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1 A Fine-Scale, Broadly-Applicable Index of Vocal Performance:
2 Frequency Excursion

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22 ABSTRACT

23 Our understanding of the evolution and function of animal displays has been advanced
24 through studies of vocal performance. A widely used metric of vocal performance, vocal
25 deviation, is limited by being applicable only to vocal trills, and also overlooks certain
26 fine-scale aspects of song structure that might reflect vocal performance. In light of
27 these limitations we here introduce a new index of vocal performance, "frequency
28 excursion". Frequency excursion calculates, for any given song or song segment, the
29 sum of frequency modulations both within and between notes on a per-time basis. We
30 calculated and compared the two performance metrics in three species: chipping,
31 swamp, and song sparrows. The two metrics correlated as expected, yet frequency
32 excursion accounted for subtle variations in performance overlooked by vocal deviation.
33 In swamp sparrows, frequency excursion values varied significantly by song type but
34 not by individual. Moreover, song type performance in swamp sparrows, according to
35 both metrics, varied negatively with the extent to which song types were shared among
36 neighbors. In song sparrows, frequency excursion values of trilled song segments
37 exceeded those of non-trilled song segments, although not to a statistically significant
38 degree. We suggest that application of frequency excursion in birds and other taxa will
39 provide new insights into diverse open questions concerning vocal performance,
40 function, and evolution.

41

42 Key words: vocalizations, bird song, vocal performance, vocal deviation, frequency
43 excursion, chipping sparrow, swamp sparrow, song sparrow

44 INTRODUCTION

45 Much research in the fields of sexual selection and animal communication has focused
46 on mating signals and displays, produced by animals as they compete for access to
47 prospective mates (Andersson 1994; Searcy & Nowicki 2005; Seyfarth et al. 2010;
48 Bradbury & Vehrencamp 2011). Some mating displays seem to require high vigor or
49 skill to be performed effectively (Darwin 1871; Byers et al. 2010). As such, only the
50 “best” signalers in a population should be able to execute the most complex or
51 challenging displays, rendering these displays reliable as indicators of signaler quality
52 (Byers et al. 2010; Cardoso 2013a). Empirical evidence available to date, while limited,
53 suggests that variation in display performance can indeed hold functional value, both to
54 males assessing potential competitors and to females assessing prospective mates
55 (e.g., Arak 1983; Vehrencamp et al. 1989; Welch et al. 1998; Barske et al. 2011;
56 Wilgers & Hebets 2011; Reichert & Gerhardt 2012; Zanollo et al. 2013).

57 Useful recent insights into display performance variation and its functional
58 consequences have emerged through studies of vocal displays in vertebrates, including
59 song in songbirds (e.g., Nowicki et al. 1998; Byers 2007; Podos et al. 2009; Spencer &
60 McDougall-Shackleton 2011; Sakata & Vehrencamp 2012). Songbirds sing using
61 multiple motor systems, namely the syrinx (sound source), respiratory system, and
62 vocal tract (reviewed by Suthers 2004; Podos & Nowicki 2004; Podos et al. 2009; Riede
63 & Goller 2014). Performance challenges arise as birds coordinate syrinx modulations
64 with intricately patterned respiratory movements, and as they track changing source
65 frequencies via precise reconfigurations of the vocal tract (Westneat et al. 1993; Hoese

66 et al. 2000; Podos et al. 2004b; Riede et al. 2006; Suthers et al. 2012). Studies of hand-
67 reared songbirds, in which males are trained with challenging song models, have
68 provided direct experimental evidence that aspects of song structure are indeed limited
69 by vocal performance capacities (Podos 1996; Podos et al. 2004a; Zollinger & Suthers
70 2004; see also Lahti et al. 2011).

71 A key component in studies of vocal performance -- in birds or otherwise -- is the
72 quantitative analysis of vocal structure, as a means for drawing inferences about vocal
73 performance limitations. One focal point for studies of vocal performance has been
74 vocalizations that feature repeated sequences of notes or syllables, i.e., trills (e.g.,
75 Thorpe & Lade 1961; Podos 1997; Figure 1). Trills with rapid rates of syllable repetition
76 (high “trill rates”), and/or that span wide ranges of fundamental frequencies (high
77 “frequency bandwidth”), should be comparatively hard to perform because they require
78 correspondingly rapid and extensive modulations of components of the vocal apparatus
79 (Podos et al. 2009). Moreover, trill rate and frequency bandwidth should relate to each
80 other inversely, because of an expected tradeoff at maximal performance between rates
81 and spans of vocal modulations. An initial structural analysis of trilled song sequences
82 of 34 species of emberizid songbirds supported this expectation: songs in a family-wide
83 trill rate by frequency bandwidth plot show a lower-left skewed triangular distribution,
84 with some trills showing fast trill rates or broad frequency bandwidths but not both
85 concurrently (Podos 1997). Similar triangular distributions have since been reported for
86 diverse taxa including numerous avian and one mammalian species (e.g., Price &
87 Lanyon 2004; Beebee 2004; Ballentine et al. 2004; Illes et al. 2006; Cramer & Price

