The acoustic features of human laughter

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Remarkably little is known about the acoustic features of laughter. Here, acoustic outcomes are reported for 1024 naturally produced laugh bouts recorded from 97 young adults as they watched funny video clips. Analyses focused on temporal features, production modes, source- and filter-related effects, and indexical cues to laugher sex and individual identity. Although a number of researchers have previously emphasized stereotypy in laughter, its acoustics were found now to be variable and complex. Among the variety of findings reported, evident diversity in production modes, remarkable variability in fundamental frequency characteristics, and consistent lack of articulation effects in supralaryngeal filtering are of particular interest. In addition, formant-related filtering effects were found to be disproportionately important as acoustic correlates of laugher sex and individual identity. These outcomes are examined in light of existing data concerning laugh acoustics, as well as a number of hypotheses and conjectures previously advanced about this species-typical vocal signal. [DOI: 10.1121/1.1391244]

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I. INTRODUCTION

Laughter plays a ubiquitous role in human vocal communication, being frequently produced in diverse social circumstances throughout life. Surprisingly, rather little is currently known about the acoustics of this species-typical vocal signal. Although there has been an enduring view that some variation may occur among the individual sounds that constitute laughter, these components are predominantly conceptualized as being vowel-like bursts (e.g., Darwin, 1872/1998; Hall and Allin, 1897; Mowrer, LaPointe, and Case, 1987; Ruch, 1993; Nwokah *et al.*, 1999; cf. Ruch and Ekman, 2001). While there is thus some information available about the mean fundamental frequency (F_0) of voiced laugh segments, reports have been markedly inconsistent. For example, the mean F_0 of male laughs has been reported to be as low as 126 Hz (Mowrer *et al.*, 1987; also see Bickley and Hunnicutt, 1992), but also as high as 424 Hz (Rothgänger *et al.*, 1998). Likewise, values for females have included an improbably low estimate of 160 Hz (Milford, 1980) and a high of 502 Hz (Provine and Yong, 1991).

Provine (1996, 2000; Provine and Yong, 1991) in particular has emphasized laughter's harmonically rich, vowel-like structure, further arguing that while vowel quality can show marked variation among laugh bouts, it is highly consistent within a series. In other words, with the possible exception of variation in the first or last sounds of a bout, Provine maintains that laughers routinely produce aspirated sequences of either "ha," "he," or "ho" sounds in discrete bouts (we infer the phonetic transcriptions of "ha" to be either /ɑ/, /ə/, or /ʌ/, and "he" and "ho" to be /i/, and /o/, respectively; cf. Edmonson, 1987). Provine also argues that the formant structure of laughter is less prominent than that of speech vowel sounds, although in neither case have quantitative formant measurements been provided in support of these claims. Given that formant structure is apparent in the spectrographic example shown in several publications (e.g., Provine, 1996, 2000; Provine and Yong, 1991) and several researchers have extracted formant values from at least a small number of laughs (Milford, 1980; Bickley and Hunicutt, 1992), this issue warrants closer scrutiny.

In contrast to Provine's emphasis on vowel-like laughter, Grammer and Eibl-Eibesfeldt (1990) drew a basic distinction between "vocalized" and "unvocalized" laughter. This contrast evidently referred to the presence or absence of voicing, and proved to be functionally important in their work. For example, individual males, after interacting with an unfamiliar female partner for a brief interval, were more interested in seeing her again if she produced voiced but not unvoiced laughter during the encounter. The importance of this basic distinction was subsequently confirmed in perceptual studies, which showed that voiced laughter induces significantly more positive emotional responses in listeners than do unvoiced laughs (Bachorowski and Owren, 2001). The latter is nonetheless a common element of laugh repertoires (Bachorowski, Smoski, and Owren, 2001), which raises the question of the relative prevalence of voiced and unvoiced laughter as a basic issue in laugh acoustics.

Other investigators have also considered laughter to be a variable signal, both in the kinds of sounds produced (Hall and Allin, 1897) and in its acoustic features (Rothgänger *et al.*, 1998). Variability of this sort is largely at odds with perspectives that treat laughter as a stereotyped vocalization. As exemplified by the work of Provine (e.g., Provine, 1996) and Grammer (1990; Grammer and Eibl-Eibesfeldt, 1990; see also Deacon, 1997), this approach proposes that laughter is—or at least resembles—a fixed action pattern (FAP) specialized for communication through an evolutionary process of "ritualization." The expected outcome of this process is

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constancy in the rate, intensity, and most importantly in the form of signal production.

The goal of the current work was to further investigate each of these issues. In so doing, we sought to improve on the number of subjects recorded, the number of laugh exemplars included for each, and the methods used in acoustic analysis. Ultimately, we examined 1024 bouts of laughter, representing every analyzable laugh sound recorded from 97 adult males and females while they watched humorous video clips presented in a comfortable laboratory setting. The resulting sample was thus significantly larger than in previous studies, which have for instance included 3 bouts from each of 3 adult females (Nwokah *et al.*, 1999), a total of 15 bouts from 1 male and 1 female (Bickley and Hunnicutt, 1992), 5 bouts produced from each of 11 males (Mowrer *et al.*, 1987), and one bout from each of 23 males and 28 females (Provine and Yong, 1991). Acoustic measures were designed to characterize temporal properties, source-energy characteristics, and spectral features of every sound, with additional attention paid to sex differences in the use of laughter as well as indexical cueing of laugher sex and individual laugher identity.

II. METHOD

A. Subjects

One hundred thirty-nine students enrolled at Vanderbilt University were recorded as they watched funny video clips either alone or as part of a same- or other-sex friend or stranger dyad. Volunteers were primarily recruited from a General Psychology course and received research credit toward that course. Participants solicited by a friend were typically paid $10 for their involvement, but could instead receive research credit if enrolled in General Psychology. Before testing, subjects provided oral and written consent to the procedures. As individuals were recorded without knowing that laughter was specifically of interest, consent to use laughter data was obtained after testing was complete.

Data collected from ten subjects were excluded because of equipment failure ($n=2$), experimenter error ($n=2$), illnesses that might affect laugh acoustics (e.g., strep throat, $n=2$,) or use of mood-altering prescription drugs (e.g., serotonin reuptake inhibitors, $n=4$). In 11 cases, data were not used because the individual was not a native American-English speaker or was tested with a partner whose native language was not English. Finally, data from 21 subjects were excluded because the three or less laughs produced during the 3.95-min film clip period were deemed too few for statistical analysis. The final sample included 45 males and 52 females who had a mean age of 19.23 years (s.d. $=1.13$) and were primarily white ($n=87$). However, the sample also included six blacks, three Asian Americans, and one Native American. None reported any speech- or hearing-related problems. Of these 97 individuals, 11 were tested alone, 24 with a same-sex friend, 21 with an other-sex friend, 20 with a same-sex stranger, and 21 with an other-sex stranger. Results concerning the use of laughter in these various social contexts are discussed elsewhere (Bachorowski *et al.*, 2001).

B. Stimuli and apparatus

Subjects all watched a total of 11 emotion-inducing film clips, two of which were included specifically for their positive-emotion and laugh-inducing potential (other clips elicited either sad, fearful, disgusted, or neutral emotional responses). The first was the 1.42-min "bring out your dead" segment from *Monty Python and the Holy Grail*, and the second was the 2.53-min "fake orgasm" scene from *When Harry Met Sally* (total time = 3.95 min). Film clips were presented using a Panasonic AG-5700 video cassette recorder (VCR) located on a shelf next to a 31-in. Panasonic CT 31G10 television monitor. Both the monitor and VCR were housed in a large media center. An experimenter operated the VCR from the adjacent control room via a Panasonic AG-A570 editing device attached through a wall conduit.

Recordings were made using Audio-Technica Pro 8 headworn microphones (Stow, OH), which were connected through the conduit to separate inputs of an Applied Research Technology 254 preamplifier (Rochester, NY) located in the control room. Each signal was amplified by 20 dB and then recorded on separate channels of a Panasonic Professional SV-4100 digital audiotape (DAT) recorder (Los Angeles, CA). Recordings were made using BASF digital audiotapes (Mount Olive, NJ). Tandy Optimus LV-20 headphones (Fort Worth, TX) connected to the DAT recorder were used to monitor participants throughout testing, and the experimenter communicated with participants as necessary through a Tandy 43-227 intercom.

C. Design and procedure

Participants were tested in a large laboratory room furnished to resemble a comfortable den. After providing informed consent, participants were told that they would be rating the emotion-inducing impact of each of a series of short film clips and that their evaluations would be used to select stimuli for upcoming studies of emotional response processes. Thus, subjects were unaware that their laughter was the focus of the research. After seating participants in futon chairs placed 3.3 m in front of the television monitor, the experimenter helped each individual position the microphone approximately 2.5 cm in front of the labiomental groove, and explained that the film-clip ratings (not relevant here) would be audio recorded. Next, input levels were adjusted, participants were given the opportunity to ask questions, and were informed that they would be left on their own and should treat the experience as if watching videos in their own living room. At the end of the viewing session, the experimenter returned to the testing room, debriefed participants as to the nature of the study, and obtained consent to use all data.

D. Laugh selection, classification, and acoustic analysis

Laughter was defined as being any perceptibly audible sound that an ordinary person would characterize as a laugh if heard under everyday circumstances. While inclusive, this broad criterion was considered reasonable on several grounds. First, these sounds were produced while subjects watched film clips selected for their likelihood of eliciting positive affect. Indeed, the clips were rated as producing positive emotional responses by virtually all participants. Second, although no restrictions were placed on talking during the film clips, subjects almost never did—thereby making it unlikely that the sounds they were making represented either linguistic or paralinguistic events. Finally, each sound was routinely heard dozens of times during the course of acoustic analysis, and questionable ones were removed from further consideration.

Borrowing terminology from acoustic primatology (e.g., Struhsaker, 1967; Owren, Seyfarth, and Cheney, 1997), laughs were analyzed at ''bout,'' ''call,'' and ''segment'' levels. Bouts were entire laugh episodes that are typically produced during one exhalation. Although many bouts ended with audible inhalations or exhalations, these sounds were not included in bout-level characterizations unless they were deemed to be critical to the laugh itself. Calls were the discrete acoustic events that together constitute a bout, and have elsewhere been referred to as ''notes'' or laugh ''syllables.'' Isolated calls that were difficult to distinguish from sighs or other nonlaugh vocalizations were excluded from analysis. Overall, however, any sound deemed integral to a laugh bout was considered to be a call. Segments were defined as temporally delimited spectrogram components that either visibly or audibly reflected a clear change in production mode occurring during the course of an otherwise continuous call.

Laughs were digitized at 50 kHz using Kay Elemetric's COMPUTERIZED SPEECH LAB (CSL; Lincoln Park, NJ). Acoustic analyses were conducted using ESPS/WAVES+ 5.2 digital signal-processing software (Entropic Research Lab, Washington, DC) implemented on a Silicon Graphics O2 unix-based processor with the Irix 6.3 operating system (SGI; Mountain View, CA). Preprocessing of files included format conversions on a personal computer using custom-written software programs by Tice and Carrell (available at http://hush.unl.edu/LabResources.html). Files were then down-sampled to 11.025 kHz and normalized to a common maximum-amplitude value.

