bias  
431 from the relationship between voice pitch and perceived body size than are physical  
432 dominance judgements.

433

#### 434 Men vs women

435 It is unclear why people are so much worse at estimating women's height than  
436 estimating men's height. One idea is that there could be stronger selection pressure to  
437 more accurately assess dominance from men's voices than from women's voices due to  
438 the differential potential costs of misinterpreting threats from men versus women  
439 (Watkins, DeBruine, Feinberg, & Jones, 2013). However, we find evidence of a more

440 parsimonious explanation. Here we found no relationship between voice pitch and  
441 height among women. If there is no relationship between pitch and size in women, but  
442 people use pitch as a cue to body size, that could explain why residual error rates when  
443 estimating women's height are so high. On the other hand, because there was a  
444 relatively high correlation between voice pitch and measured height among men, this  
445 bias could easily result in more accurate assessment of height – coincidentally rather  
446 than causally.

447         Height mediated the relationship between voice pitch and dominance judgements  
448 among women's voices more than it mediated the relationship between voice pitch and  
449 dominance judgements among men's voices. This is consistent with the idea that there  
450 may be stronger selection pressure to more accurately judge the dominance of men's  
451 voices than of women's voices (Watkins et al., 2013). Alternatively, this could potentially  
452 be an artefact of the relative strength of association between voice pitch and physical  
453 height in our sample. Here, there was no relationship between measured height and  
454 voice pitch among women, whereas there was a medium sized effect between voice  
455 pitch and height among men. If inaccurate perception of body size from voice pitch  
456 drives the mediation of pitch and dominance, then in cases where there is more  
457 accuracy, we would expect less mediation. More research is required to determine  
458 whether or not this is the case.

459         How the observed effects might change as a function of socio-cultural factors  
460 (e.g., typical mating strategies or gender equality) remains to be investigated. It is  
461 possible, for example, that the magnitude of the effects of pitch on dominance  
462 perceptions decline as gender equality increases, much as some previous research

463 suggests that the size of sex differences in mate preferences are correlated with the  
464 Global Gender Gap Index (Zentner & Mitura, 2012).

465

#### 466 Pitch vs Vocal Tract

467         We found that the relationship between body size and dominance was  
468 inconsistently mediated by apparent vocal tract length. This is likely because this is an  
469 inappropriate statistical model. Here apparent vocal tract length was not strongly linked  
470 to body size. Our effect sizes here are still within the expected range of results (Pisanski  
471 et al., 2014b). It should be noted that even though vocal tract length explains a very  
472 large proportion of variance in body size, most of this explanatory power is lost when  
473 we translate this into formant frequencies. Formant frequencies cannot explain 85% of  
474 the variance in body size among same-sex adults. Here it is important to note that even  
475 though voice pitch and formants are both tied to the perception of body size (Collins,  
476 2000; Collins & Missing, 2003; Feinberg et al., 2005; Pisanski, Feinberg, Oleszkiewicz,  
477 & Sorokowska, 2017; Pisanski et al., 2014b; Pisanski, Oleszkiewicz, & Sorokowska,  
478 2016; Pisanski & Rendall, 2011; Rendall et al., 2007; Smith & Patterson, 2005), and  
479 formants are tied to physical height (Pisanski et al., 2014b), these cues are not used in  
480 the same way in many mate-choice relevant decisions (Feinberg et al., 2011; Feinberg  
481 et al., 2005; Pisanski & Rendall, 2011; Pisanski et al., 2014c). Furthermore, processing  
482 of voice pitch and formants take different neural pathways, where voice pitch processing  
483 occurs later, and contributes more to bias in perception of size, whereas formant  
484 information is used earlier for acoustic size scaling (von Kriegstein, Warren, Ives,  
485 Patterson, & Griffiths, 2006), which aids in vowel perception (Turner, Walters,

486 Monaghan, & Patterson, 2009). Although there is an overlap in qualities evoked by the  
487 perception of pitch and formants, our results show that these voice qualities cannot be  
488 used synonymously in theoretical and experimental contexts (Feinberg et al., 2005).

489

#### 490 Bias in pitch perceptions

491 We found that perceived size mediated the relationship between voice pitch and  
492 dominance. Therefore, the perception of dominance is conditional upon perception of  
493 height. Perception of height was relatively accurate for men's voices, but not for  
494 women's voices. Regardless, we found that the proportion of variance in perceived  
495 height left unexplained by actual height was the more important component driving  
496 perceptions of dominance.

