

Tennis grunts communicate acoustic cues to sex and contest outcome

Article (Accepted Version)

Raine, Jordan, Pisanski, Katarzyna and Reby, David (2017) Tennis grunts communicate acoustic cues to sex and contest outcome. *Animal Behaviour*, 130. pp. 47-55. ISSN 0003-3472

This version is available from Sussex Research Online: <http://sro.sussex.ac.uk/id/eprint/68600/>

This document is made available in accordance with publisher policies and may differ from the published version or from the version of record. If you wish to cite this item you are advised to consult the publisher's version. Please see the URL above for details on accessing the published version.

Copyright and reuse:

Sussex Research Online is a digital repository of the research output of the University.

Copyright and all moral rights to the version of the paper presented here belong to the individual author(s) and/or other copyright owners. To the extent reasonable and practicable, the material made available in SRO has been checked for eligibility before being made available.

Copies of full text items generally can be reproduced, displayed or performed and given to third parties in any format or medium for personal research or study, educational, or not-for-profit purposes without prior permission or charge, provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way.

Tennis grunts communicate acoustic cues to sex and contest outcome

Jordan Raine*, Katarzyna Pisanski, David Reby

Mammal Vocal Communication and Cognition Research Group, School of Psychology,

University of Sussex, Falmer, East Sussex, United Kingdom, BN1 9QH

* Corresponding author.

Email address: j.w.raine@sussex.ac.uk

Phone number: 07568 598127

Postal address: 6 Egginton Close, Brighton, East Sussex, BN2 4QH

Word count: 8952

Despite their ubiquity in human behaviour, the communicative functions of nonverbal vocalisations remain poorly understood. Here, we analysed the acoustic structure of tennis grunts, nonverbal vocalisations produced in a competitive context. We predicted that tennis grunts convey information about vocalizer and context, similar to nonhuman vocal displays. Specifically, we tested whether the fundamental frequency (F0) of tennis grunts conveys static cues to a player's sex, height, weight, and age, and covaries dynamically with tennis shot type (a proxy of body posture) and the progress and outcome of male and female professional tennis contests. We also performed playback experiments (using natural and resynthesised stimuli) to assess the perceptual relevance of tennis grunts. The F0 of tennis grunts predicted player sex, but not age or body size. Serve grunts had higher F0 than forehand and backhand grunts, grunts produced later in contests had higher F0 than those produced earlier, and grunts produced during contests that players won had a lower F0 than those produced during lost contests. This difference in F0 between losses and wins emerged early in matches, and did not change in magnitude as the match progressed, suggesting a possible role of physiological and/or psychological factors manifesting early or even before matches. Playbacks revealed that listeners use grunt F0 to infer sex and contest outcome. These findings indicate that tennis grunts communicate information about both vocalizer and contest, consistent with nonhuman mammal vocalisations.

Keywords: dominance, fundamental frequency, nonverbal vocalisations, pitch, tennis grunts, vocal communication.

Despite their ubiquitous use across ages, sexes, contexts and cultures, human nonverbal vocalisations remain underinvestigated. In fact, aside from laughter (see

Bryant et al., 2016; Scott, Lavan, Chen, & McGettigan, 2014) and infant cries (Lingle, Wyman, Kotrba, Teichroeb, & Romanow, 2012 for review), human nonverbal vocalisations (such as moans, sighs, roars, screams, and grunts) have received little attention, especially from a functional and evolutionary perspective.

Indeed, the majority of research on human nonverbal vocalisations has focused on their classification according to emotional content (e.g. Belin, Fillion-Bilodeau, & Gosselin, 2008; Lima, Castro, & Scott, 2013; Sauter, Eisner, Calder, & Scott, 2010), while overlooking their potential to convey indexical cues about the vocalizer such as age, sex, body size, and social dominance. Such cues are typically present in the vocal signals of nonhuman mammals, and function to mediate interactions in social and sexual contexts (Briefer, 2012; Taylor, Charlton, & Reby, 2016). Human nonverbal vocalisations likely predate language, and appear homologous in structure and function with nonhuman vocalisations (e.g. laughter Davila-Ross, Owren, & Zimmermann, 2010; Pisanski, Cartei, McGettigan, Raine, & Reby, 2016; infant distress vocalisations Lingle et al., 2012). As such, they may constitute a relatively direct link between animal and human vocal systems. Investigating their production, control and perception may therefore provide a unique window into the origins and evolution of human vocal behaviour (Pisanski, Cartei, et al., 2016).

Here, we examined whether the acoustic structure of tennis grunts – a nonverbal vocalisation produced during a competitive contest – contains functionally relevant and perceptible cues. While there are clear qualitative differences between tennis matches and nonhuman mammal contests (tennis players do not voluntarily yield to dominant competitors, and there are more clearly defined rules and endpoints), animal contests often follow ritualised rules and structures, during which competitors produce signals that contain static and dynamic information about their respective physical condition

and motivation (e.g. ungulates: Jennings & Gammell, 2013). Thus tennis matches provide a potentially useful model to examine whether similar information is communicated in human competitive interactions.

Investigations of the function of tennis grunts have so far focused on their distracting quality to opponents (Farhead & Punt, 2015; Sinnett & Kingstone, 2010), and their enhancement of ball velocity without increasing oxygen cost (e.g. O'Connell, Hinman, Hearne, Michael, & Nixon, 2014). No previous study has examined their possible communicative value. We hypothesized that tennis grunts are competitive nonverbal vocalisations homologous to those produced by nonhuman animals in agonistic contexts. Accordingly, we predicted that grunts would contain static and dynamic cues to anatomical and physiological traits of the vocaliser. As vocalisations produced in a competitive context, tennis grunts may be affected by changes in players' physiological and psychological state (e.g. arousal and stress, which correlate positively with F0, Briefer, 2012; Pisanski, Nowak, & Sorokowski, 2016). Thus, we predicted that grunt F0 would correlate with the outcome of competitive contests (i.e., tennis matches). Finally, we predicted that listeners would be able to use these static and dynamic cues to make functionally relevant inferences about both the tennis player and the match.

Recent research generalising the source-filter model of speech production (Fant, 1960) to vertebrate vocal signals has highlighted the function of fundamental frequency (F0, affecting perceived pitch) and formant frequencies (resonances of the supralaryngeal vocal tract, affecting perceived timbre) in communicating various static and dynamic cues in nonhuman mammal vocalisations (see Briefer, 2012; Taylor et al., 2016). For example, sexually-selected calls communicate F0-based cues to dominance (e.g. male deer groans Liu et al., 2015; Vannoni & McElligott, 2008) and formant cues

to body size (red deer Reby et al., 2005; Australian sea lions Charrier, Ahonen, & Harcourt, 2011; dogs Taylor, Reby, & McComb, 2010). However, whether fundamental and formant frequencies also communicate similar information in human nonverbal vocalisations remains to be determined.

To address this, we investigated the acoustic structure of tennis grunts produced by male and female tennis players during professional matches. Because tennis grunts are relatively high-pitched vocalisations characterised by a low spectral density, formant frequencies were poorly defined and difficult to both perceive and measure (Pisanski, Fraccaro, Tigue, O'Connor, & Feinberg, 2014; Ryalls & Lieberman, 1982). We therefore focused our analyses on the mean F0 of grunts. We recorded the sex, height, weight, and age of the vocalisers (static cues), the type of tennis shot accompanying the grunt (forehand/backhand/serve), and the outcome of the given match (vocaliser won/lost) (dynamic cues). We then investigated whether tennis grunts have perceptual and functional relevance in playback experiments using a separate sample of natural and F0-resynthesised tennis grunts.