In preparation for automatic extraction of various acoustic measurements using unix-csh-script routines, each file was first segmented with cursor-based onset and offset marks for every bout, call, and segment. Each of these levels was then categorized as to type. At the bout level, laughs were assigned to one of three mutually exclusive types. Bouts consisting primarily of voiced sounds were considered ''song-like,'' and included comparatively stereotyped episodes of multiple vowel-like sounds with evident F_0 modulation as well as sounds that might best be described as giggles and chuckles. Bouts largely comprised of unvoiced calls with perceptually salient nasal-cavity turbulence were labeled ''snort-like.'' Acoustically noisy bouts produced with turbulence evidently arising in either the laryngeal or oral cavities were called ''unvoiced grunt-like'' sounds, and included breathy pants and harsher cackles. To assess the reliability of bout-level categorizations, a second research assistant independently labeled each bout. The obtained kappa coefficient of 0.92, $p<0.001$, indicated a high level of inter-rater agreement in bout-level classification.

Both bouts and individual calls were identified as either ''voiced,'' ''unvoiced,'' or ''mixed,'' and segments were labeled as being either voiced or unvoiced. Calls were further labeled according to whether the sound was perceived as being produced with the mouth open or closed. Inter-rater reliability for mouth-position judgments was high: a kappa coefficient of 0.91, $p<0.001$, was obtained for 329 calls from 100 randomly selected bouts that were each coded independently by two raters. Finally, calls and segments that showed evidence of non-normative, atypical source energy were also noted. These events included vocal fry, in which individual glottal pulses are perceptually discernible, as well as a number of nonlinear types (i.e., glottal whistles, subharmonics, and biphonation; see Wilden *et al.*, 1998).

Acoustic measurements focused on durations, F_0-related features, and spectral characteristics of bouts, calls, and segments. Durations were readily extracted from onset and offset markers, but because F_0 is routinely much higher in laughter than in speech, pitch-tracking algorithms designed for the latter did not always perform well. These analyses were therefore conducted at the call level by first using the ESPS/WAVES+ pitch-tracking routine to extract an F_0 contour for each sound, and then overlaying the resulting plot on a corresponding narrow-band spectrogram. If the algorithm failed, the first harmonic was manually enclosed both in time and frequency using cursor settings, and its frequency contour was extracted as a series of maximum-amplitude points occurring one per column in the underlying spectrogram (Owren and Casale, 1994).

Spectral measurements focused on formant frequencies, which were derived from smooth spectral envelopes produced through linear predictive coding (LPC). The measurement procedure included first producing both a narrow-band, FFT-based (40-ms Hanning window, 0.94 preemphasis factor, 512-point FFT, 2-ms step size) and a wideband, LPC-based (fast modified Burg method, 40-ms rectangular window, 0.94 preemphasis factor, 10 coefficients, 2-ms step size) spectrogram of each sound. One location was then designated within each call or segment based on these displays, selected so as to provide clear outcomes that were also representative of the sound as a whole (see Fig. 1). Setting the cursor in this location produced a display of both underlying spectral slices, with the LPC envelope overlaid on the FFT-based representation. Formant-peak locations were located through visual inspection, marked on the LPC function by setting the cursor, and automatically recovered from the associated data record. Formant measurements were not taken from unvoiced, snort-like sounds. Although their resonances were often consistent with normative values from nasal speech sounds, many of these calls also seemed to be affected by noisiness resulting from airstream interactions with the microphone element.

Estimates of supralaryngeal vocal-tract length (VTL) were derived from formant frequencies using the following equation (adapted from Lieberman and Blumstein, 1993):

$$\mathrm{VTL}=\frac{(2k+1)c}{4F_{k+1}},$$

where $k=(0,1,2)$, F_{k+1} is the frequency of the formant of

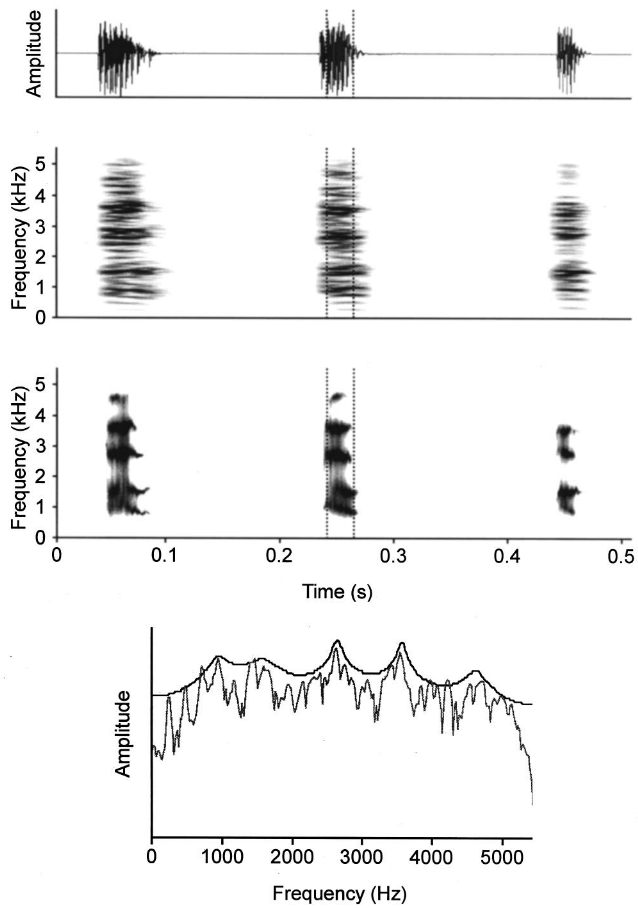

FIG. 1. Waveform (top) and corresponding narrow-band (second panel) and wideband (third panel) spectrograms of a voiced-laugh bout. Dotted vertical lines in the second of the three calls indicate the window from which spectral measurements were made. At the bottom, the smoothed LPC envelope is shown overlaid on the FFT-based representation.

interest, and c is the speed of sound (34 400 cm/s). Separate calculations were made for each of the five formants, and the mean of these estimates provided the VTL value used in classification analyses of laugher sex and individual identity.

III. RESULTS

A. Laugh types and durations

1. Bout-level descriptive outcomes

Descriptive outcomes associated with bout-level analyses are provided in Table Ia, and representative spectrograms of male and female voiced song-like, unvoiced grunt-like, and unvoiced snort-like bouts are shown in Fig. 2. Sample laughs can be heard at http://www.psy.vanderbilt.edu/faculty/bachorowski/laugh.htm. A total of 1024 laugh bouts was analyzed. Of these, 30% were predominantly voiced, 47.6% were mainly unvoiced, 21.8% were a mix of voiced and unvoiced components, and the remaining 0.7% were largely comprised of glottal whistles. Of the unvoiced bouts, 37.2% were grunt-like, whereas the remaining 62.8% were snort-like. This bout-level variability did not appear to be a matter of differences in individual laugher style. Many individuals (40.2%) produced all three of the most common bout types (i.e., voiced song-like, unvoiced snort-like, and unvoiced grunt-like), just as many produced two types (43.3%), while comparatively few (16.5%) produced just one types. Bouts that were either mixed or not readily classified were not included in further analysis of bout type.

Laugh bouts were highly variable in duration, with a standard deviation of 0.77 associated with the mean of 0.87 s. Outcomes of an analysis of variance (ANOVA) and Scheffé follow-up comparisons showed that a main effect of bout type, $F(2,933)=30.52$, $p<0.001$, was due to the shorter durations of snort-like rather than either song- or grunt-like bouts (see Table Ia). On average, males and females did not differ in the number of laughs produced, $F(1,96)=0.14$, ns. However, laugher sex did mediate the type of bout produced, $\chi^2(5)=137.26$, $p<0.001$. Follow-up binomial tests revealed that females produced significantly more voiced, song-like bouts than did males ($p<0.001$), whereas males produced significantly more unvoiced, grunt-like laughs than did females ($p<0.025$). There were no sex differences in the number of unvoiced, snort-like laughs produced. Laugher sex exerted a slight influence on bout duration, $F(1,935)=4.75$, $p<0.05$, with male laughs being a bit longer than female laughs.

2. Call-level descriptive outcomes

Descriptive outcomes associated with the corpus of 3479 calls are provided in Table Ib. On average, laugh bouts were comprised of 3.39 calls, but the associated standard deviation of 2.71 indicates that the number of calls per bout was highly variable. Most calls (45.2%) were unvoiced, but a notable proportion were either voiced (34.2%) or a mix of production modes (13.0%). In addition, 3.5% of the calls were essentially glottal pulses, 2.5% were produced in the fry register, and 1.6% were glottal whistles. On average, fewer than two call types were used in the course of bout production ($M=1.62$, s.d.$=0.84$), although some bouts consisted of as many as five types. Like bout durations, call durations were highly variable, with a standard deviation of 0.14 associated with the mean of 0.17 s. Call duration was strongly related to the type of call produced, $F(5,3473)=175.97$, $p<0.001$. Calls involving two or more production modes were the longest and, not surprisingly, glottal pulses were the shortest (see Table Ib).

The total number of calls produced did not differ by laugher sex, $F(1,96)=0.21$, ns. Consistent with their longer overall durations, male bouts contained somewhat more calls than did bouts produced by females, $F(1,1021)=6.90$, $p=0.01$ ($M_{\text{male}}=3.63$, s.d.$=2.86$; $M_{\text{female}}=3.18$, s.d.$=2.56$). Laugher sex had a strong influence on the proportions of call types produced, $\chi^2(5)=155.17$, $p<0.001$ (see Table Ib). Follow-up binomial tests showed that females produced significantly more voiced calls than did males ($p<0.001$), and that males produced significantly more unvoiced calls and glottal pulses than did females (p's<0.001). Laugher sex did not mediate either the acoustic complexity of laughs (as indexed by the number of call types per bout), call durations, or the number of calls produced per second [$F(1,1023)=1.83$, ns; and $F(1,3469)=0.01$, ns; $F(1,1023)=0.30$, ns, respectively].

TABLE I. Descriptive statistics associated with (a) bout- and (b) call-level analyses, separated according to laugher sex. Values in parentheses are standard deviations.