497 In our sample, there was no relationship between measured body size and voice  
498 pitch for women's voices, and yet voice pitch had a large effect (Cohen 1988) on  
499 perceived body size. People continue to perceive a relationship between voice pitch and  
500 body size where none exists. If people were actually judging body size, and not using a  
501 general heuristic of "low is large", then we would not expect to see people judge women  
502 with low-pitched voices as larger than women with high-pitched voices. Other research  
503 has shown that people will ascribe large size to voices with pitch outside the range of  
504 human vocal production, suggesting that these heuristics are applied widely in human  
505 vocal perception (Smith & Patterson, 2005). The tendency to perceive lower-pitch  
506 sounds as belonging to larger organisms is also found in 3-month old infants  
507 (Pietraszewski, Wertz, Bryant, & Wynn, 2017), so it is seen very early in human

508 development. Additionally, visual experience does not improve the accuracy of size  
509 judgments from listening to voices; blind and sighted adults are not different in their  
510 accuracy rates when making these assessments (Pisanski et al 2016b; Pisanski et al  
511 2017a). For a recent review on sensory exploitation and evolution of sex differences in  
512 voice pitch among humans, see Feinberg, Jones, & Armstrong (in press)

513         Having a sensory bias to perceive low-pitched sounds as originating from larger  
514 sources would be consistent with the idea that large objects emit low frequency noises,  
515 and suggests the costs of misses in interpreting a large object as small because of its  
516 pitch, outweigh incremental benefits gained from increased accuracy in detecting size  
517 among same-sex adults (see Feinberg, Jones, & Armstrong, in press, for review).

#### 518 Mediation and causality

519         Our experimental design is correlational in nature. Therefore, results from the  
520 mediation tests do not demonstrate causality, which is why they were discussed as  
521 “conditional” rather than “causal”. Indeed, mediation results obtained here should be  
522 considered “indirect effects”, rather than “causal mediation effects”. Future research  
523 could use time-locked sequential events to help establish whether the results we  
524 obtained here are causal or not.

525

526

#### 527 SUMMARY

528         In summary, we found that height mediated the relationship between voice pitch  
529 and dominance. These findings were driven by the portion of variance in perceived size

530 that was *inaccurate*. Size mediation of pitch-dominance relationships was stronger  
531 among women's voices than men's voices, and stronger for physical dominance  
532 judgements than social dominance judgements among men's voices. Collectively, these  
533 results suggest that perceptions of dominance are conditional on perception of size.  
534 Perception of size, in turn, is likely to be based on general heuristics rather than  
535 observational learning. Thus, dominance judgements are conditional upon the same  
536 heuristics that low pitch is dominant. Therefore voice pitch is not an honest indicator of  
537 physical dominance. Consequently, the evolution of low voice pitch in men may be  
538 based on sensory exploitation rather than honest or costly signalling. In absence of any  
539 real-world correspondence between voice pitch and determinants of physical  
540 dominance, theories of the evolution of low voice pitch in men cannot rely on honest  
541 signalling or good genes explanations of sexual selection. Our results suggest that  
542 dominance ratings may be the result of a bias to perceive low pitch as large, rather than  
543 the result of honest communication. Here, sensory exploitation of the bias to attribute  
544 large size to low pitched voices explains that a pre-existing bias that "low is large"  
545 predated the evolution of low voice pitch in men. Those men that were able to exploit  
546 this relationship by using a low-pitched voice to secure their positions as strong group  
547 leaders may have enjoyed the highest reproductive success. In turn, this can select for  
548 lower-pitched voices in men that sound more dominant – even in the absence of a real-  
549 world correspondence between voice pitch and physical markers of dominance (see  
550 Feinberg, Jones, & Armstrong, in press, for review).

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740

741 Table 1: Number and Age of Participants

742

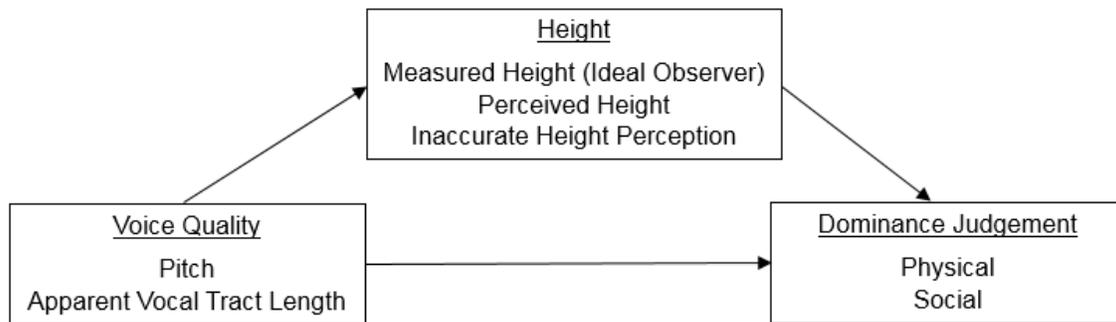
<i>Rating Attribute</i>	<i>Gender of Raters</i>	<i>N</i>	<i>Mean (S.D.) Age</i>
<i>Female Voices</i>			
Perceived Height	Women	56	18.7 (1.33)
	Men	33	18.6 (0.87)
Perceived Physical Dominance	Women	53	18.5 (1.44)
	Men	41	18.7 (1.30)
Perceived Social Dominance	Women	52	18.9 (2.21)
	Men	38	18.9 (1.32)
<i>Male Voices</i>			