We predicted that (i) females would produce tennis grunts with higher F0 than males due to sexual dimorphism in human vocal folds and F0 (Taylor et al., 2016; Titze, 1994); (ii) F0 would not indicate height, weight, or age in our sample of young adult players due to the weak relationship between speaking F0 and body size within-sexes in human speech (Pisanski, Fraccaro, Tigue, O'Connor, Röder, et al., 2014 for meta-analysis) and other mammal vocalisations (Taylor et al., 2016 for review), and based on the relative stability of F0 in human speech after puberty (Fouquet, Pisanski, Mathevon, & Reby, 2016); (iii) postural differences between shot types would affect F0 due to the influence of dynamic biomechanical constraints on vocal production mechanisms (Fitch & Hauser, 1995; Titze, 1994); and (iv) the F0 of vocalisations

occurring during match losses would be higher than during match wins. This final prediction stems from the aforementioned negative relationship between F0 and dominance, and evidence that F0 increases under stress, distress, and arousal in both humans (Pisanski, Nowak, et al., 2016) and nonhuman mammals (Briefer, 2012 for review). Finally, we predicted that F0 cues in tennis grunts would influence listeners' attributions of vocalizer sex and match outcome.

METHODS

Analysis of Tennis Grunts

Within-subject variables

From the top 30 professional tennis players in the world at the time of data collection, we identified seven males and seven females who consistently grunt when hitting both serves and groundstrokes within and between matches (see Appendix for additional details).

Using PRAAT 5.3.62 DSP package (Boersma & Weenink, 2014) and Boom 2 software (Global Delight Technologies, 2014), we extracted 367 tennis grunts from direct audio output of television footage of 50 matches provided by the International Tennis Federation and the IMG Sport Video Archive. Recordings were saved as WAV files at 44.1 kHz sampling frequency and 16 bits amplitude resolution. For each grunt, we coded shot type (forehand/backhand/serve – the most common shot types, Johnson & McHugh, 2006), the duration of the match at the point of grunt production (hereafter *match progress*, expressed as a percentage of total match duration), and match outcome (win/loss). For each match, two grunts per set were recorded for males, and three for

females. This resulted in an equal number of grunts per match for each sex, as women play best-of-three sets while men play best-of-five. Grunts were sampled at equally spaced time intervals across the duration of each set. Within each match, an equal number of forehands, backhands, and serves were recorded. Within each vocaliser, we recorded a roughly equal number of grunts from match wins and losses. Within the constraints of the limited number of televised matches available to us, we matched wins and losses as closely as possible in terms of tournament stage, so as to control for the potential effect of match importance on physiological and psychological state.

Between-subject variables

To test whether player sex, height, weight, and age predicted grunt F0, we conducted an additional between-subject analysis. Because F0 variation between serve vocalisations in the within-subjects dataset was relatively small (see Figure 1a), we randomly selected two serve vocalisations from each of the 14 players described above, and extracted 92 serve vocalisations from an additional 23 male and 23 female professional tennis players (mean age \pm SD = 25.09 \pm 0.42), to achieve an adequate sample size of 30 players per sex and 120 serve vocalisations. We chose serve vocalisations because they are always produced at the start of rallies, from an initially stationary position where posture is most standardised. Player sex, height, weight, and age data were acquired from www.atpworldtour.com and www.wtatennis.com. We also extracted 10-second pre-match interview clips to measure each player's mean speaking F0.

Acoustic analysis

We extracted mean F0 using a dedicated processing script in PRAAT (Boersma & Weenink, 2014). We systematically inspected each extracted pitch contour and verified it using a narrow band spectrogram displaying the first 2,000 Hz of the signal. Erroneous pitch values (e.g. octave jumps) were manually corrected. Fifty recordings were omitted from the within-subject dataset due to insufficient quality for pitch extraction ($N = 41$) or aperiodicity exceeding 50% of clip duration ($N = 9$). Thus, 317 grunts were used in the final within-subject analysis (mean \pm SD per player = 23.29 ± 0.19). No recordings were omitted from the between-subject analysis. Each extracted F0 contour (pitch object) was used to derive mean F0. This acoustic analysis procedure has been applied successfully in previous studies of a human nonverbal vocalisation (e.g. babies' cries Reby, Levréro, Gustafsson, & Mathevon, 2016).

Statistical analysis

We ran all statistical analyses with IBM SPSS Statistics 22 (IBM Corp., Armonk, NY, U.S.A.). We tested for effects of predictor variables on mean grunt F0 using Linear Mixed Models (LMMs, covariance structure: variance components, restricted maximum likelihood). We expected the distributions of F0 between sexes to show little to no overlap (due to strong sexual dimorphism in F0), and therefore conducted separate analyses for male and female players. For models examining within-subject variables, we calculated AICc values with every possible combination of variables and interactions, and employed model selection to arrive at a best-fitting final model (Symonds & Moussalli, 2011). Further detail on model selection parameters is provided in the Appendix. Model structures detailing fixed and random effects are given in the footnotes of Table 1.

Playback Experiments

We tested whether listeners can accurately gauge sex and match outcome from tennis grunts using a newly recorded set taken from television and YouTube footage of professional matches. We also examined whether natural or experimentally manipulated variation in grunt F0 influenced how listeners attributed sex and match outcome.

Participants

Thirty University of Sussex students (16 male, 14 female, mean \pm SD age = 24.97 \pm 9.46) participated in the sex attribution task, 16 of whom were competitive tennis team players. Eighteen competitive tennis players (including the 16 who completed the sex attribution task) participated in the match outcome attribution task (11 males, 7 females, mean \pm SD age = 20.89 \pm 2.61).

Stimuli and procedure

Participants completed the playback experiments in a quiet room. Stimuli were presented on a laptop computer via the Experiment Multiple Forced Choice tool in PRAAT and through Sony MDR XB500 headphones at a comfortable pre-set volume, standardised within participants.

For the sex attribution task, participants were presented with 1 grunt per trial from 10 male and 10 female players and asked to identify the sex of the player. Participants were only presented with natural grunts and completed a total of 20 trials.

For the match attribution task, participants were presented with pairs of 6-grunt sequences from 6 male and 6 female players and asked to identify which sequence in

the pair came from the match the player lost. Each pair consisted of one sequence of grunts from the end of a match the player won without losing a set (win sequence), and a sequence of grunts from a match that same player lost without winning a set (loss sequence). Participants completed 12 trials for natural grunt-sequence pairs (though only 11 pairs were included in statistical analysis, see Appendix).

In addition, we resynthesised the F0 of grunt-sequence pairs to create four F0-resynthesis conditions: two in which the loss sequence was higher in F0 than the win sequence, and two in which the win sequence was higher in F0 than the loss sequence. We resynthesised the F0 of entire loss and win grunt sequences by equal amounts, such that the mean F0 difference between grunt-sequences within each pair was equal to the mean F0 difference between loss and win grunts measured from our samples of professional tennis players (± 27 Hz and ± 58 Hz for males, and ± 39 Hz and ± 100 Hz for females, to fit the mean difference $\pm N$ SD, with $N = 0$ and 1). Two of the 12 grunt-sequences could not be resynthesised because F0 could not be detected. Thus, participants completed 40 trials for resynthesised grunt-sequence pairs (10 pairs x 4 resynthesis conditions). For additional details see Appendix.

Participants entered ratings by clicking on the chosen button on the screen. They could either confirm their choice (“OK” button), replay the sound (“replay” button), or change their rating (“back” button), before moving on to the next stimulus.

Non-tennis playing participants completed only the sex attribution task. Competitive tennis playing participants completed both the sex attribution task and the two match outcome attribution tasks in separate blocks. As the resynthesised match outcome task stimuli consisted of four repetitions of previously heard stimuli, this task was split into two blocks and pseudo-randomised so that two resyntheses of the same stimulus pair were presented at least six trials apart. These two ‘match outcome’ blocks

were separated by the sex attribution task (for all but two listeners who did not complete the sex attribution task), so as to minimise recognition of exemplar repetition. Block order was counterbalanced, and within blocks, stimulus presentation was randomised and counterbalanced.