(a) Bout level			Males ($n=45$)		
Total (n)	465				
M Duration	0.95 (0.82)				
Bout type	Voiced	Unvoiced grunt-like	Unvoiced snort-like	Mixed	Glottal whistles
% Males producing	82.2	66.7	82.2	40.0	2.2
% of Total bouts	26.0	24.7	31.0	17.6	0.6
M Duration (s)	1.08 (0.83)	0.99 (0.91)	0.65 (0.49)	1.13 (0.96)	0.64 (0.42)
			Females ($n=52$)		
Total (n)	559				
M Duration	0.82 (.72)				
Bout type	Voiced	Unvoiced grunt-like	Unvoiced snort-like	Mixed	Glottal whistles
% Females producing	88.5	53.9	76.9	51.9	9.6
% of Total bouts	33.3	13.4	27.4	25.2	0.7
M duration (s)	1.04 (0.88)	0.79 (0.67)	0.53 (0.39)	0.90 (0.72)	0.51 (0.25)
(b) Call level			Males ($n=45$)		
Total (n)	1705				
M Calls per bout	3.61 (2.84)				
M Duration (s)	0.17 (0.14)				
Call type	Voiced	Unvoiced	Mixed	Glottal pulses	Glottal whistles
% Males producing	84.4	97.8	84.4	40.0	24.4
% of Total calls	27.6	52.6	13.0	5.5	1.3
M Duration (s)	0.11 (0.08)	0.20 (0.14)	0.24 (0.11)	0.03 (0.02)	0.22 (0.30)
			Females ($n=52$)		
Total (n)	1774				
M Calls per bout	3.20 (2.58)				
M Duration (s)	0.17 (0.14)				
Call-type	Voiced	Unvoiced	Mixed	Glottal pulses	Glottal whistles
% Females producing	88.5	96.2	90.4	23.1	38.5
% of Total calls	45.3	38.2	13.0	1.6	1.9
M Duration (s)	0.11 (0.08)	0.22 (0.15)	0.28 (0.17)	0.02 (0.02)	0.22 (0.20)

Further analyses examined temporal characteristics of calls within bouts. On average, 4.37 calls were produced per second, with comparable call- and intercall durations (i.e., 0.17 and 0.13 s, respectively). These two measures were also equivalent when examined only for voiced, open-mouth calls (0.11 and 0.12 s, respectively). A more fine-grained analysis examined the pattern of call- and intercall durations through the course of bouts that contained at least three but no more than eight calls. As can be seen in Fig. 3, bouts were typically initiated with comparatively long calls ($M=0.28$, s.d.$=0.15$) and followed by calls that were roughly half as long in duration ($M=0.13$, s.d.$=0.10$). This pattern was observed regardless of the number of calls per bout. The longer terminal-call durations of bouts with six or more calls contradict this general pattern, and largely reflect the prolonged inhalations and exhalations used to conclude some of these laugh episodes. The overall pattern of intercall intervals showed that regardless of the number of calls per bout, call production was denser towards the beginning of laugh bouts. Intercall durations gradually increased over the course of bouts and were longer than call durations by bout offset, especially for bouts comprised of six or more calls. Intercall intervals could become as long as twice that of call durations, but only by the seventh call in eight-call bouts.

3. Segment-level descriptive outcomes

A significant proportion of calls (30.9%) was composed of two or more discrete acoustic components. Most multisegment calls (75.8%) contained two components, an additional 20.7% contained three, and a small subset (3.5%) consisted of either four, five, or six segments. Mean segment duration was 0.11 s (s.d.$=0.11$), and there were no sex differences in the number of multisegment calls produced, $\chi^2(4)=5.50$, ns.

B. F_0-related outcomes

Descriptive statistics associated with F_0-related outcomes are shown in Table II. F_0 could be measured from 1617 voiced calls or voiced call segments. The ESPS/WAVES+ pitch-tracking algorithm performed well for about 65% of these cases, and the remaining measurements were made by extracting maximum-amplitude points from the first harmonic. Four dependent measures were of interest: mean F_0, s.d. F_0, F_0-excursion [(maximum call F_0)–(minimum call F_0)], and F_0 change [|(call-onset F_0)–(call-offset F_0)|].

Statistical tests involving F_0 measures used only those calls for which mouth position (i.e., open or closed) was readily perceptible, with a MANOVA used to test the extent

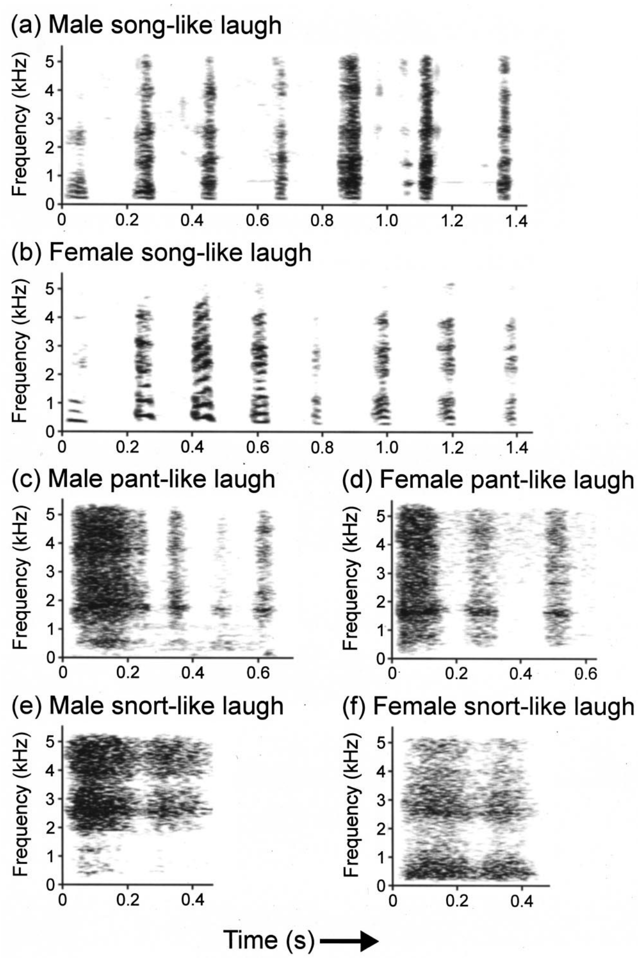

FIG. 2. Narrow-band spectrograms of (a) male and (b) female voiced laughs, wideband spectrograms of (c) male and (d) female unvoiced grunt-like laughs, and wideband spectrograms of unvoiced snort-like (e) male and (f) female laughs. Sample laughs can be heard at http://www.psy.vanderbilt.edu/faculty/bachorowski/laugh.htm

to which laugher sex and mouth position were associated with differences in the four dependent variables. Outcomes for all measures were strongly influenced by laugher sex: Results for mean F_0, s.d. F_0, F_0 excursion, and F_0 change were $F(1,1538)=165.10$, 45.58, 43.80, and 37.22, respectively (all p's<0.001). Not unexpectedly, the mean of 405 Hz (s.d.$=$193) measured from female laughs was considerably higher and more variable than the mean of 272 Hz (s.d.$=$148) found for male laughs. Also notable were the male and female absolute-maximum F_0 values of 1245 and 2083 Hz, respectively (for an example of a high F_0 call, see Fig. 4). Within-call F_0 standard deviations were quite high, on average being 21.41 and 29.98 Hz for male and female laughs, respectively. Mean F_0 excursion was also large for both sexes, but especially so for females ($M_{\text{male}}=59$ Hz, s.d.$=49.74$; $M_{\text{female}}=86$ Hz, s.d.$=76.83$). Both sexes were similarly found to have large onset to offset F_0 ranges, with females again showing the biggest change ($M_{\text{male}}=44$ Hz, s.d.$=42.38$; $M_{\text{female}}=64$ Hz, s.d.$=63.60$). There was also a significant main effect of mouth position for mean F_0, $F(1,1538)=33.43$, $p<0.001$, which was due to the higher F_0's of open- than closed-mouthed calls. Mouth position did not mediate outcomes for any of the three variability measures, and the interactions between laugher sex and mouth position were all nonsignificant.

Temporal patterning of F_0 at the call level was examined for the 297 voiced calls that were produced during the course of 96 randomly selected, predominantly voiced bouts. Using terminology common to the infant-directed speech literature (e.g., Katz, Cohn, and Moore, 1996), the F_0 contour of each call was characterized as being either "flat," "rising," "falling," "arched," or "sinusoidal." Using this classification scheme, the most common contour designation was flat (38.0%). However, falling (29.0%) and sinusoidal (18.9%) types each accounted for a sizable proportion of call contours, and arched (8.1%) and rising (6.1%) contours were not uncommon.

Several remarkable aspects of laugh acoustics were highlighted by examining F_0 measures at the bout level. Using a MANOVA, bouts containing two or more voiced calls or call segments were tested, with the number of voiced segments contributing to each bout as a weighted least-squares regression coefficient (Darlington, 1990). Laugher sex and bout length were used as fixed factors, the latter being a dichotomous variable created by classifying laughs into "short" and "long" categories based on the median number of voiced segments. Short bouts therefore contained either two or three voiced segments, whereas long bouts consisted of four or more voiced segments.

As was certain to be the case given call-level outcomes, the main effects of laugher sex were significant for both mean F_0 and F_0 excursion [$F(1,388)=85.63$, $p<0.001$, and $F(1,388)=10.05$, $p<0.01$, respectively]. Both measures were also found to be strongly associated with the number of voiced segments in a laugh episode [$F(1,388)=21.20$, $p=0.01$, and $F(1,388)=56.72$, $p<0.001$, for mean F_0 and F_0 excursion, respectively]. Compared to short bouts, long bouts were found to have higher mean F_0's as well as greater F_0 excursions (see Table III). For male laughs, the difference in mean F_0 between short and long bouts was 77 Hz, whereas this difference was 48 Hz for females. Very large differences were found for F_0 excursion, with the discrepancies between short and long bouts being 161 and 189 Hz for male and female laughs, respectively. Also noteworthy were the extreme F_0 excursions that occurred during bout production, with a male maximum of 947 Hz and corresponding female value of 1701 Hz. Moreover, such extreme excursions were not altogether rare events: 7 males produced a total of 12 bouts with F_0 excursions of 500 Hz or more, and 13 females produced a total of 31 bouts with excursions of this magnitude or greater.

Patterns of mean F_0 over the course of bout production were also examined. Briefly, we found no evidence of an overall decline in F_0. For bouts with either two, three, or four voiced components, F_0 at bout offset was nearly the same as at bout onset. For bouts with greater numbers of voiced segments, F_0 routinely increased and decreased, but did not fluctuate in an obvious pattern. Here, bout-offset F_0's were often higher than bout-onset F_0's.