88 2007; Cardoso et al. 2007; Liu et al. 2008; Janicke et al. 2008; Sockman 2009; Cardoso
89 & Hu 2011, Juola & Searcy 2011; Pasch et al. 2011; Derryberry et al. 2012; see also
90 Wilson et al. 2014).

91 Descriptions of trill rate and frequency bandwidth, and of tradeoffs between the two, not
92 only help describe constraints on trill production but have also provided a means to test
93 the functional relevance of trill performance variations. Trill rate and frequency
94 bandwidth are in themselves useful measures of vocal performance. Moreover, as a
95 composite index of performance for any trill, one can graph a trill sequence of interest
96 on a taxon-wide plot of trill rate by frequency bandwidth, and calculate the offset
97 between the trill in question and the putative performance constraint. Operationally this
98 calculation involves the derivation of a trill rate by frequency bandwidth “upper-bound
99 regression” (Podos 1997), and calculation of the orthogonal distance between the upper
100 bound regression and the trill of interest (Podos 2001; Ballentine et al. 2004). The
101 resulting distance, termed “vocal deviation”, corresponds inversely to presumed vocal
102 performance requirements: higher vocal deviations are indicative of low performance
103 songs, and vice versa. Vocal deviation, trill rate, and frequency bandwidth have now
104 been calculated in a diverse array of studies, and shown in some cases to correlate with
105 beak dimensions (Podos 2001; Huber & Podos 2006; Ballentine 2006; Sockman 2009;
106 Derryberry et al. 2012), body mass and age (Ballentine 2009), the vigor of solicitation
107 displays or strength of spatial preference by females (Ballentine et al. 2004; Caro et al.
108 2010; see also Draganoiu et al. 2002), the strength and direction of song playback
109 responses by territorial males (Illes et al. 2006; Cramer & Price 2007; DuBois et al.

110 2011; Moseley et al. 2013; see also de Kort et al. 2009; Goodwin & Podos 2014), and
111 body condition or reproductive success (Janicke et al. 2008; Juola & Searcy 2011).

112 While vocal deviation has been widely-used as a composite index of vocal performance,
113 it is limited in two notable ways. First, it fails to account for subtle phonologically-based
114 aspects of vocal structure that may impact performance and thus hold signal value. In
115 particular, vocal deviation cannot account for frequency and temporal variations within
116 syllables, beyond calculated differences between minimum and maximum frequencies.
117 These variations include numbers and sequences of notes within syllables, rates and
118 patterns of frequency modulation within notes, and relationships between ending and
119 starting frequencies of sequential notes (e.g., Podos et al. 2009, their Fig. 1; see also
120 Geberzahn & Aubin 2014). In all of these parameters, the production of syllables or
121 syllable sequences with gradually or steadily shifting frequencies should entail less
122 vigorous motor activity than the production of syllables or syllable sequences with rapid
123 or numerous frequency shifts or reversals. A second main limitation of the vocal
124 deviation index is that it can be applied only to trilled sequences (Geberzahn & Aubin
125 2014; Cardoso 2014). While many species trill, others do not and at present we have no
126 clear guideline for quantifying non-trilled song performances, or for comparing
127 performances of songs with trilled versus non-trilled syntax.