Statistical analysis

We used Generalised Linear Mixed Models (GLMMs) with binary logistic regression link in SPSS to test for accuracy in listeners' attributions. We also examined the effects of natural and artificial variation in mean F0, and for the sex attribution task, the effect of level of tennis experience, on these attributions. All GLMMs included listener identity as a subject variable, and the model testing the effect of F0 on match outcome attributions in resynthesised grunts also included actual match outcome as a random factor. Effect sizes were estimated using R coefficients derived from simple linear regressions between the mean F0 (or mean F0 difference) and the ratings averaged by exemplar and listener (sex, match outcome). Listener sex did not significantly predict how listeners attributed sex or match outcome in any model, and therefore was not included in reported models.

Ethical Note

The Sciences and Technology Cross-Schools Research Ethics Committee of the University of Sussex reviewed and approved this research (ER/JR307/1).

RESULTS

Do Tennis Grunts Contain Static and Dynamic Cues?

Effects of sex, age, height, weight, and speaking F0 on grunt F0

Player sex significantly predicted mean grunt F0 ($F_{1,58} = 104.73$, $P < 0.001$): the mean F0 of female grunts (573.9 ± 24.36 Hz) was higher than that of male grunts (296.9 ± 24.46 Hz). F0 variation was greater among females than males (Figure 1a, Levene's test: $F_{1,100} = 47.87$, $P < 0.001$). Figure 1b illustrates that there was very little overlap in the frequency distributions of male and female grunts. Age, height, and weight (examined separately for each sex) did not significantly predict mean grunt F0 (all P s > 0.198), nor did speaking F0 (P s > 0.161), although there was a non-significant trend for female grunt F0 to increase with speaking F0 (Table 1).

Table 1

Correlates of grunt F0: LMMs testing the effects of vocaliser traits and match factors on mean grunt F0

Model	Males			Females		
	<i>df</i> ₁ , <i>df</i> ₂	<i>F</i>	<i>P</i>	<i>df</i> ₁ , <i>df</i> ₂	<i>F</i>	<i>P</i>
<i>Model 1: Effect of between-subjects predictors on mean grunt F0 for each sex</i>						
Intercept	1, 26.7	0.01	0.921	1, 25.4	0.01	0.928
Height	1, 26.3	0.54	0.468	1, 25.1	0.94	0.341
Weight	1, 26.3	0.18	0.674	1, 25.2	1.75	0.198
Age	1, 29.0	0.89	0.352	1, 28.0	0.17	0.688
Speaking F0	1, 24.9	1.15	0.295	1, 25.3	2.09	0.161
<i>Model 2: Effect of within-subjects predictors on mean grunt F0 for each sex</i>						
Intercept	1, 17.0	1435.57	< 0.001	1, 6.9	180.15	< 0.001
Shot type	2, 145.2	8.12	< 0.001	2, 138.4	3.64	0.029
Match outcome	1, 16.5	7.53	0.014	1, 12.3	3.07	0.105
Match progress	1, 145.8	6.70	0.011	1, 139.6	4.19	0.043

Linear mixed models (LMMs) testing the main effects of height, weight, age, speaking F0, shot type, match outcome, and match progress on professional tennis players' mean grunt F0. Model 1 (30 males, 30 females; 2 grunts per player): LMM included player identity as subject variable. Height and weight were strongly correlated in males ($r = 0.59$) and females ($r = 0.53$). Model 2 (7 females, mean grunts per player: 23.29, 7 males, mean grunts per player: 23.29): LMM included player identity as subject variable, and the match identity as a random factor.

Effects of shot type, match progress, and match outcome on grunt F0

The effects of shot type, match progress, and match outcome on mean grunt F0 were assessed separately for males and females. For both sexes, shot type predicted mean grunt F0 (males: $F_{2,145} = 8.12$, $P < 0.001$, females: $F_{2,138} = 3.64$, $P = 0.029$, Table 1). Planned pairwise comparisons indicated that the F0 of grunts accompanying serves (males: mean \pm SD = 325.0 ± 7.3 Hz, females: mean \pm SD = 650.0 ± 44.1 Hz) was significantly higher than for forehands (males: mean \pm SD = 311.8 ± 7.0 Hz, $p = 0.052$;

females: mean \pm SD = 616.0 \pm 44.0 Hz, $P = 0.045$) and backhands (males: mean \pm SD = 297.5 \pm 7.1 Hz, $P < 0.001$; females: mean \pm SD = 606.1 \pm 44.1 Hz, $P = 0.011$).

For both sexes, grunt F0 increased as the match progressed (males: $F_{1,146} = 6.70$, $P = 0.011$, females: $F_{1,140} = 4.19$, $P = 0.043$, Table 1). To examine this effect further we categorised grunts according to which third of the match they were produced in. Male grunt F0 was significantly higher in the last third of matches (mean \pm SD = 320.87 \pm 7.14 Hz) than in the first third (mean \pm SD = 305.89 \pm 7.32 Hz, $P = 0.027$). There was a similar but non-significant trend among female players (last third: 633.70 \pm 44.06 Hz; first third: 602.36 \pm 44.26 Hz, $P = 0.059$).

Among males, grunt F0 was higher during losses (mean \pm SD = 319.97 \pm 6.97 Hz) than wins (mean \pm SD = 302.97 \pm 6.65 Hz, $F_{1,17} = 7.53$, $P = 0.014$). Among female players, grunt F0 was not significantly higher during losses (mean \pm SD = 640.53 \pm 44.18 Hz) than wins (mean \pm SD = 607.65 \pm 43.87 Hz, $F_{1,12} = 3.07$, $P = 0.105$, Table 1).

Following AICc comparison for model selection (Symonds & Moussalli, 2011), our final reported models were 2.94 times (males) and 2.31 times (females) more likely to be the best approximating model than the models with the next lowest AICc values, which included the non-significant interaction between match outcome and match progress for both sexes ($P_s > 0.451$). The final model showed that the difference in F0 between losses and wins in male players emerged early in matches, and the magnitude of this difference did not change as the match progressed; F0 increased with match progress for both winners and losers by an equal degree.

Can Listeners Gauge Sex and Match Outcome From Tennis Grunts?

Attribution of sex by listeners

Acoustic analysis of the playback stimuli confirmed that player sex significantly predicted mean grunt F0 ($F_{1,18} = 475.88, P < 0.001$). Males produced grunts with lower F0 (mean \pm SD = 329 ± 27.70 Hz) than did females (mean \pm SD = 525.59 ± 27.70 Hz).

Playback experiments showed that listeners correctly identified the sex of players from their grunts ($F_{1,598} = 256.53, P < 0.001$). Listeners correctly attributed the sex of the player for 95% of male and 91% of female grunts. All female exemplars were identified with at least 93% accuracy except for two females with relatively low grunt F0, who were identified with 57% and 67% accuracy. All male exemplars were identified with 87% accuracy or above. Competitive tennis players attributed sex with a higher degree of accuracy (mean \pm SD = $96 \pm 1\%$) than did non-playing participants (mean \pm SD = $90 \pm 2\%$, $F_{1,598} = 7.32, P = 0.007$).

Grunts with higher F0 were significantly more likely to be identified as female, and those with lower F0 as male ($F_{1,598} = 162.94, P < 0.001$), even within sexes for females ($F_{2,597} = 119.78, P < 0.001$). This effect was large collapsing across sexes ($R = 0.81$), and within females ($R = 0.50$).

Attribution of match outcome by listeners

Acoustic analysis of the playback stimuli showed that match outcome significantly predicted mean grunt F0 in both males ($F_{1,15} = 10.85, P = 0.005$) and females ($F_{1,15} = 5.65, P = 0.031$). Grunt F0 was higher during lost than won matches for both males (mean \pm SD diff = 26.68 ± 8.10 Hz) and females (mean \pm SD diff = 39.08 ± 16.44 Hz).