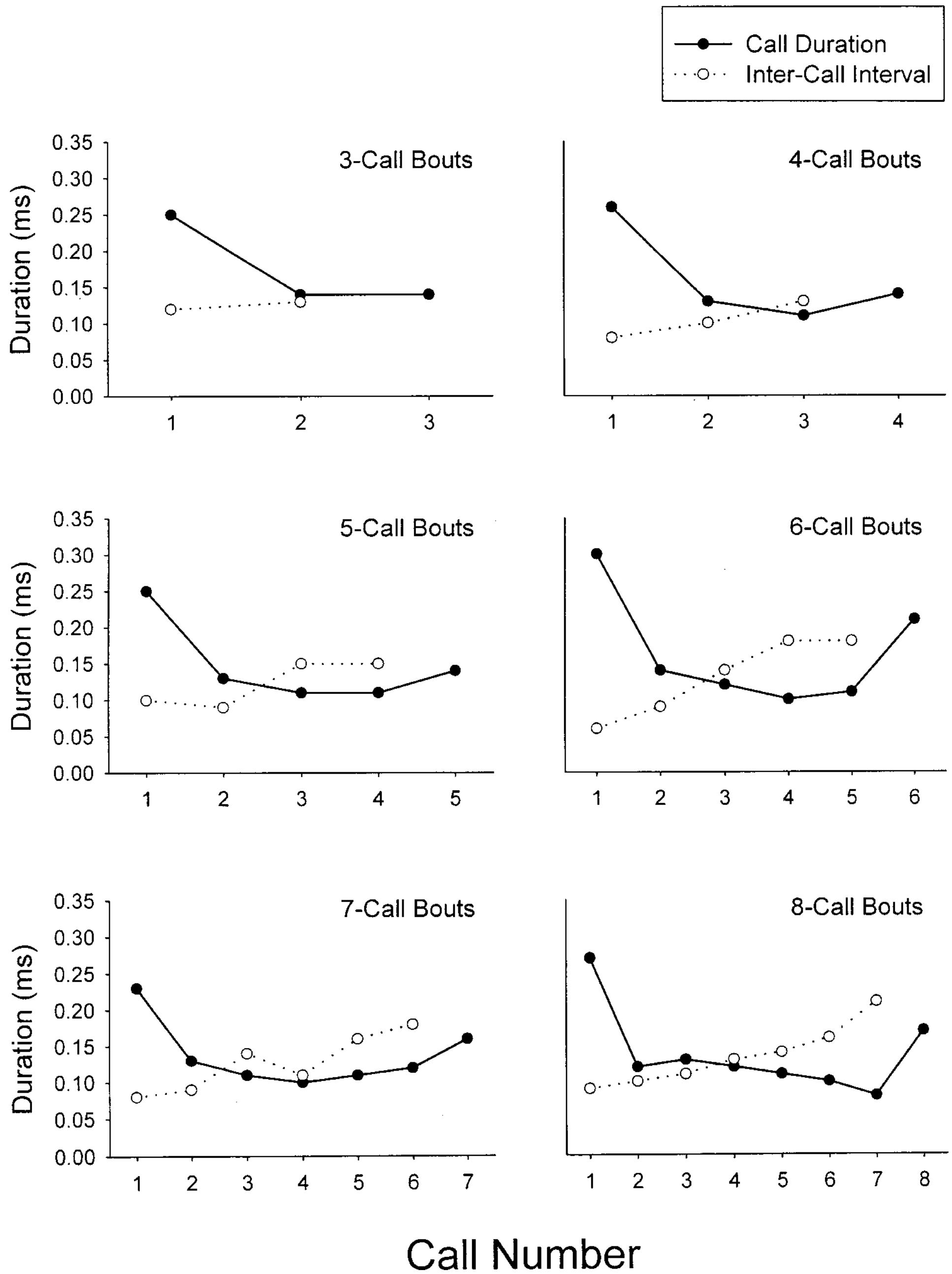

FIG. 3. Call durations and intercall intervals for laugh bouts comprised of three through eight calls.

C. Non-normative source energy

The 22 instances of open-mouth vocal fry for which F_0 could be measured showed very low F_0's, with pulses visible even on narrow-band spectrograms. A main effect of laugher sex was found for mean F_0 in vocal fry, $F(1,21) = 6.65$, $p < 0.025$ ($M_{\text{male}} = 80$ Hz, s.d. = 19.60; $M_{\text{female}} = 110$ Hz, s.d. = 31.99). However, males and females did not differ on any of the three variability indices (i.e., s.d. F_0, F_0 excursion, and F_0 change).

A total of 136 calls with nonlinear phenomena was identified (see Riede *et al.*, 2000; Wilden *et al.*, 1998). Of these, 105 were labeled as glottal whistles [see Fig. 5(a)], possibly reflecting airstream vortices induced by the medial edges of the vocal folds. These calls sounded wheeze-like, were typically low amplitude and quasiperiodic, and exhibited waveforms that were virtually indistinguishable from those of whistled /s/'s that can occur in naturally produced speech. The second sort of nonlinear phenomenon was the occurrence of subharmonics [Fig. 5(b)], typically period doubling, which was found in 26 calls. Perceptually, these sounds had a rather tinny quality. Finally, we observed five instances of biphonation, which involves the occurrence of two independent fundamental frequencies [Fig. 5(c)]. These calls sounded shrill and dissonant.

D. Formant-related outcomes

The primary goal of this series of analyses was to provide normative data concerning the spectral properties of laughter. Whenever possible, peak frequencies of five vocal-tract resonances were measured. However, accurate spectral measurements were difficult for any of several reasons. First, the noisiness of many unvoiced calls precluded adequate for-

TABLE II. F_0-related outcomes for call-level analyses, separated according to laugher sex and mouth position (i.e., open or closed). Tabled values are means, with standard deviations in parentheses.

	Males		Females	
Measures[a] (Hz)	Open mouth ($n=563$)	Closed mouth ($n=131$)	Open mouth ($n=862$)	Closed mouth ($n=276$)
MF_0	279 (146)	216 (92)	415 (193)	355 (127)
s.d. F_0	22 (17)	19 (16)	30 (24)	30 (25)
F_0-Excursion[b]	60 (51)	51 (42)	88 (78)	82 (72)
F_0-Change[c]	45 (43)	40 (39)	63 (62)	66 (69)

[a]Data from 34 males and 43 females contributed to analysis of open-mouth calls, whereas data from 25 males and 33 females were used for analysis of closed-mouth calls.
[b]F_0-Excursion $=[(\text{maximum call-}F_0)-(\text{minimum call-}F_0)]$.
[c]F_0-Change $=[|(\text{call-onset } F_0)-(\text{call-offset } F_0)|]$.

TABLE III. Bout-level F_0 measures, separated according to laugher sex. Values in parentheses are standard deviations.

Measures[a] (Hz)	Males		Females	
	Short bouts[b]	Long bouts[c]	Short bouts	Long bouts
MF_0	223 (168)	305 (262)	373 (266)	426 (332)
MF_0-Excursion[d]	141 (197)	299 (429)	191 (342)	405 (683)
Absolute minimum F_0-excursion	13	44	29	62
Absolute maximum F_0-excursion	741	947	991	1701

[a]Data from 37 males and 40 females contributed to short-bout analyses, whereas data from 24 males and 31 females were used in long-bout analyses.
[b]Short bouts contained either two or three voiced calls or call segments.
[c]Long bouts contained four or more voiced calls or call segments.
[d]F_0-Excursion $=[(\text{maximum call-}F_0)-(\text{minimum call-}F_0)]$.

mant resolution. Second, LPC outcomes were occasionally driven by the high-amplitude harmonics associated with some voiced calls. Third, the harmonically sparse spectra of calls with very high F_0's left little opportunity for supralaryngeal filtering to have a visible effect. In either of these last two cases, peak frequencies were coincident with one or more harmonics and adjusting the number of coefficients had little or no impact on the LPC solution. Resonance-harmonic correspondence was observed for 428, 135, 85, 55, and 36 instances of $F1$ through $F5$ measurements, respectively. Our overall strategy was therefore to take measurements from those calls for which three or more formants were readily identifiable, and for which peak frequencies did not coincide with harmonics. As noted earlier, we did not measure formant frequencies of unvoiced, snort-like sounds because the

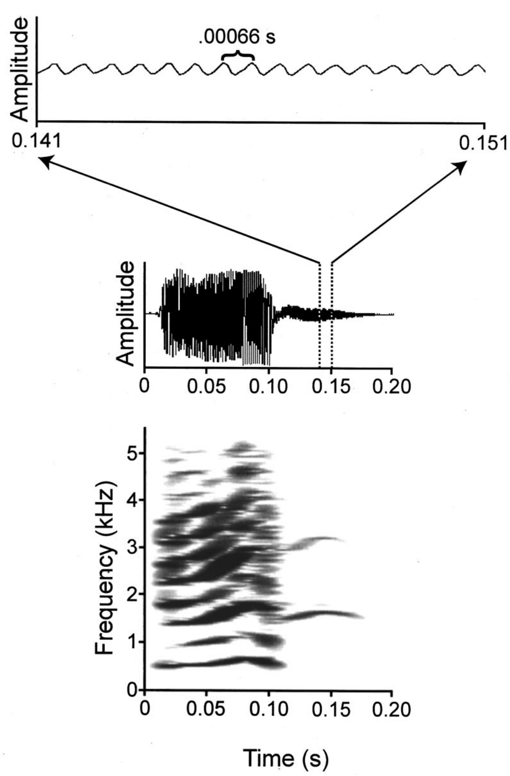

FIG. 4. Waveform (middle) and corresponding narrow-band spectrogram (bottom) of a very high F_0 call. Dotted vertical lines frame the portion of the waveform that is enlarged at the top.

extent to which airstream interactions with the microphone element were contributing to spectral characteristics was unclear. Finally, outcomes are not shown for either glottal pulses or whistles. The former were usually too brief for reliable measurement, and the latter were notably unstable. This overall selection procedure resulted in a sample of 1717 calls from 89 individuals. The reader is referred to Footnote 1[1] for details concerning treatment of missing data.

A grand MANOVA confirmed that formant frequencies differed depending on call-production mode (i.e., voiced open mouth, open-mouth vocal fry, voiced close mouth, and unvoiced open mouth). Further MANOVAs were therefore conducted within each production mode, with detailed outcomes provided in Table IV. For voiced, open-mouth laughs, formant frequencies were significantly lower in males than in females, at least for $F1$, $F2$, and $F3$, $F(1,587)=115.81$, 77.06, and 316.61 (all p's<0.001). However, laugher sex did not mediate $F4$ values, $F(1,587)=0.14$, ns, and female $F5$ values were actually significantly *lower* than in males, $F(1,587)=43.34$, $p<0.001$. For voiced, closed-mouth calls, only $F3$ values distinguished between the sexes, with male sounds being lower $F(1,86)=5.20$, $p=0.025$. Vocal fry was associated with significantly lower $F2$ and $F3$ values in males than in females $[F(1,38)=5.50$, $p<0.025$, and $F(1,38)=32.67$, $p<0.001$, respectively$]$. As was found for voiced open-mouth calls, $F5$ values were significantly lower for female than for male fry laughter $F(1,38)=15.12$, $p<0.001$. Peak frequencies of unvoiced, open-mouth calls were significantly lower for males than for females for the lowest three formants, $F(1,358)=81.95$, 20.90, and 95.93, respectively (all p's<0.001), but laugher sex did not affect the two highest resonances.