128 In light of these limitations, we here introduce a new vocal performance index, which we
129 term "frequency excursion". The frequency excursion index, which builds upon Taft's
130 (2011, 2014) use of landmarks in spectrograph analysis, aims to account for fine-scale
131 phonological, performance-based variations in song structure, and to be applicable
132 irrespective of a vocalization's syntactical organization. Frequency excursion is

133 calculated in two steps, as described in more detail in the methods section below. First,
134 for each vocal segment of interest, we calculate peak frequencies in successive time
135 bins, thus characterizing the segment's frequency contours. Second, we sum
136 spectrogram "distances" between successive time by frequency points across the entire
137 sample, including across inter-note and inter-syllable intervals, and standardize this
138 summed distance to a per-second basis. Frequency excursion thus provides a
139 cumulative assessment of frequency modulation rates across the course of an entire
140 song or song segment. As in Gerberzahn & Aubin (2014), frequency excursion accounts
141 for the vocal performance assumed to occur during silent intervals between notes,
142 following the assumption that reconfigurations of the vocal apparatus are more
143 extensive when note transitions involve larger frequency jumps (see also Westneat et
144 al. 1993; Podos et al. 2004b; Cardoso 2014). Higher frequency excursion values
145 should correspond to more active, rapid, or extensive vocal activity (i.e., more
146 pronounced reconfigurations of the vocal apparatus per unit time), and thus indicate
147 greater required vocal performance.

148 Along with this report we are making available a program one of us (JM) has written to
149 facilitate the measurement of frequency excursion (Appendix 1). We also present
150 sample applications focusing on three diverse questions about vocal performance in
151 three songbird species (Fig. 1): chipping sparrows (*Spizella passerina*), swamp
152 sparrows (*Melospiza georgiana*), and song sparrows (*Melospiza melodia*). First, for all
153 three species we calculate correlations between vocal deviation and frequency
154 excursion, and ask how songs' distributions on regression plots correspond to their
155 spectrographic structure. Following the logic presented above, we expect that frequency

156 excursion will provide a more precise accounting of within-syllable vocal performance,
157 as inferred from spectrograms and based on assumptions about vocal mechanics. We
158 next ask, within our swamp sparrow sample, the following question: for a species with
159 song repertoires and a population that shares song types, how does song performance
160 vary within individuals versus within song types (across individuals)? As first noted by
161 Cardoso et al. (2009, see also 2012), birds with song repertoires likely vary in
162 performance levels across their song types, whereas song types that are shared among
163 birds likely attain similar performance levels across the population. As with dark-eyed
164 juncos (*Junco hyemalis*), we expect that performance variation within the repertoires of
165 individual swamp sparrows will exceed performance variation within shared song types
166 (Cardoso et al. 2009). In our swamp sparrow sample we also compare performance
167 levels of shared versus unshared song types. We predict that the vocal performance of
168 shared song types will exceed that of unshared song types, following the hypothesis
169 that shared song types provide a means for comparing multiple singers and thus might
170 be subject to enhanced sexual selection pressures (Logue & Forstmeier 2008).

171 Consistent with this prediction, Poesel & Nelson (2015) have shown that vocal
172 performance (*sensu* Forstmeier et al. 2002) is higher for shared than unshared song
173 types in Puget Sound white-crowned sparrows (*Zonotrichia leucophrys pugetensis*).

174 Finally we ask, within our song sparrow sample, whether performance levels in trilled
175 song sequences exceed those in non-trilled song sequences. This test is possible in
176 song sparrows given that their songs include both trilled and non-trilled segments
177 (Figure 1). Trill structure in numerous species has been shown to be subject to
178 performance constraints (e.g., Podos 1996; Zollinger & Suthers 2004; Suthers et al.

179 2012), and trills may thus be particularly well suited to reveal variation among males in
180 their performance abilities (e.g., Brumm & Slater 2006; Logue & Forstmeier 2008;
181 Schmidt et al. 2008; Cardoso 2013a; Petruskova et al. 2014). By contrast, limited data
182 are available regarding the performance levels of non-trilled songs. We thus propose,
183 as a working hypothesis, that in song sparrows, trilled song segments will achieve
184 higher performance levels than non-trilled song segments.

185 METHODS

186 Song sample

187 Songs of swamp and song sparrows used in this analysis were recorded from banded
188 populations in Western Massachusetts (Hampshire and Franklin County MA). Chipping
189 sparrow songs were obtained from the same region from both banded and un-banded
190 populations, with supplementary recordings obtained from the Macaulay Library at the
191 Cornell Lab of Ornithology. Field recordings were made using Marantz PMD660 digital
192 recorders (sample rate 44.1 kHz) and Sennheiser directional microphones (ME66) or
193 omnidirectional microphones (ME62) mounted in Telinga parabolas. Some of these
194 recordings were obtained in prior studies (Lahti et al. 2011, Moseley et al. 2013,
195 Goodwin & Podos 2014). Swamp sparrow and chipping sparrow songs are comprised
196 of single trills; song sparrow songs include trills interspersed with note complexes
197 (Marler & Peters 1987; illustrated in Fig. 1). For each song sparrow song, we chose the
198 longest-duration trill and the longest-duration note-complex within each song for
199 analysis. Some song sparrow trills start at a slow pace; in such cases, we only
200 measured in our analyses the final, temporally-consistent segment of the trill (e.g., Fig.