In playback experiments involving natural grunt sequences, actual match outcome significantly predicted how often listeners accurately choose the match that

the player lost ($F_{1,196} = 8.63$, $P = 0.004$). The mean percentage of correct identification ($61\% \pm 3.5\%$) was marginally higher than chance (50%). Furthermore, the relatively higher F0 grunt sequence was more likely to be attributed as coming from a loss ($F_{1,196} = 25.41$, $P < 0.001$), and the higher the F0 of the loss sequence relative to the win sequence, the more accurately listeners attributed match outcome ($F_{1,196} = 17.06$, $P < 0.001$, Figure 2a). These effects of F0 were large (both $R_s = 0.71$). In playbacks involving resynthesised grunt sequences, relatively higher F0 grunt sequences were significantly more likely to be attributed as coming from losses than were relatively lower F0 sequences ($F_{1,718} = 16.29$, $P < 0.001$, Figure 2b). This effect was also large ($R = 0.51$).

DISCUSSION

Our results show that tennis grunts contain static cues to speaker sex, and dynamic cues to tennis shot type, match progress and contest outcome. Female grunts, serve grunts, and loss grunts were characterised by a higher F0 (voice pitch) than were male, groundstroke, and win grunts, respectively, supporting our predictions. We also found that listeners could accurately judge player sex and match outcome, with F0 cues strongly predicting listeners' categorisations. These findings are consistent with existing literature describing the influence and functional relevance of sex, dominance, muscular control, and arousal on F0 production in humans and other mammals (Taylor et al., 2016).

Cues to sex, but not height, weight, or age in tennis grunts

The mean F0 of tennis serve grunts (females: 574 Hz, males: 297 Hz) was three times higher than in modal human speech (i.e. speaking F0) for both males (120 Hz) and females (210 Hz) (Pisanski, Fraccaro, Tigue, O'Connor, Röder, et al., 2014). Nevertheless, we found that sexual dimorphism in tennis grunts (a ratio of 1:1.9) is roughly the same as that previously observed for human speech (1:1.8, Pisanski, Fraccaro, Tigue, O'Connor, Röder, et al., 2014). Sexual dimorphism in adult laughter also varies around this ratio (Bachorowski, Smoski, & Owren, 2001; Szameitat, Darwin, Szameitat, Wildgruber, & Alter, 2011), indicating that the constraints imposed by sex differences in vocal fold dimensions on the F0 of human speech extend to adult nonverbal vocalisations.

We found that listeners accurately attributed the sex of tennis players. Although competitive tennis players attributed sex more accurately than did non-playing listeners, possibly because they may have recognised the identity of some players, the difference in accuracy was small (6%) and both groups correctly identified sex with very few errors. Higher F0 grunts were more likely to be perceived as female, as is the case in adult human speech (Hillenbrand & Clark, 2009), and babies' cries (despite no sex differences in F0) (Reby et al., 2016). However, other acoustic characteristics known to be sexually dimorphic in speech signals, such as vocal tract resonances (Titze, 1994) and the variability of the pitch contour (Puts, Apicella, & Cárdenas, 2012), may also have helped listeners to accurately attribute the sex of players.

In concordance with widespread evidence that F0 is a poor predictor of body size when controlling for sex and age in animal vocalisations (Taylor et al., 2016) and human speech (Pisanski, Fraccaro, Tigue, O'Connor, Röder, et al., 2014), neither height nor weight predicted mean grunt F0 in our study. This lack of covariation has been attributed to the fact that vocal fold growth is not tightly constrained by skull and body

dimensions (Lieberman, McCarthy, Hiiemae, & Palmer, 2001), thus the relationship between body size and vocal fold size – and therefore F0 – does not generate reliable information on inter-individual variation in body size (Pisanski, Fraccaro, Tigue, O'Connor, Röder, et al., 2014). Between-individual differences in grunt F0 may however covary with between-individual differences in androgen levels. Indeed, adult men with higher circulating levels of testosterone speak with a lower modal F0 than do men with lower levels of testosterone (Cartei, Bond, & Reby, 2014; Dabbs Jr. & Mallinger, 1999). While we did not have access to hormonal data, future studies should investigate the influence of androgens on F0 in nonverbal vocalisations.

Age did not predict grunt F0 in our sample of adult players, aged 16 to 35. Due to overall body growth (and differential vocal fold growth in males during puberty), the F0 of children's voices is much higher than that of adults in both modal speech (e.g. Peterson & Barney, 1952) and laughter (Bachorowski et al., 2001; Hudenko, Stone, & Bachorowski, 2009). However, despite sizeable between-individual differences in F0 among men, longitudinal observations show that within individuals, F0 remains largely stable after puberty and throughout men's adulthood, at least until about age 60 (Fouquet et al., 2016), consistent with our findings.

Speaking F0 did not reliably predict grunt F0. Thus, while F0 reliably indicates sex in both speech and grunts, there is a decoupling of inter-individual F0 variation between modal speech and this vocalisation. This decoupling suggests that the biomechanical constraints affecting inter-individual differences in F0 differ between these two modes of vocal production.

Acoustic cues to shot type

Grunt F0 differed across shot types. The observation that serves were characterised by a significantly higher F0 than forehands and backhands may be attributed to biomechanics: groundstrokes involve more pelvic rotation and lower limb drive, whereas serves involve powerful contractions of the abdominal muscles to facilitate the shoulder-over-shoulder trunk flexion that accelerates the body before ball impact (Elliott, 2006). As such, abdominal muscle activity is higher during serves than groundstrokes (Chow, Park, & Tillman, 2009; Knudson & Blackwell, 2000). Contraction of the abdominal muscles is known to produce an increase in subglottic air pressure – for example, singers actively manipulate their abdominal muscles to precisely control subglottic pressure (e.g. Sundberg, Leanderson, von Euler, & Knutsson, 1991). Given that F0 increases with subglottic pressure during speech (Plant & Younger, 2000) and singing (Sundberg, Titze, & Scherer, 1993), the increased abdominal muscle contraction required for serving may lead to the production of grunts characterised by a higher F0.

Acoustic cues to tennis match progress and outcome

Our acoustic analyses showed that both male and female players produced grunts with a lower F0 at the beginning than at the end of matches, consistent with evidence that F0 increases under moderate physical load, and again prior to exhaustion (Johannes et al., 2007). Professional players tire as matches progress (Reid & Duffield, 2014), but maintain constant serve speed and accuracy over the duration of long matches (Maquirriain, Baglione, & Cardey, 2016). Thus, the degradation of shot technique (e.g. lower height of ball toss for the serve) may be compensated for by an increase in muscle activation to achieve the same kinetic force (Kibler, 2014). This

increased physical effort may be accompanied by increased vocal effort when grunting, which would raise F0 (Lagier et al., 2010). Players are also likely to experience greater physiological arousal and stress in later stages of matches as, being more proximal to the outcome of the match, individual points become more important in determining the winner. As F0 positively correlates with arousal and stress (Briefer, 2012; Pisanski, Nowak, et al., 2016), including psychological stress elicited during short-term physical tasks (Wittels, Johannes, Enne, Kirsch, & Gunga, 2002), this may contribute to the rise in F0 with match progress.

We also found that, independent of match progress, male players produced grunts with overall higher F0 in losses than wins, by an average of 17 Hz or roughly one semitone. This is consistent with observations that F0 increases in response to stressors in both humans and nonhuman mammals (e.g. Briefer, 2012; Pisanski, Nowak, et al., 2016; Wittels, Johannes, Enne, Kirsch, & Gunga, 2002). Men's testosterone levels, which correlate negatively with F0 (Cartei et al., 2014; Dabbs Jr. & Mallinger, 1999), are also higher in winners than losers of competitive encounters (Booth, Shelley, Mazur, Tharp, & Kittok, 1989; Campbell, Orourke, & Rabow, 1988; Elias, 1981; Mazur & Lamb, 1980), and dynamic F0 shifts depend on perceived dominance in dyadic competitive scenarios (Puts, Gaulin, & Verdolini, 2006). In addition, losing in competitive sport is stressful (Scanlan & Passer, 1977) and may result in increased physical and vocal effort during the match in attempts to avoid defeat, which, as discussed previously, may also contribute to the F0 difference between grunts occurring in wins and losses.