One way to characterize these outcomes was to plot $F1$ and $F2$ values in standard vowel space representations. Plots of voiced open-mouth and unvoiced open-mouth data were made using both Peterson and Barney's (1952) classic depiction and Hillenbrand *et al.*'s (1995) more recent version. For brevity, we show outcomes only using the latter representation [Figs. 6(a)–(d)]. Regardless of laugher-sex or call-production mode, these depictions show that laughter predominantly consists of central sounds. In males, for instance, the great majority of voiced open-mouth calls fell within /ɝ/ and /ʌ/ ellipses. Female outcomes were more variable, but

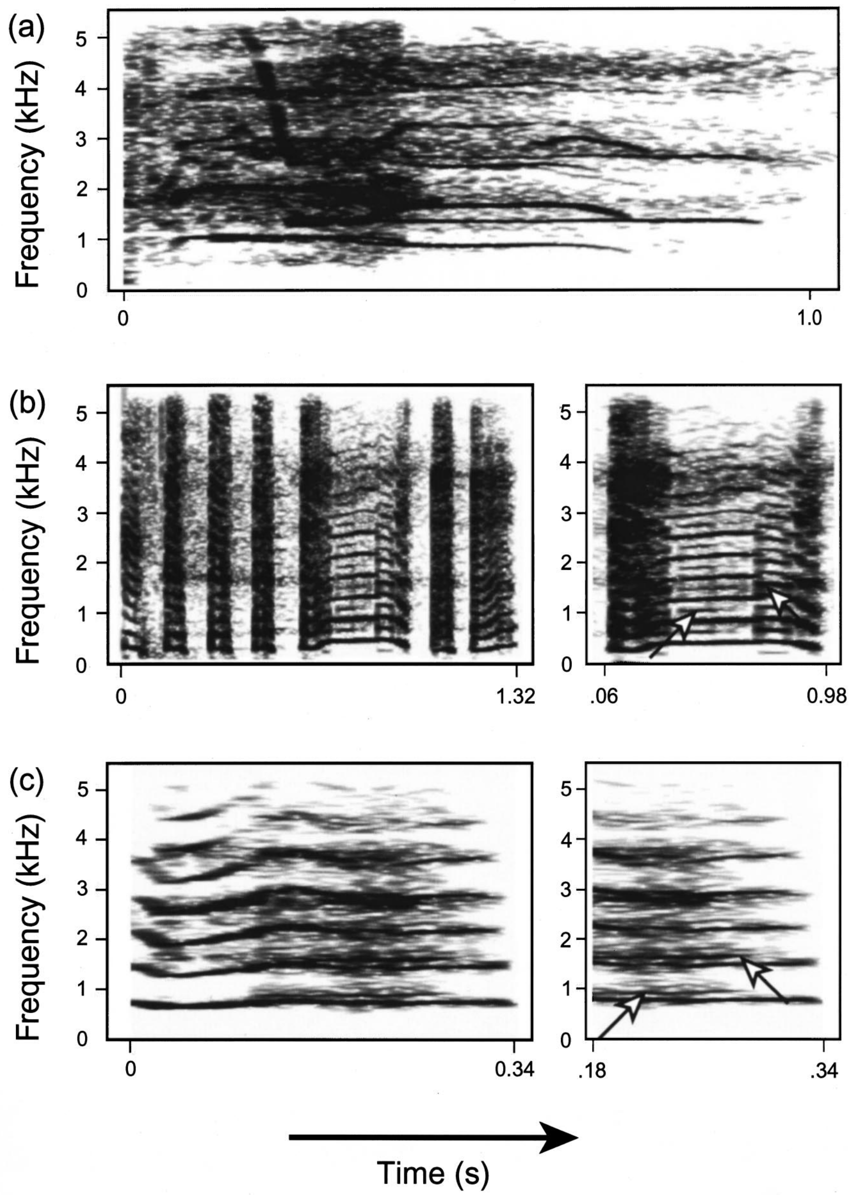

FIG. 5. Narrow-band spectrographic representations of three types of non-normative source energy. At the top (a), the kinds of spectral nonlinearities characteristic of glottal whistles are clearly evident. In (b), subharmonics are apparent in the last three calls of this seven-call bout, with arrows on the enlarged version to the right pointing to subharmonic energy. An instance of biphonation is depicted in (c), with the narrow-band spectrogram to the left revealing independent frequencies, and arrows highlighting two of these frequencies to the right.

most cases of voiced open-mouth calls were nonetheless located within central ellipses (i.e., /ɝ/, /ʌ/, /ɑ/ and /ɛ/). In contrast, there were very few observations of noncentral sounds by either sex, contrary to stereotypical notions that laughter includes sounds like ‘‘tee-hee’’ or ‘‘ho-ho.’’ In fact, no observations fell into the /i/ range, and very few were found within either the /ɪ/ or /o/ ellipses. Quite similar outcomes were found for male unvoiced open-mouth calls, whereas the majority of female versions of these sounds fell within /ɛ/ and /a/ ellipses and the undefined region between these two spaces.

In part to handle the large scaling differences between $F1$ and $F2$, vowel space depictions typically use nonequivalent axes. For instance, Peterson-and-Barney-type representations plot $F1$ using a linear scale but show $F2$ values on a logarithmic scale. Hillenbrand *et al.* did use linear scales for

TABLE IV. Male and female formant-frequency values according to call type. Tabled values are means, with standard deviations in parentheses.

	Sex (n)	$F1$	$F2$	$F3$	$F4$	$F5$
Voiced open mouth	M (41)	535 (112)	1592 (153)	2576 (180)	3667 (180)	4593 (160)
	F (34)	653 (155)	1713 (182)	2875 (227)	3673 (223)	4506 (157)
Voiced closed mouth	M (27)	445 (142)	1746 (187)	2527 (128)	3693 (278)	4588 (195)
	F (17)	501 (155)	1738 (291)	2636 (212)	3616 (238)	4548 (172)
Vocal fry	M (18)	582 (109)	1551 (115)	2509 (117)	3591 (126)	4574 (211)
	F (16)	638 (92)	1655 (153)	2764 (153)	3695 (220)	4290 (237)
Unvoiced open mouth	M (36)	594 (163)	1661 (155)	2589 (214)	3660 (183)	4602 (126)
	F (34)	770 (176)	1746 (171)	2826 (196)	3678 (205)	4583 (169)

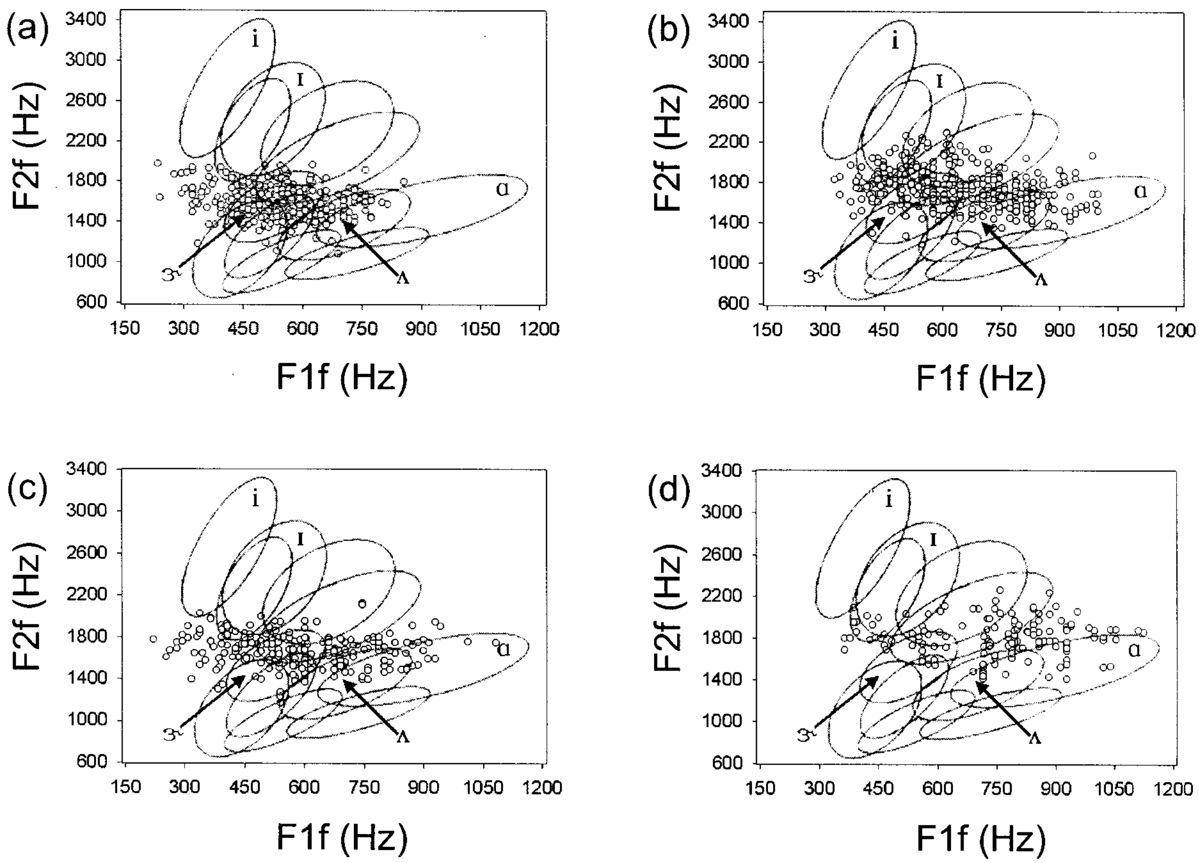

FIG. 6. Values of $F1$ and $F2$ plotted for (a) male open-mouth voiced calls; (b) female open-mouth voiced calls; (c) male open-mouth unvoiced calls, and (d) female open-mouth unvoiced calls; using Hillenbrand *et al.*'s (1995) vowel-space map.

both axes, but with different tick-mark intervals. In order to examine variability unconfounded by scaling differences, we also plotted the data using equivalent axes [Figs. 7(a)–(d)]. These representations yielded circular rather than elliptical distributions, indicating that on average the variability associated with the two resonances is essentially equivalent. Comparing the $F1$ and $F2$ distribution moments confirmed these impressions (outcomes can be obtained from author J.A.B.).

E. Acoustic correlates of laugher sex and individual identity

Earlier work involving a large set of homogeneous vowel sounds excised from running speech revealed that acoustic characteristics related to F_0 and formants play prominent but varying roles in differentiating talkers by sex and individual identity (Bachorowski and Owren, 1999). Similar analyses were conducted here, although with a smaller number of observations. This testing focused on voiced open-mouth and unvoiced open-mouth calls. For voiced calls, mean F_0, s.d. of F_0, F_0 excursion, F_0 change, $F1-F5$, VTL, and call duration were the measures used, while $F1-F5$, VTL, and call duration were examined for unvoiced calls. For each call type, only participants represented by six or more completely analyzable observations were used in classification analyses. Given these selection criteria, data from 19 males and 13 females were available for tests with voiced open-mouth sounds, whereas data from 11 males and 7 females contributed to analyses of unvoiced open-mouth calls. Eight males and five females were represented in both voiced and unvoiced call analyses.