201 1E opening trill, final 3 syllables only). The three focal species vary in song type
202 repertoire sizes: individual chipping sparrows sing only a single song type; swamp
203 sparrows sing between 2 and 5 song types, and song sparrows sing about 12 to 15
204 song types. Our sample size was as follows: chipping sparrows, 54 birds, 54 song
205 types; swamp sparrows, 12 birds, 34 song types; song sparrows, 6 birds, 13 song
206 types. This listing of song type sample size does not consider whether song types were
207 shared among birds. We analyzed three renditions of each song type for chipping and
208 song sparrows, and one to five renditions of each song type for swamp sparrows.
209 Performance values measured from multiple renditions per bird of the same song type
210 were averaged prior to further statistical assessment.

211 Calculating vocal deviation

212 Vocal deviations from swamp and chipping sparrow songs, and from trilled segments of
213 song sparrow songs, were calculated using established methods (Podos 1997, 2001;
214 Huber & Podos 2006; Moseley et al. 2013). In brief, for each trill type from each bird, we
215 calculated, using SIGNAL 4.0 (Beeman 2002), two parameters: (1) trill rate (Hz) as the
216 number of syllables produced per second, measured from waveforms and spectrograms
217 using an on-screen cursor; and (2) frequency bandwidth (kHz) i.e., the difference
218 between maximum and minimum frequencies, as measured from amplitude spectra at -
219 24 dB relative to the trill's peak amplitude (illustrated in Podos 1997, see also Zollinger
220 et al. 2012). We then calculated the orthogonal distance of each trill to two family-wide
221 upper-bound regressions of trill rate (Hz) by frequency bandwidth (kHz). The first of
222 these upper-bound regressions was calculated using a standard method, in which

223 sample data were parsed into x-axis bins of equal width, and maximal values per bin
224 used for the regression calculation ($y = -0.124x + 7.55$, Podos 1997). The second
225 upper-bound regression was calculated using a 90% quantile regression method, which
226 aims to avoid biases associated with skewed sample distributions (G. Beckers, C. ten
227 Cate, & E. Meelis pers. comm., Wilson et al. 2014; $y = -0.089x + 5.96$ for the data set
228 from Podos 1997). Results from analyses using both upper-bound regressions were
229 highly similar, as indicated in several ways including very strong correlations between
230 vocal deviation values calculated by the standard and quantile methods (chipping
231 sparrows, $r=0.977$; swamp sparrows, $r=0.996$, song sparrows, $r=-0.995$; all $P < 0.001$).
232 For the remainder of the paper we report vocal deviation data based only on the first
233 method.

234 Calculating frequency excursion

236 Frequency excursion ("FEX") was calculated using an original open-source Linux
237 program, "FEX calculator" (see Appendix 1 for program code, operational notes, and
238 program website). FEX calculator queries users for three input parameters: (1)
239 frequency filter values (to filter out extraneous noise above or below those of interest);
240 (2) the selected amplitude threshold value (dB below peak threshold), below which
241 sound energy in each clip is excluded in peak frequency calculations; and (3) fft sample
242 size (# of samples per time bin). For all of our analyses here, we applied a frequency
243 filter to exclude input below 1.25 kHz or above 10 kHz, an amplitude threshold value of -
244 24 dB relative to the segment's peak frequency (the same threshold used for our vocal

245 deviation calculations), and an fft value of 256 points (which allows a frequency
246 resolution of 0.172 kHz for audio clips with a standard 44.1 kHz sample rate). Applied to
247 an input sound clip, FEX calculator generates a spectrogram (Fig. 2A) indicating all
248 points above the dB threshold (Fig. 2B) with peak frequency value points overlaid (Fig.
249 2C). While most of these points map cleanly onto song notes, others appear in the
250 intervening silences between notes, or occasionally correspond to background sounds
251 or noise. FEX calculator allows users to zoom in and delete “false” bin points as
252 assessed by eye, i.e. points that appear to correspond to background noise or other
253 sources besides the focal signal. FEX calculator then calculates and sums the linear
254 distances, on the spectrogram, between temporally adjacent points including those that
255 span silent intervals (Fig. 2D). This value, standardized for time (divided by the total
256 signal time considered) is the frequency excursion value. Frequency excursion values
257 were calculated only for 6 syllables within (the middle portions of) chipping sparrow and
258 swamp sparrow trills, and calculated across the full temporally-stable duration of song
259 sparrow trills.