The effect of match outcome on mean F0 was marginally non-significant in female players. This may be partially attributed to the larger intra-individual variance in female than male grunt F0 (Figure 1a), and to our modest sample size. This result

may also reflect humans' polygynous evolutionary history (Puts, 2016), whereby the emphasis on male competition and female choice results in greater sexual dimorphism through greater pressures for acoustic communication of dominance and formidability in males than in females (Puts et al., 2016). Nevertheless, we observed a similar trend in females, with grunts during match losses on average 33 Hz higher in F0 than those occurring during wins, a difference perceptually equivalent to that found in males (roughly one semitone).

Crucially, the average intra-individual difference in F0 between grunts produced in lost and won matches did not vary significantly as matches progressed. Thus, while grunt F0 dynamically varies within matches irrespective of match outcome, likely as a function of fatigue and/or arousal, players consistently grunt at a relatively higher F0 in lost than won matches, even at the start of matches. This suggests that rather than dynamic shifts due to short-term scoreboard dominance, the difference in F0 between male winners and losers may reflect longer-term physiological and/or psychological factors that may manifest even before the commencement of a match. For example, head-to-head record (i.e. the outcome of all previous matches between the two players), the outcome of the previous encounter, current form, world ranking, and physical condition may influence self-perceived dominance and/or stress, and affect grunt F0 from the beginning of matches. Future research could examine the influence of these factors.

Playback experiments revealed that listeners with experience of competitive tennis could identify which of two grunt sequences produced by the same player came from a match that the player lost. The F0 difference between these sequences predicted the accuracy with which listeners attributed match outcome, and systematic F0 resynthesis of grunt sequences further confirmed that F0 influenced match outcome

judgments. These results are consistent with the sensitivity of male fallow deer to F0 resynthesis of competitive calls of other males (indicating dominance)(Pitcher, Briefer, & McElligott, 2015), and suggest that tennis grunts, like visual nonverbal cues (basketball, table tennis Furley & Schweizer, 2014b), provide functional cues that allow human receivers to infer contest outcome.

Our results indicate that the acoustic structure of tennis grunts, like nonhuman mammal calls, contains perceptible static and dynamic cues to anatomical and physiological attributes of the speaker. In future work researchers may examine the functional relevance of these cues by testing how they affect tennis players' behaviour and internal state. For example, acoustic cues to contest outcome in tennis grunts may influence opposing players' confidence, as is the case with visual nonverbal cues (Furley & Schweizer, 2014a). Furthermore, although our sample included players who grunt sufficiently frequently to allow for behavioural observation (see Appendix), future work may investigate predictors of variation in the occurrence of grunting both within- and between-players to more fully understand the mechanisms and functions of tennis grunts. Finally, researchers may also examine whether, in addition to grunts, other types of human vocalisations such as aggressive roars, fear screams, and sexual vocalisations convey evolutionarily important information. Such vocalisations constitute an intermediary link between nonhuman mammal vocalisations and human speech, and investigating their production and perception may provide additional insight into the evolution of human vocal communication and vocal control, a necessary prerequisite for speech (Pisanski, Cartei, et al., 2016).

Data availability

The dataset supporting this article has been uploaded to the Sussex Research Online (SRO) repository (to be given at copyediting/proof stage: Item #, <http://sro.sussex.ac.uk/id/eprint/#>).

REFERENCES

- Bachorowski, J. A., Smoski, M. J., & Owren, M. J. (2001). The acoustic features of human laughter. *The Journal of the Acoustical Society of America*, 110(3), 1581–1597. <https://doi.org/10.1121/1.1391244>
- Belin, P., Fillion-Bilodeau, S., & Gosselin, F. (2008). The Montreal Affective Voices: a validated set of nonverbal affect bursts for research on auditory affective processing. *Behavior Research Methods*, 40(2), 531–539.
- Boersma, P., & Weenink, D. (2014). Praat: doing phonetics by computer (Version 5.4). Retrieved from <http://www.praat.org/>
- Booth, A., Shelley, G., Mazur, A., Tharp, G., & Kittok, R. (1989). Testosterone, and winning and losing in human competition. *Hormones and Behavior*, 23(4), 556–571. [https://doi.org/10.1016/0018-506X\(89\)90042-1](https://doi.org/10.1016/0018-506X(89)90042-1)
- Briefer, E. (2012). Vocal expression of emotions in mammals: mechanisms of production and evidence. *Journal of Zoology*, 288(1), 1–20. <https://doi.org/10.1111/j.1469-7998.2012.00920.x>
- Bryant, G. A., Fessler, D. M. T., Fusaroli, R., Clint, E., Aarøe, L., Apicella, C. L., ... Zhou, Y. (2016). Detecting affiliation in laughter across 24 societies. *Proceedings of the National Academy of Sciences*, 113(17), 4682–4687. <https://doi.org/10.1073/pnas.1524993113>

- Campbell, B. C., Orourke, M. T., & Rabow, M. W. (1988). Pulsatile response of salivary testosterone and cortisol to aggressive competition in young males. In *American Journal of Physical Anthropology* (Vol. 75, pp. 193–194). New York, NY, US: John Wiley & Sons.
- Cartei, V., Bond, R., & Reby, D. (2014). What makes a voice masculine: Physiological and acoustical correlates of women's ratings of men's vocal masculinity. *Hormones and Behavior*, 66(4), 569–576.
<https://doi.org/10.1016/j.yhbeh.2014.08.006>
- Charrier, I., Ahonen, H., & Harcourt, R. G. (2011). What makes an Australian sea lion (*Neophoca cinerea*) male's bark threatening? *Journal of Comparative Psychology*, 125(4), 385–392. <https://doi.org/10.1037/a0024513>
- Chow, J. W., Park, S.-A., & Tillman, M. D. (2009). Lower trunk kinematics and muscle activity during different types of tennis serves. *BMC Sports Science, Medicine and Rehabilitation*, 1(1), 24. <https://doi.org/10.1186/1758-2555-1-24>
- Dabbs Jr., J. M., & Mallinger, A. (1999). High testosterone levels predict low voice pitch among men. *Personality and Individual Differences*, 27(4), 801–804.
[https://doi.org/10.1016/S0191-8869\(98\)00272-4](https://doi.org/10.1016/S0191-8869(98)00272-4)
- Davila-Ross, M., Owren, M. J., & Zimmermann, E. (2010). The evolution of laughter in great apes and humans. *Communicative & Integrative Biology*, 3(2), 191–194. <https://doi.org/10.4161/cib.3.2.10944>
- Elias, M. (1981). Serum cortisol, testosterone, and testosterone-binding globulin responses to competitive fighting in human males. *Aggressive Behavior*, 7(3), 215–224. [https://doi.org/10.1002/1098-2337\(1981\)7:3<215::AID-AB2480070305>3.0.CO;2-M](https://doi.org/10.1002/1098-2337(1981)7:3<215::AID-AB2480070305>3.0.CO;2-M)

- Elliott, B. (2006). Biomechanics and tennis. *British Journal of Sports Medicine*, 40(5), 392–396. <https://doi.org/10.1136/bjsm.2005.023150>
- Fant, G. (1960). *Acoustic theory of speech production: with calculations based on X-ray studies of Russian articulations*. Walter de Gruyter.
- Farhead, N., & Punt, T. D. (2015). Silencing sharapova's grunt improves the perception of her serve speed. *Perceptual and Motor Skills*, 120(3), 722–730. <https://doi.org/10.2466/30.PMS.120v20x2>
- Feinberg, D. R., Jones, B. C., Little, A. C., Burt, D. M., & Perrett, D. I. (2005). Manipulations of fundamental and formant frequencies influence the attractiveness of human male voices. *Animal Behaviour*, 69(3), 561–568. <https://doi.org/10.1016/j.anbehav.2004.06.012>
- Fitch, W. T., & Hauser, M. D. (1995). Vocal production in nonhuman primates: Acoustics, physiology, and functional constraints on 'honest' advertisement. *American Journal of Primatology*, 37(3), 191–219. <https://doi.org/10.1002/ajp.1350370303>
- Fouquet, M., Pisanski, K., Mathevon, N., & Reby, D. (2016). Seven and up: individual differences in male voice fundamental frequency emerge before puberty and remain stable throughout adulthood. *Open Science*, 3(10), 160395. <https://doi.org/10.1098/rsos.160395>
- Furley, P., & Schweizer, G. (2014a). 'I'm pretty sure that we will win!': The influence of score-related nonverbal behavioral changes on the confidence in winning a basketball game. *Journal of Sport and Exercise Psychology*, 36(3), 316–320. <https://doi.org/10.1123/jsep.2013-0199>