Here, each subject was first entered as a unique independent variable in a MANOVA. Only those acoustic measures for which individual laughers differed from each other were subsequently used in discriminant-function analyses (Tabachnik and Fidell, 1996), which in practice meant that call duration, F_0 change, and $F4$ were not used in voiced-call laugher-sex analyses, $F4$ was not used in unvoiced-call laugher-sex analyses, and call duration was not used for individual laugher classification of females. The remaining variables were then entered in stepwise fashion in discriminant function analyses using the Mahalanobis-distance method, and the performance of discriminant functions was cross validated with the jackknife procedure. Functions were derived using the actual number of cases available for each subject. The overall approach was to compare outcomes for the full set of acoustic measures with particular subsets of interest.

Classification outcomes for laugher sex are given in Table V. Results are shown for classification accuracies in derivation and test phases, as well as the percent error reduction associated with the former. This last metric takes into account chance error rate, producing an unbiased measure of classification accuracy. For voiced open-mouth calls, the most successful classification (86.3%) occurred with the complete set of dependent measures, but only $F1$, $F2$, $F3$,

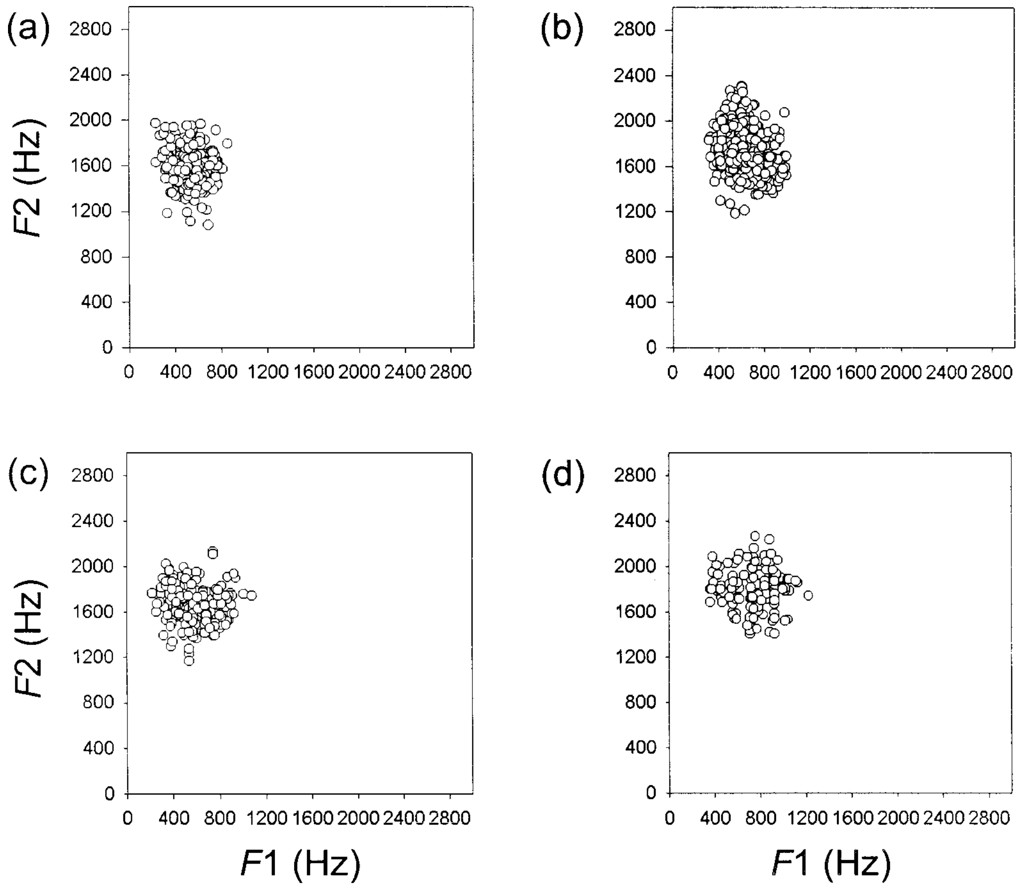

FIG. 7. Using linear axes to anchor values of both $F1$ and $F2$, data are plotted for (a) male open-mouth voiced calls; (b) female open-mouth voiced calls; (c) male open-mouth unvoiced calls; and (d) female open-mouth unvoiced calls.

and VTL met entry criteria. In other words, none of the F_0-related measures contributed significantly to classification by sex when tested in conjunction with spectrally related cues. Other comparisons also showed formant frequencies to be the most important in sorting laughers by sex. For instance, the set of four formant frequencies that entered the analysis was associated with 85.4%-correct classification (70.8% error reduction), whereas the three F_0-related measures together led to 60.6%-correct classification (only 21.2% error reduction). Similarly, VTL alone classified 79.5% of cases (59.0% error reduction), whereas mean F_0 produced only 61.2% correct (22.4% error reduction). Filter-related cues were also found to be important for sorting unvoiced calls by laugher sex. For instance, classification accuracy was 84.8% (69.6% error reduction) using only the four formant frequencies, and testing VTL alone led to virtually identical outcomes.

Classification of individual laughers within each sex was less successful. Even so, these outcomes were significantly better than expected by chance, and should be useful in developing more refined hypotheses concerning individual distinctiveness of laugh sounds. Here, we note only a few of the outcomes (also see Table VI). Overall, more effective classification occurred for female than for male calls—an outcome at least partly attributable to the smaller number of females being classified. For voiced calls produced by either sex, formant frequencies were again far more important in classifying individuals than were F_0-related measures. Whereas the former were associated with 41.2% and 49.0% correct classification for males and females, respectively, the latter produced corresponding values of only 15.4% and 22.6%. For males but not females, classification of unvoiced calls was also effective.

IV. DISCUSSION

The present study provides detailed acoustic outcomes for a large corpus of laugh sounds produced by a correspondingly large number of laughers. In addition to providing an extensive characterization of laugh acoustics, this work also suggests four broad findings concerning these sounds. First, in contrast to perspectives that emphasize stereotypy in laughter, we found this signal to be notable for its acoustic variability. Second, this variability was associated with a diversity of evident underlying vocal-production modes. Third, we found vowel-like laughs to be comprised of central, unarticulated sounds and lacking in the vowel-quality distinctions commonly thought to be present. Finally, we obtained preliminary evidence that indexical cues to laugher sex and individual identity are conveyed in laugh acoustics. The following sections elaborate on both these and other results, and include comparisons to previously reported outcomes and hypotheses concerning laugh acoustics (see Table VII for key comparisons between the current work and other studies).

TABLE V. Results of discriminant function analyses for laugher-sex classification using both the full complement of acoustic cues and theoretically derived groups of measures. Test accuracy was assessed with the jackknife procedure. Chance classification accuracy was 50%.

	Derivation accuracy	Test accuracy	Error reduction[a]
Voiced open-mouth calls[b]			
All measures[c]	86.7	86.3	72.6
$F1,F2,F3,F5$	85.4	85.4	70.8
$F1,F2,F3$	84.4	84.4	68.8
F_0-related measures[d]	60.8	60.6	21.2
VTL, mean F_0	78.9	78.7	57.4
VTL	79.5	79.5	59.0
Mean F_0	61.2	61.2	22.4
Unvoiced open-mouth calls[e]			
All measures[f]	88.2	87.4	74.8
$F1f,F2f,F3f,F5f$	84.8	84.8	69.6
$F1f,F2f,F3f$	80.7	80.3	60.6
VTL	85.4	84.6	69.2

[a]Error reduction=([(100—chance rate)−(100—observed rate)]×100)/(100—chance rate).
[b]Data came from 19 males and 13 females.
[c]Mean F_0, s.d. F_0, F_0-excursion, $F1-F5$, VTL, and call duration.
[d]Mean F_0, s.d. F_0, F_0-excursion.
[e]Data came from 11 males and 7 females.
[f]$F1-F5$, VTL, call duration.

TABLE VI. Results of discriminant function analyses for individual laughers within each sex using both the full complement of acoustic cues and theoretically derived groups of measures. Test accuracy was assessed with the jackknife procedure. Chance classification accuracies were 5.3% and 7.7% for male and female voiced open-mouth calls, and 9.1% and 14.3%, for male and female unvoiced open-mouth calls, respectively.

	Derivation accuracy	Test accuracy	Error reduction
I. Voiced open mouth			
(a) Males ($n=19$; 271 cases)			
All measures[a]	58.3	42.8	39.6
$F1,F2,F3,F4,F5$	45.5	41.2	38.1
F_0-related measures[b]	17.1	15.4	10.9
Mean F_0, VTL	24.0	21.5	17.1
Mean F_0	15.4	15.4	10.9
VTL	13.3	11.6	6.7
(b) Females ($n=13$; 211 cases)			
All measures[c]	61.3	53.2	49.3
$F1,F2,F3,F4,F5$	55.7	49.0	44.7
F_0-related measures	26.9	22.6	16.1
Mean F_0, VTL	28.5	25.8	19.6
Mean F_0	23.5	23.5	17.1
VTL	28.1	27.1	21.0
II. Unvoiced open mouth			
(a) Males ($n=11$; 207 cases)			
All measures[d]	53.5	47.6	42.4
$F1,F2,F3,F4,F5$	50.8	48.1	42.9
VTL	31.6	27.8	20.6
(b) Females ($n=7$; 63 cases)			
All measures[e]	76.3	40.7	30.8
$F1,F2,F3,F4,F5$	69.5	35.6	24.9
VTL	39.0	37.3	26.8

[a]Mean F_0, s.d. F_0, F_0-excursion, F_0-change, $F1-F5$, VTL, and call duration.
[b]Mean F_0, s.d. F_0, F_0-excursion, F_0-change.
[c]Mean F_0, s.d. F_0, F_0-excursion, F_0-change, $F1-F5$, VTL, and call duration. With the exception of call duration, measures for females were the same as those for males.
[d]$F1-F5$, VTL, and call duration.
[e]$F1-F5$ and VTL.

A. Laughter is highly variable

1. Temporal variability

On average, laugh bouts were a bit less than 1 s in duration (i.e., 870 ms) and consisted of 3.39 calls, each 170 ms long and 130 ms apart. However, considerable variability was found for every measure examined. For instance, bouts could be as short as 40 ms but as long as 5699 ms, while call durations ranged from 5 to 1053 ms. The number of calls involved was also highly variable, with many bouts consisting of only a single call but others including up to 20.