Perceived Height	Women	54	18.7 (1.33)
	Men	31	19.1 (1.13)
Perceived Physical	Women	55	19.1 (2.39)
Dominance	Men	35	18.8 (1.30)
Perceived Social	Women	52	19.1 (1.93)
Dominance	Men	33	18.9 (1.29)

743

744 Figure 1: Mediation model showing predictor variable (voice pitch), mediating variables  
745 (height perceptions) and outcome variables (dominance perceptions).

746

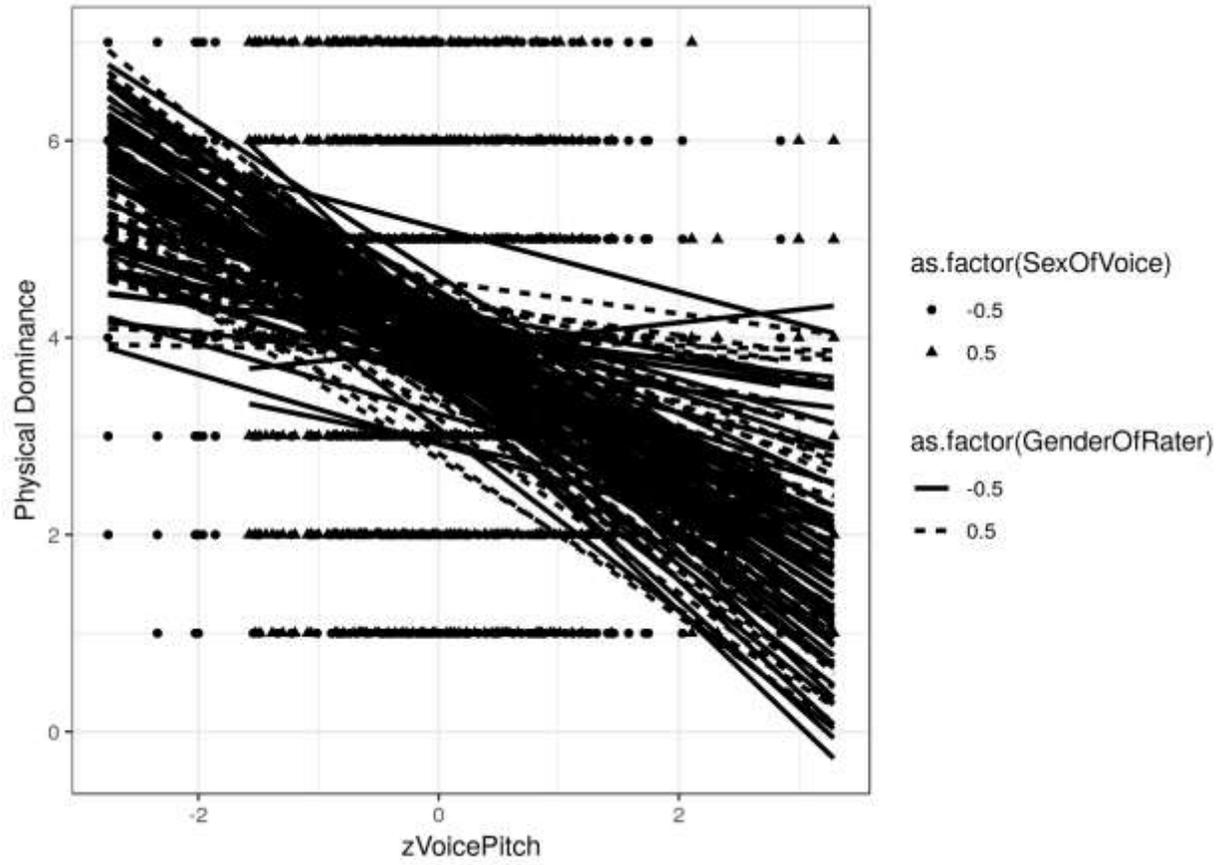


747

748 Figure 2 – The relationship between voice pitch and perceived physical dominance.

749 Each line represents a participant's ratings. -0.5 represents data from cisgender

750 women, 0.5 represents data from cisgender men.



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