- Furley, P., & Schweizer, G. (2014b). The expression of victory and loss: Estimating who's leading or trailing from nonverbal cues in sports. *Journal of Nonverbal Behavior*, 38(1), 13–29. <https://doi.org/10.1007/s10919-013-0168-7>
- Global Delight Technologies. (2014). Boom 2 (Version 1.6). Global Delight Technologies. Retrieved from www.globaldelight.com/boom
- Hillenbrand, J. M., & Clark, M. J. (2009). The role of f0 and formant frequencies in distinguishing the voices of men and women. *Attention, Perception, & Psychophysics*, 71(5), 1150–1166. <https://doi.org/10.3758/APP.71.5.1150>
- Hudenko, W. J., Stone, W., & Bachorowski, J. A. (2009). Laughter differs in children with autism: An acoustic analysis of laughs produced by children with and without the disorder. *Journal of Autism and Developmental Disorders*, 39(10), 1392–1400. <https://doi.org/10.1007/s10803-009-0752-1>
- Jennings, D. J., & Gammell, M. P. (2013). Contest behaviour in ungulates. In I. C. W. Hardy & M. Briffa (Eds.), *Animal contests* (pp. 304–321). Cambridge: Cambridge University Press.
- Johannes, B., Wittels, P., Enne, R., Eisinger, G., Castro, C. A., Thomas, J. L., ... Gerzer, R. (2007). Non-linear function model of voice pitch dependency on physical and mental load. *European Journal of Applied Physiology*, 101(3), 267–276. <https://doi.org/10.1007/s00421-007-0496-6>
- Johnson, C. D., & McHugh, M. P. (2006). Performance demands of professional male tennis players. *British Journal of Sports Medicine*, 40(8), 696–699. <https://doi.org/10.1136/bjsm.2005.021253>
- Kibler, W. B. (2014). Understanding the kinetic chain in tennis performance and injury. *Aspetar Sports Medicine Journal*, 2, 492–497.

- Knudson, D., & Blackwell, J. (2000). Trunk muscle activation in open stance and square stance tennis forehands. *International Journal of Sports Medicine*, 21(5), 321–324. <https://doi.org/10.1055/s-2000-3776>
- Lagier, A., Vaugoyeau, M., Ghio, A., Legou, T., Giovanni, A., & Assaiante, C. (2010). Coordination between posture and phonation in vocal effort behavior. *Folia Phoniatrica et Logopaedica*, 62(4), 195–202. <https://doi.org/10.1159/000314264>
- Lieberman, D. E., McCarthy, R. C., Hiiemae, K. M., & Palmer, J. B. (2001). Ontogeny of postnatal hyoid and larynx descent in humans. *Archives of Oral Biology*, 46(2), 117–128. [https://doi.org/10.1016/S0003-9969\(00\)00108-4](https://doi.org/10.1016/S0003-9969(00)00108-4)
- Lima, C. F., Castro, S. L., & Scott, S. K. (2013). When voices get emotional: A corpus of nonverbal vocalizations for research on emotion processing. *Behavior Research Methods*, 45(4), 1234–1245. <https://doi.org/10.3758/s13428-013-0324-3>
- Lingle, S., Wyman, M. T., Kotrba, R., Teichroeb, L. J., & Romanow, C. A. (2012). What makes a cry a cry? A review of infant distress vocalizations. *Current Zoology*, 58(5), 698–726.
- Liu, N., Jiang, Z., Zhang, L., Zhong, Z., Ping, X., Xu, H., & Li, C. (2015). Bioacoustic cues and their relations to dominance rank in Père David's deer stags. *Animal Production Science*.
- Maquirriain, J., Baglione, R., & Cardey, M. (2016). Male professional tennis players maintain constant serve speed and accuracy over long matches on grass courts. *European Journal of Sport Science*, 16(7), 845–849. <https://doi.org/10.1080/17461391.2016.1156163>

Mazur, A., & Lamb, T. A. (1980). Testosterone, status, and mood in human males.

Hormones and Behavior, 14(3), 236–246. <https://doi.org/10.1016/0018->

506X(80)90032-X

O’Connell, D. G., Hinman, M., Hearne, K. F., Michael, Z. S., & Nixon, S. L. (2014).

The effects of ‘grunting’ on serve and forehand velocity in collegiate tennis players. *Journal of Strength and Conditioning Research*, 1.

<https://doi.org/10.1519/JSC.0000000000000604>

Peterson, G. E., & Barney, H. L. (1952). Control methods used in a study of the

vowels. *The Journal of the Acoustical Society of America*, 24(2), 175–184.

<https://doi.org/10.1121/1.1906875>

Pisanski, K., Cartei, V., McGettigan, C., Raine, J., & Reby, D. (2016). Voice

modulation: A window into the origins of human vocal control? *Trends in*

Cognitive Sciences, 20(4), 304–318. <https://doi.org/10.1016/j.tics.2016.01.002>

Pisanski, K., Fraccaro, P. J., Tigue, C. C., O’Connor, J. J. M., & Feinberg, D. R.

(2014). Return to Oz: Voice pitch facilitates assessments of men’s body size.

Journal of Experimental Psychology: Human Perception and Performance,

40(4), 1316–1331. <https://doi.org/10.1037/a0036956>

Pisanski, K., Fraccaro, P. J., Tigue, C. C., O’Connor, J. J. M., Röder, S., Andrews, P.

W., ... Feinberg, D. R. (2014). Vocal indicators of body size in men and

women: a meta-analysis. *Animal Behaviour*, 95, 89–99.

<https://doi.org/10.1016/j.anbehav.2014.06.011>

Pisanski, K., Nowak, J., & Sorokowski, P. (2016). Individual differences in cortisol

stress response predict increases in voice pitch during exam stress. *Physiology*

& Behavior, 163, 234–238. <https://doi.org/10.1016/j.physbeh.2016.05.018>

- Pitcher, B. J., Briefer, E. F., & McElligott, A. G. (2015). Intrasexual selection drives sensitivity to pitch, formants and duration in the competitive calls of fallow bucks. *Bmc Evolutionary Biology*, 15, 149. <https://doi.org/10.1186/s12862-015-0429-7>
- Plant, R. L., & Younger, R. M. (2000). The interrelationship of subglottic air pressure, fundamental frequency, and vocal intensity during speech. *Journal of Voice*, 14(2), 170–177. [https://doi.org/10.1016/S0892-1997\(00\)80024-7](https://doi.org/10.1016/S0892-1997(00)80024-7)
- Puts, D. A. (2016). Human sexual selection. *Current Opinion in Psychology*, 7, 28–32. <https://doi.org/10.1016/j.copsyc.2015.07.011>
- Puts, D. A., Apicella, C. L., & Cárdenas, R. A. (2012). Masculine voices signal men's threat potential in forager and industrial societies. *Proceedings of the Royal Society of London B: Biological Sciences*, 279(1728), 601–609. <https://doi.org/10.1098/rspb.2011.0829>
- Puts, D. A., Gaulin, S. J. C., & Verdolini, K. (2006). Dominance and the evolution of sexual dimorphism in human voice pitch. *Evolution and Human Behavior*, 27(4), 283–296. <https://doi.org/10.1016/j.evolhumbehav.2005.11.003>
- Puts, D. A., Hill, A. K., Bailey, D. H., Walker, R. S., Rendall, D., Wheatley, J. R., ... Ramos-Fernandez, G. (2016). Sexual selection on male vocal fundamental frequency in humans and other anthropoids. *Proc. R. Soc. B*, 283(1829), 20152830. <https://doi.org/10.1098/rspb.2015.2830>
- Reby, D., Levréro, F., Gustafsson, E., & Mathevon, N. (2016). Sex stereotypes influence adults' perception of babies' cries. *BMC Psychology*, 4(1). <https://doi.org/10.1186/s40359-016-0123-6>
- Reby, D., McComb, K., Cargnelutti, B., Darwin, C., Fitch, W. T., & Clutton-Brock, T. (2005). Red deer stags use formants as assessment cues during intrasexual