Overall, call durations and intercall durations were found to be quite comparable (cf. Ruch and Ekman, 2001). However, more detailed examinations showed that intercall intervals were markedly shorter than call durations at bout onset (see Fig. 3), with call production thus being more densely packed at the beginning than at the end of bouts. In other words, while our outcomes replicated the gradual increase in intercall interval noted by Provine (1996; Provine and Yong, 1991), we did not find evidence of a proposed monotonic decrease in call duration over the course of each bout (e.g., Provine and Yong, 1991; Ruch and Ekman, 2001). We instead found that calls produced at bout onset were much longer than later calls, with little subsequent variation among the latter.

Outcomes concerning the rate of laugh-sound production are also of interest. Using data from one male and one female laugher, Bickley and Hunnicutt (1992) found a rate of 4.7 calls/s, which is a bit greater than our obtained mean of 4.37 calls/s. Treating laugh calls as syllables, both of these rates are faster than the mean discourse rate of 3.26 syllables/s produced by comparably aged young adults (Venkatagiri, 1999). Conversely, young adults have been shown to produce laugh-like syllables at higher rates than those found here. For instance, a mean maximum-repetition rate of 5.46 was found for females producing /hʌ/ syllables (Shanks, 1970), whereas a mean maximum-repetition rate of 5.1 was reported for males producing /ʌ/ syllables (Ptacek *et al.*, 1966). Taken together, these comparisons indicate that average sound-production rates are faster in laughter than in conversational speech, without reaching the maximum possible rate.

2. Source variability

Many of the outcomes associated with F_0-related measures were remarkable. Here, we focus primarily on analyses of open-mouth calls or segments, as these accounted for the vast majority of voiced-laugh components. Consistent with several previous reports (Provine and Yong, 1991; Rothgänger *et al.*, 1998; Nwokah *et al.*, 1999; see Table VII), we found that mean F_0 of both male (282 Hz) and female (421 Hz) laughter was considerably higher than in modal speech (120 and 220 Hz for males and females, respectively). However, lower mean F_0 values have been reported by others, which we suspect may reflect either that those studies examined laughter from subjects that were tested alone (e.g.,

TABLE VII. Comparisons among the present results and other published reports. Tabled values are means, with standard deviations in parentheses.

Study	Sample size	Laugh-sampling method	Number of laugh bouts	Bout duration	Calls per bout	Minimum and Maximum calls per bout	Call duration
Bachorowski, Smoski, and Owren (2001)	45 males 52 females	Humorous video clips	1024	0.87 s (0.77)	3.39 (2.71)	1, 20	0.17 s (0.14)
Bickley and Hunnicutt (1992)	1 male 1 female	Spontaneous laughs produced during speech task	15		Laugher 1: 6.7 Laugher 2: 1.2		
Milford (1980)	15 males 15 females	Social, tension-release, humor, and tickle		1.34 s			
Mowrer, LaPointe, and Case (1987)	11 males	Humorous video clips	55	1.22 s (0.44)[a]	7.16 (2.42)	1, 25	
Nwokah, Hsu, Davies, and Fogel (1999)[b]	3 females	Mothers interacting with their infants	3	2.14	8.67	6, 14	
Provine and Yong (1991)	23 males 28 females	First "spontaneous" laugh after request to laugh	51		4.00	4, 16	0.08 s (0.02)[c]
Rothganger, Hauser, Cappellini, and Guidotti (1998)	20 males 20 females	Humorous video clips	187	0.75	5.90 (2.18)		0.13 s (0.06)

Study	Mean F_0 (Hz)	F_0 Range (Hz)	$F1f$ (Hz)	$F2f$ (Hz)	$F3f$ (Hz)	$F4f$ (Hz)	$F5f$ (Hz)
Bachorowski Smoski, and Owren (2001)[d]	M: 284 (155)[e] F: 421 (208)	M: 67 (76) F: 91 (85)	M: 534 (111) F: 637 (149)	M: 1589 (153) F: 1734 (193)	M: 2571 (182) F: 2887 (253)	M: 3663 (184) F: 3725 (273)	M: 4594 (161) F: 4513 (167)
Bickley and Hunnicuttt (1992)	M: 138 F: 266	M: 55 F: 315	M: 650 F: 650	M: 1700 F: 1800	M: 2200 F: 2760		
Milford (1980)	M: 175 F: 160		M: 543 F: 599	M: 1687 F: 1847			
Mowrer, LaPointe, and Case (1987)	M: 126 (42.7)	M: 69					
Nwokah, Hsu, Davies, and Fogel (1999)[b]	F: 365 (28)	F: 161					
Provine and Yong (1991)[g]	M: 276 (95) F: 502 (127)						
Rothganger, Hauser, Cappellimi, and Guidotti (1998)	M: 424 F: 475 (125)						

[a]Laugh selection required that bout duration be at least 250 ms.
[b]Some outcomes provided here were derived from results given in the original reports.
[c]Given the authors' descriptions, we assume these durations to reflect voiced portions of calls.
[d]Acoustic outcomes shown here are for voiced, open mouth calls.
[e]M=male; F=female.
[f]These formant outcomes were provided as examples rather than arithmetic means.
[g]F_0 measurements were made for the first call of each bout examined.

Bickley and Hunnicutt, 1992; see Bachorowski *et al.*, 2001), or were influenced by uncorrected errors occurring in automated pitch extraction. For example, algorithm failures likely contributed to Milford's (1980) implausibly low mean F_0 of 160 Hz for female laughter. Automated pitch-extraction errors are particularly likely to occur in laughter because F_0 variation in both calls and bouts is quite high. Although individual voiced calls were found to be quite brief, their mean F_0 excursions were nonetheless 67 and 91 Hz for males and females, respectively (also see Mowrer *et al.*, 1987; Nwokah *et al.*, 1999). Across all sounds, male F_0 was found to be as low as 43 Hz but as high as 898 Hz, whereas female F_0 was shown to be as low as 70 Hz and as high as 2083 Hz. Laughers can thus span the full range of possible F_0 variation, from the lowest vocal fry to the highest falsetto (see Hollien, Dew, and Phillips, 1971; Rothgänger *et al.*, 1998).

Consistent with Bickley and Hunnicutt's (1992) results, we found no evidence that F_0 necessarily decreases across the course of a multicall bout. In other words, laughter does not appear to exhibit the F_0-declination effect that at least some researchers report to be characteristic of human speech (see 't Hart, Collier, and Cohen, 1990). However, we did find that F_0 characteristics were markedly different depending on the length of a bout. Specifically, long bouts were associated with both higher mean F_0 and greater F_0 variability than were shorter ones.

3. Variability in production modes

In contrast to perspectives that treat laugh sounds as being comparatively stereotyped (e.g., Grammer and Eibl-Eibesfeldt, 1990; Provine and Yong, 1991; Provine, 1996), we found laughter to be a repertoire of highly variable vocalizations that includes qualitatively distinct voiced song-like, unvoiced grunt-like, and unvoiced snort-like versions. Like the outcomes reported by Grammer and Eibl-Eibesfeldt (1990), our results showed that females produced more song-like bouts than males, whereas males produced proportionately more grunt-like laughs than females. These sex differences aside, individual laughers did not seem to rely on any particular style, with two of the three major bout types being produced by 84% of the individuals in this sample. Given that these laughs occurred within a 3.95-min window, it seems reasonable to assume that everyone produces each kind of bout at least some of the time. We also suspect that within the three broad types identified here, there may be subtypes that are acoustically and perhaps functionally important. That may be most relevant to voiced laughs, for which significant acoustic distinctions were found between shorter and longer bouts. However, a larger sample of voiced laughs would be necessary to reliably evaluate the possibility of subtypes.

While fewer than two production modes were found in most bouts, some included up to five production modes. Individual calls could also be acoustically complex, with the majority of compound calls consisting of both voiced and unvoiced components. Of these, it was more often the case that voiced segments preceded unvoiced segments than the converse (cf. Provine and Yong, 1991; Ruch and Ekman, 2001). A number of other combinations also occurred. For example, several instances of adjacent vocal fry and very high F_0 segments were noted, indicating that laughers can effect substantial and instantaneous changes in vocal-fold vibration rates (see also Rothgänger *et al.*, 1998). Variability in production modes may be driven by a number of factors, including individual style differences, linkages between laugher arousal and production processes, and social-context-based influences (Bachorowski *et al.*, 2001).

In addition to voicing distinctions, variability was also evident in the variety of non-normative source energies used in laugh production. Taken together, instances of vocal fry, glottal pulses, laryngeal whistles, subharmonics, and biphonation accounted for nearly 10% of the 3479 calls in this sample. The occurrence of subharmonics and biphonation in laughter is of particular interest (see also Riede, Wilden, and Tembrock, 1997; Švec *et al.*, 2000), as these kinds of nonlinearities are prominent features of some of the call types produced by any number of mammalian species. For instance, subharmonics have been observed in the calls of African wild dogs (Wilden *et al.*, 1998), rhesus and Japanese macaques (Riede *et al.*, 1997; Owren, 2001), and in the cries of human infants (Mende, Herzel, and Wermke, 1990; Hirschberg, 1999). Sounds with perceptually salient nonlinearities of this sort should be particularly effective in eliciting listener attention and arousal (see Owren and Rendall, 2001), and we expect the same to be true of nonlinear laugh sounds. We more specifically suspect that many instances of laugh nonlinearities are likely to be perceptually somewhat aversive if heard in isolation, but that these sounds may nonetheless enhance laughter's emotion-inducing effects when heard in conjunction with comparatively tonal calls.

B. Laughter is not articulated

Formant outcomes were generally within the bounds expected of speech acoustics for both sexes. As is typically the case due to dimorphism in supralaryngeal vocal-tract length, peak formant-frequency values of male calls were significantly lower than those of female calls for each of the lowest three resonances.

Plots of $F1$ and $F2$ outcomes in traditional vowel space showed that laugh utterances are generally clustered in /ɝ/ and /ʌ/ ellipses (Hillenbrand *et al.*, 1995; see also Ladefoged, 1993; Olive, Greenwood, and Coleman, 1993; Pullum and Ladusaw, 1996), thus being largely comprised of central, unarticulated sounds (see also Edmonson, 1987; Ruch and Ekman, 2001). To a lesser extent, observations also occurred within /ɑ/ and /ɛ/ ellipses. In the absence of large discrepancies between plots of voiced open-mouth and unvoiced open-mouth calls, the centrality of laugh sounds does not appear to be differentially associated with the presence or absence of harmonic energy. Alternative plots that relied on linear scalings for both *x*- and *y* axes showed that distributions of $F1$ and $F2$ were essentially normal for both call types. This impression was further supported by examining the statistical moments of these distributions, with the tight clustering of observations supporting Bickley and Hunnicutt's (1992) notion of a "laugh vowel sound." Our finding that laugh sounds are consistently found in the central regions of vowel space contrasts with previous speculation that voiced laughter routinely shows vowel-quality distinctions (Provine, 1996, 2000; Provine and Yong, 1991; also see Darwin, 1872/1998; Hall and Allin, 1897; Mowrer *et al.*, 1987; Nwokah *et al.*, 1993; Nwokah *et al.*, 1999; Ruch, 1993). Hypothesizing that "ha" is the most prevalent, Provine has for example contended that "ho" and "he" are also common. In contrast, we observed comparatively few /ɑ/ sounds, and found no /o/ and /i/ variants.