- agonistic interactions. *Proceedings of the Royal Society of London B: Biological Sciences*, 272(1566), 941–947.
<https://doi.org/10.1098/rspb.2004.2954>
- Reid, M., & Duffield, R. (2014). The development of fatigue during match-play tennis. *British Journal of Sports Medicine*, 48(Suppl 1), i7–i11.
<https://doi.org/10.1136/bjsports-2013-093196>
- Ryalls, J. H., & Lieberman, P. (1982). Fundamental frequency and vowel perception. *The Journal of the Acoustical Society of America*, 72(5), 1631–1634.
<https://doi.org/10.1121/1.388499>
- Sauter, D. A., Eisner, F., Calder, A. J., & Scott, S. K. (2010). Perceptual cues in nonverbal vocal expressions of emotion. *The Quarterly Journal of Experimental Psychology*, 63(11), 2251–2272.
<https://doi.org/10.1080/17470211003721642>
- Scanlan, T. K., & Passer, M. W. (1977). Factors related to competitive stress among male youth sport participants. *Medicine and Science in Sports*, 10(2), 103–108.
- Scott, S., Lavan, N., Chen, S., & McGettigan, C. (2014). The social life of laughter. *Trends in Cognitive Sciences*, 18(12), 618–620.
<https://doi.org/10.1016/j.tics.2014.09.002>
- Sinnett, S., & Kingstone, A. (2010). A preliminary investigation regarding the effect of tennis grunting: does white noise during a tennis shot have a negative impact on shot perception? *PLoS ONE*, 5(10), e13148.
<https://doi.org/10.1371/journal.pone.0013148>
- Sundberg, J., Leanderson, R., von Euler, C., & Knutsson, E. (1991). Influence of body posture and lung volume on subglottal pressure control during singing.

Journal of Voice, 5(4), 283–291. [https://doi.org/10.1016/S0892-1997\(05\)80057-8](https://doi.org/10.1016/S0892-1997(05)80057-8)

Sundberg, J., Titze, I., & Scherer, R. (1993). Phonatory control in male singing: A study of the effects of subglottal pressure, fundamental frequency, and mode of phonation on the voice source. *Journal of Voice*, 7(1), 15–29. [https://doi.org/10.1016/S0892-1997\(05\)80108-0](https://doi.org/10.1016/S0892-1997(05)80108-0)

Symonds, M. R. E., & Moussalli, A. (2011). A brief guide to model selection, multimodel inference and model averaging in behavioural ecology using Akaike's information criterion. *Behavioral Ecology and Sociobiology*, 65(1), 13–21. <https://doi.org/10.1007/s00265-010-1037-6>

Szameitat, D. P., Darwin, C. J., Szameitat, A. J., Wildgruber, D., & Alter, K. (2011). Formant characteristics of human laughter. *Journal of Voice*, 25(1), 32–37. <https://doi.org/10.1016/j.jvoice.2009.06.010>

Taylor, A. M., Charlton, B. D., & Reby, D. (2016). Vocal production by terrestrial mammals: Source, filter, and function. In R. A. Suthers, W. T. Fitch, R. R. Fay, & A. N. Popper (Eds.), *Vertebrate Sound Production and Acoustic Communication* (pp. 229–259). Springer International Publishing. https://doi.org/10.1007/978-3-319-27721-9_8

Taylor, A. M., Reby, D., & McComb, K. (2010). Size communication in domestic dog, *Canis familiaris*, growls. *Animal Behaviour*, 79(1), 205–210. <https://doi.org/10.1016/j.anbehav.2009.10.030>

Titze, I. R. (1994). *Principles of voice production*. National Center for Voice and Speech.

Vannoni, E., & McElligott, A. G. (2008). Low frequency groans indicate larger and more dominant fallow deer (*Dama dama*) males. *PLOS ONE*, 3(9), e3113.
<https://doi.org/10.1371/journal.pone.0003113>

Wittels, P., Johannes, B., Enne, R., Kirsch, K., & Gunga, H.-C. (2002). Voice monitoring to measure emotional load during short-term stress. *European Journal of Applied Physiology*, 87(3), 278–282.
<https://doi.org/10.1007/s00421-002-0625-1>

APPENDIX

SUPPLEMENTARY METHODS

Analysis of tennis grunts

Within-subject variables

Of the top 30 players in the world at the time of data collection, 90% of male players and 76% of female players produced tennis grunts during matches. Of these, 50% of male players and 63% of female players grunted sufficiently frequently to allow for behavioral observation (i.e., during at least 75% of tennis shots) and were therefore eligible for inclusion in our data sample. A further 40% of males and 13% of females grunted less frequently (e.g. only in later stages of tournaments, and/or during important points), and were therefore not eligible for inclusion in our data sample. Thus, from these top 30 players, we identified seven male and seven female professional tennis players for analysis who consistently grunted when hitting both serves and groundstrokes within and between matches.

Playback experiments

Natural stimuli

Each stimulus was saved as a WAV file at 44.1 kHz and 16 bits amplitude resolution. Editing was performed in Praat (Boersma & Weenink, 2014). The intensity of all stimuli was standardised to 65 dB, and a 0.2s fade in and out was applied to the stadium's ambient noise in each stimulus.

For the match attribution task, participants were presented with pairs of 6-grunt sequences from 6 male and 6 female players and asked to identify which sequence in the pair came from the match the player lost. Each pair consisted of one sequence of grunts from the end of a match the player won without losing a set (win sequence), and a sequence of grunts from a match that same player lost without winning a set (loss sequence). Participants completed 12 trials for natural grunt-sequence pairs.

Grunts were only recorded from the last five games of the final set, and where the player was losing or winning by at least two games (a 'break'), or in the small number of cases where the final set went to a tiebreak, where the player was losing or winning by at least two points (a 'mini-break'). Match losses and wins were matched as closely as possible in terms of tournament stage, so as to control for the potential effects of match importance on physiological and psychological state. There was some overlap in player identity between the playback sample and the observational sample, but no overlap in identity within the playback tasks.

The six separate grunts were amalgamated into one sound file, with roughly 500 ms of ambient noise from the TV footage separating each grunt. Non-overlapping conspicuous noises (e.g. ball strikes, trainers squeaking) were removed, and no acoustic information regarding the opposing player was available.

Resynthesised stimuli

Acoustic resynthesis was performed in Praat (Boersma & Weenink, 2014). We used PSOLA-resynthesis to manipulate the F0 of match outcome grunt sequences. PSOLA resynthesis enables the independent rescaling of F0 while leaving all other parameters of the signal unchanged, and is a well-established method for independently manipulating acoustic features in nonhuman vocalisations (e.g. Reby et al., 2005),

human vocalisations (Reby et al., 2016), and human speech (Feinberg, Jones, Little, Burt, & Perrett, 2005). We performed resynthesis using the *To Manipulation...* command, which allows for the correction of spurious and undetected pitch values before resynthesis.

We resynthesised the F0 of grunt-sequence pairs to create four F0-resynthesis conditions: two in which the loss sequence was higher in F0 than the win sequence, and two in which the win sequence was higher in F0 than the loss sequence. We resynthesised the F0 of entire loss and win grunt sequences by equal amounts, such that the mean F0 difference between grunt-sequences within each pair was equal to the mean F0 difference (and the mean F0 difference +1 SD) between loss and win grunts measured from our samples of professional tennis players. As the observational sample contained grunts from throughout each match whereas the playback experiment sample consisted only of grunts from the end of matches, we applied inclusion criteria to ensure that grunts from the observational sample were from equivalent match stages as the playback experiment sample. Specific criteria are as follows:

For males, grunts were included only if the player was losing/winning by at least (i) one set to love and a break in a straight sets match; (ii) two sets to love and a break in a four-set match; or (iii) two sets to one and a break in a four-set match. For females, grunts were included only if the player was losing/winning by at least (i) one set to love and a break; or (ii) a break in the final set. Criteria differed between sexes as men play best-of-five sets in Grand Slams, whereas women play best-of-three sets. Many matches on the women's tour go to a final set, therefore it was considered necessary to include grunts from these closer matches.

We determined resynthesis values based on the mean F0 difference between win and loss grunts as measured from the playback sample stimuli and the observational

sample stimuli meeting inclusion criteria. These F0 difference values were ± 27 Hz and ± 58 Hz for males, and ± 39 Hz and ± 100 Hz for females, to fit the mean difference $\pm N$ SD (with $N = 0$ and 1). One player from the playback experiment sample was excluded from the calculation of the mean F0 difference (and from playback statistical analysis), as the mean difference between her loss and win sequences far exceeded any other player's (i.e., 2.63 SDs).

One of the 12 original stimulus pairs was not suitable for resynthesis due to high levels of aperiodicity. Another was removed because the F0 difference between the win and loss sequence exceeded 400 Hz and could not be resynthesised. Thus, listeners heard 40 resynthesised stimulus pairs (10 exemplars x 4 conditions). One grunt per pair was removed from the resynthesised versions of two pairs because the *To Manipulation...* command did not adequately detect and resynthesise F0 values for that specific grunt only, leaving 32 pairs consisting of six-grunt sequences, and 8 pairs consisting of five-grunt sequences.

REPLICATION OF STATISTICAL ANALYSIS USING ERBs

We also ran analysis using equivalent rectangular bandwidths (ERBs), a semi-logarithmic scale that controls for the nonlinear relationship between F0 and perceived pitch. The significance of all statistical tests remained unchanged, and therefore these statistics are not reported.

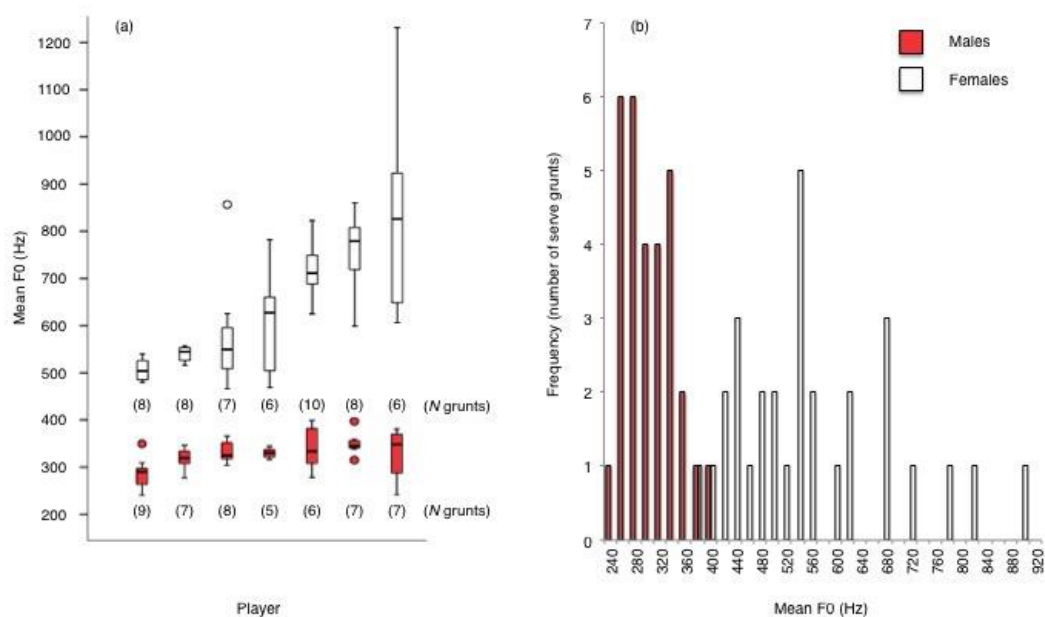


Figure 1. (a) Frequency distribution of mean F0 for grunts accompanying serves; male $N = 7$, female $N = 7$ players. N of grunts per player is displayed beneath each boxplot. Boxplots represent the distribution of serve grunt F0 for each recorded player. Central lines within boxes represent the median; box edges represent the interquartile range. For boxes without outliers (represented by circles), whiskers represent minima and maxima. For boxes with outliers, whiskers represent the highest and lowest cases within 1.5 times the interquartile range, and circles represent cases lying outside this range. **(b)** Frequency distribution of mean F0 for grunts accompanying serves. Male $N = 30$, female $N = 30$ players. N grunts per player = 2.

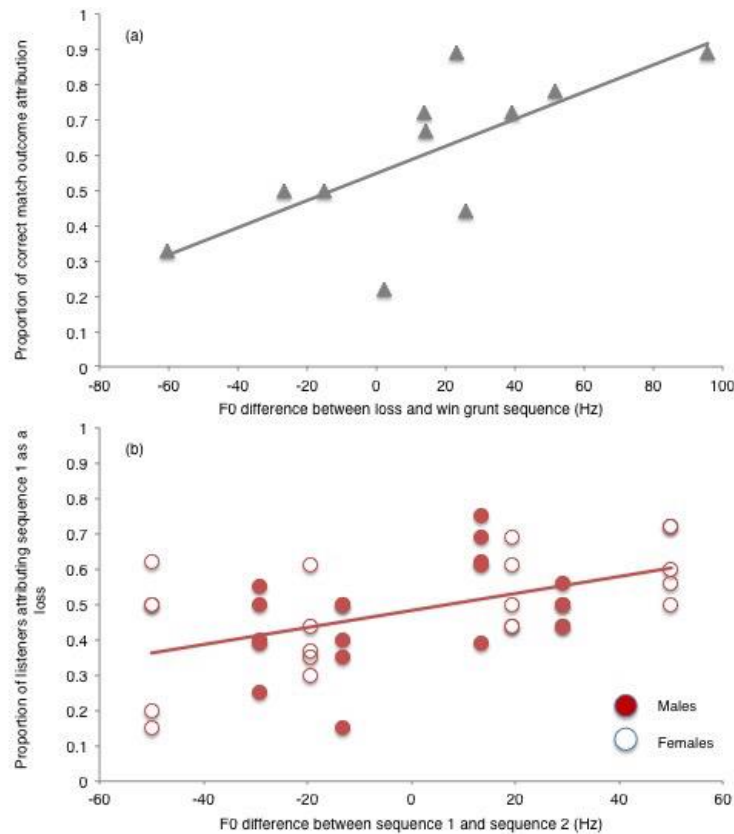


Figure 2. Attribution of match outcome by adult listeners as a function of natural and manipulated F0 differences **(a)** Triangles represent the average probability that listeners (male $N = 11$, female $N = 7$ listeners) correctly identified which of two natural six-grunt sequences with different F0 profiles came from a match the player lost (11 pairs (win/loss), male $N = 6$, female $N = 5$ players). Positive x-axis values indicate that the F0 of the loss sequence was higher. **(b)** Dots represent the average probability that listeners (male $N = 11$, female $N = 7$ listeners) presented with pairs of six-grunt sequences attributed the sequence presented first as coming from a match loss (10 pairs, male $N = 5$, female $N = 5$ players), for each of four resynthesis variants of the mean F0 difference between sequences. Filled dots represent male exemplars, hollow dots represent female exemplars. Positive x-axis values indicate that sequence 1's F0 was higher.