Contrary to expectations, $F4$ frequencies for both call types were essentially the same in both sexes, rather than being higher in females. Even more surprising, female $F5$ values were actually significantly lower than in males for voiced open-mouth calls. Across the spectrum, outcomes for males were largely consistent with those expected of unarticulated sounds, which was also the case for the lowest three formants in females (e.g., Stevens, 1998). In other words, $F4$ and $F5$ outcomes in females must be considered anomalous, in spite of the conservatism of our analyses. The precautions involved included being careful not to overspecify the spectrum by using too many LPC coefficients, comparing the smoothed spectrum to corresponding narrow-band FFT representations in every case, and excluding values in which the purported formant was more likely to be "tracking" the energy of an individual harmonic rather than a supralaryngeal resonance. Difficulties in formant extraction are expected when fundamental frequencies are high (e.g., Titze, Mapes, and Story, 1994), which was certainly the case here. Furthermore, as the energy of the higher harmonics of voiced sounds is typically substantially less than at lower frequencies, the most likely interpretation of the unexpected outcomes obtained for female $F4$ and $F5$ values appears to be that the measurements did not accurately reflect actual production characteristics in these individuals. Alternatively, it may be that the higher resonances are different in laughter than in speech—at least for females. This question is not readily resolvable given the current data, and will therefore be left for future research.

C. Indexical cuing in laughter

Discriminant-function analyses were used to test whether individual laugh calls could be classified according to the sex and individual identity of the person who produced the sound. These questions were of particular interest because acoustic cues to laugher identity have been proposed to play a role in listener responses (e.g., Owren and Bachorowski, 2001a; Smoski and Bachorowski, in press), and because results from voiced, open-mouth calls could be compared to findings from a previous study of an /ɛ/ vowel segment excised from naturally occurring speech (Bachorowski and Owren, 1999). One result of interest in that study was that extremely accurate classification of talker sex occurred using either mean F_0 or the lowest three formant frequencies considered as a set ($F4$ and $F5$ were not included in those analyses). However, when these frequencies were used in combination as an estimator of vocal tract length (VTL), mean F_0 and VTL together provided better overall classification than any other combination of variables.

Current results concerning classification by sex showed both similarities and differences from this earlier work. First, classification accuracy was reasonably high overall (i.e., 72.6% error reduction), but noticeably lower than with the /ɛ/ sound (i.e., 97.2%). Second, entering the $F1$ through $F3$ frequencies as a set again provided accurate classification (i.e., 68.8% error reduction), while F_0 tested alone now had very little power (i.e., 22.4%). The latter outcome is of course to be expected, given the dramatic variability observed in F_0-related measures, regardless of laugher sex. Adding the higher formants neither clarified nor improved these classification outcomes. $F4$ values were not tested because values did not differ according to sex, and classification performance of $F5$ was equivocal. When VTL was calculated using all five formants rather than just the lowest three, classification performance declined accordingly (i.e., 59.0% error reduction). As discussed above, it is simply unknown at this point whether the $F4$ and $F5$ values observed here show laughter to be different from normative speech, or instead reflect the difficulty of obtaining accurate measurements of these formants when high F_0 values are involved. However, one clear conclusion is that $F1$, $F2$, and $F3$ frequencies are primary cues to vocalizer sex, regardless of whether that individual is producing a vowel sound or a voiced, open-mouth laugh sound. The relative unimportance of F_0 in laughter left these formant characteristics as the predominant factor for successful sorting based on these sounds, as was also true for unvoiced open-mouth laughs. This outcome suggests that listeners are able to rely on the same sorts of cues in both instances (see Rendall, Owren, and Rodman, 1998, for related discussion in analogous call types produced by nonhuman primates).

Individual laughers within each sex were less successfully classified (e.g., 39.6% and 49.3% overall error reduction for males and females, respectively), both due to the larger numbers of classes (i.e., laughers) being sorted, and because within-sex acoustics were more similar than between-sex acoustics. Analogous sorting of individual talkers in the earlier study of /ɛ/ vowels also showed reduced accuracy, but there the decline was less precipitous (e.g., 78.6% and 64.3%). Results in both cases nonetheless showed that filter-related cues were again much more important than F_0-related cues in successful classification of individuals, whether male or female. Thus, individually distinctive cues appear to be less prominent in laugh sounds than in vowel sounds, but are nonetheless present in the form of supralaryngeal filtering effects. Classification performance based on formant frequencies in unvoiced, open-mouth calls was similar for males, while somewhat less successful for females. Outcomes for the latter were nonetheless significantly above chance.

D. Theoretical comments

Several aspects of the present findings provide support for our broader theoretical perspective concerning the use and functions of laughter (reviewed in Owren and Bachorowski, 2001a; see also Bachorowski and Owren, 2001; Owren and Bachorowski, 2001b). Drawing on Owren and Rendall's (1997, 2001) model of nonhuman primate vocal signaling, we have proposed that laughter largely functions to elicit emotional responses in listeners and thereby shape their subsequent behavior. Laughter is hypothesized to influence listeners through two mechanisms. For the first, signal acoustics are thought to directly affect listener attention, arousal, and emotional response processes. Laughs with features such as abrupt rise times, high F_0's, perceptually salient F_0 modulation, and perhaps acoustic nonlinearities should be particularly effective in engaging listener response systems. Some empirical support for direct-effect notions comes from the results of perceptual studies, which showed that listeners had significantly more positive emotional responses to voiced than to unvoiced laughs (Bachorowski and Owren, 2001). Further work will more specifically delineate the features and combinations of features that most effectively elicit listener responses. In the meantime, the present results show that many laughs have acoustic features likely to directly "tweak" listeners. For the second, more indirect mechanism, learned, positive emotional responses are thought to occur as a result of repeated pairings of the laugher's distinctive acoustics with positive affect occurring in a listener. It was therefore important to find here that both voiced and unvoiced sounds could be statistically classified by individual laugher. Additional work along these lines is thus warranted, for instance testing listener responses to familiar and unfamiliar laugh acoustics.

Another important piece of our theoretical perspective involves sex differences in the use of laughter. We have reported elsewhere that both the rate and selected acoustic features of the laughs analyzed here varied according to social context (Bachorowski *et al.*, 2001; see also Grammer and Eibl-Eibesfeldt, 1990). Overall, those results indicated that variability in individual male laughter is associated with his relationship to his social partner (i.e., friend or stranger), whereas individual female laughter is more closely associated with the sex of her social partner. We interpreted these outcomes to indicate that both males and females use laughter nonconsciously but strategically, in accordance with evolved, sex-based psychological mechanisms (Owren and Bachorowski, 2001a). In this perspective, the remarkable acoustic variability documented here is interpreted as being functionally significant. Individuals of either sex are expected to produce laughs with direct effects on listener response systems when arousal induced in the listener elicits or heightens positive affect, but expected not to when the effect of such arousal is to exacerbate a negative state in that individual (see also Patterson, 1976). Acoustic variability is probably also related to a number of other factors, such as the potency of laugh-eliciting stimuli, individual differences in emotion-based response processes, and sociocultural influences on both the rate and form of signal production. We nonetheless suggest that interactions among laugher sex and social context are likely primary determinants of acoustic variability in laughter.

V. CONCLUSIONS

The data considered here show that laughter is a highly complex vocal signal. A variety of types involving distinct production modes was evident, with song-, grunt-, and snort-like versions being most readily discernible. The observed variability highlights the need for large sample sizes in studying laughter, and suggests that previous work has tended to underestimate the range of acoustic features involved. Although some aspects of laughter were found to resemble speech, most outcomes showed notable differences between the two signals. For instance, voiced laughter showed much more striking source-related variability than is associated with normative speech. Furthermore, while supralaryngeal-filtering effects were as much in evidence in laughter as in speech vowels and sonorants, there was no evidence of analogous articulation. Instead, voiced laughter in American-English speakers overwhelmingly consists of sounds located close to the center of their vowel space. Finally, classification results involving vocalizer sex and individual identity based on the characteristics of individual sounds resembled typical findings from speech in showing filter-related cues to be disproportionately important. However, there was much less of a role for F_0-related features.

Overall, these results stand in contrast to claims that laughter is a stereotyped vocal signal and highlight the difficulty of trying to characterize laughter as being a single acoustic form (e.g., Provine, 1996; Provine and Yong, 1991; cf. Grammer and Eibl-Eibesfeldt, 1990; Rothgänger *et al.*, 1998). Instead, laughter appears to be better conceptualized as a repertoire of sounds, with the prevalence of various subtypes perhaps best gauged by recording laughter that occurs in response to controlled laugh-eliciting stimuli. That approach is also likely to be crucial in eventually understanding the functional importance of the various production modes and the acoustic features associated with them, as we have found in testing variously composed subject dyads (Bachorowski *et al.*, 2001). Important extensions will necessarily involve examining the use of laughter in explicitly interactive circumstances (e.g., Smoski and Bachorowski, in press). Finally, the impact of laugh subtypes on listener responsiveness should be examined through perceptual testing. Other research could include testing the extent to which bout-level temporal patterning is individually distinctive and thereby contributes to indexical cueing (see Owren and Rendall, 1997), examining whether acoustically coherent subtypes occur within the broad categories identified here, and studying the functional importance of unvoiced laughs.

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[1]Formant-frequency values were considered ''missing'' both for instances of harmonic-resonance overlap and for cases in which there was no spectrographic evidence of a resonance in an expected region (see also Hillenbrand *et al.*, 1995). So that multivariate statistics could be used, missing values were replaced with the mean of the relevant formant frequency on a subject-by-subject basis. One should note, however, that this procedure can constrain true variability. Additional precautions were thus taken to ensure that the data set was not unduly influenced by mean replacements. First, preliminary analyses indicated that formant frequencies measured from voiced open-mouth, voiced closed-mouth, vocal fry, and unvoiced open-mouth calls were significantly different from each other. Therefore, replacement values were calculated separately for the four call types. While thus increasing the likelihood of finding differences associated with call-production mode, this approach was preferred because treating all call types as one would create the converse problem of obscuring differences that did exist. Second, statistical outliers were identified on a formant-by-formant basis as those values that were either less than or greater than 3 s.d.s' from the mean for that subject. The 19 cases identified in this fashion were then treated as missing. Third, and again on a formant-by-formant basis, mean replacements were only conducted for instances in which four or more measurements were available and replacements did not account for more than half of a given subject's formant-frequency values. Replacements were not conducted for 17 subjects because too few formant measurements were taken. For the remaining data, a total of 963 replacements was made (i.e., 13% of the observations used in statistical analyses), which was found to change the resulting mean only by approximately 4 Hz. More replacements were made for $F1$ ($n=300$) and $F5$ ($n=281$) than for $F2$ through $F4$ ($n=100$, 132, and 150, respectively).

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