260 Question 1: How do frequency excursion and vocal deviation compare as measures of
261 vocal performance?

262 For each of the three species, we calculated and tested the significance of correlations
263 between frequency excursion and vocal deviation. Note that these calculations excluded
264 non-trilled sequences in song sparrows, as vocal deviation cannot be calculated for
265 non-trills. We expected correlations between vocal deviation and frequency excursion to
266 be negative, given that higher performance songs should correspond to lower vocal

267 deviation values (i.e., shorter distances from the upper-bound maxima) and higher
268 frequency excursion values. Next, in a qualitative exercise, we plotted frequency
269 excursion as a function of vocal deviation, overlaid linear regressions, and then
270 assessed the position of sample points relative to the regression line. We expected that
271 position on these plots relative to the regression line would correspond to a trill's fine-
272 scale phonological structure, especially in terms of the extent and/or rapidity of fine-
273 scale frequency modulations. In particular we expected that trills with the abrupt and
274 rapid modulations (within-notes) and transitions (between notes) – both attributes
275 invisible to vocal deviation -- would be positioned above the regression line, whereas
276 trills with relatively smooth frequency modulations and transitions would appear below
277 the regression line.

278 Question 2: For repertoire species, what are the relationships between vocal
279 performance and song type sharing?

280 This analysis focused on swamp sparrows, which in our sample featured some song
281 types that were shared by two or more birds (with sharing determined by visual
282 assessment of spectrograms). We calculated, for each song type sung by each bird, our
283 two indices of vocal performance. Next, for each bird and song type, we calculated
284 index means, standard errors, and coefficients of variation (CV).

285 We then assessed, via ANOVA, the relative contributions of song type versus bird (i.e.,
286 within-individual versus between-individual factors) to variation in each metric of vocal
287 performance. We also calculated eta-squared effect sizes for song type and for bird, for

288 each vocal performance index. We expected that variation would be detected at both
289 bird and song type levels and that, as with dark-eyed juncos, we would observe more
290 variation between song types than between birds (Cardoso et al. 2009).

291 Finally we assessed, using Spearman rank correlations, the relationship between the
292 mean vocal performance of different song types (as measured by both indices) and the
293 number of birds in our sample who shared those song types. We calculated song
294 sharing in two ways: (i) narrowly, within our sample of analyzed songs only; and (ii)
295 broadly, including additional birds from our population whose songs were not analyzed
296 here. Our hypothesis, as outlined in the introduction, is that song types with greater
297 sharing would achieve higher performance levels than song types with less sharing.

298 Question 3: How does vocal performance vary in trilled versus non-trilled song
299 sequences?

300 This analysis focused on our song sparrow sample, a species whose songs contain
301 both trilled and non-trilled song sequences. For each song analyzed we calculated
302 frequency excursion from one note complex and one trilled sequence. There were a
303 number of decisions we had to make when calculating frequency excursion for note-
304 complexes. First, we only focused on segments of note complexes that appeared in
305 multiple renditions of songs. This was necessary given that song sparrows regularly
306 omit some segments from their note complexes across multiple renditions of a given
307 type (Podos et al. 1992). Second, when perusing of song sparrow songs for these
308 analyses, we noted an unexpectedly large proportion of songs that featured double-
309 voicing, in which two fundamental frequencies are voiced simultaneously. While this is a

310 potentially important aspect of vocal performance, our frequency excursion metric is not
311 able to account for this axis of performance, given that calculating frequency excursion
312 requires selection of a single peak frequency per time bin. We thus excluded songs
313 without double-voicing from our sample. Third, we opted to omit buzzes in our note
314 complex frequency excursion calculations. Most note complexes include buzzes,
315 defined as having amplitude modulation rates of 35 Hz or greater, and being produced
316 via pulsatile rather than mini-breath respiration (e.g., Hartley & Suthers 1989). For each
317 note complex with one or more buzzes, we calculated frequency excursion for all song
318 segments before, after, and between buzzes, and then generated a composite
319 frequency excursion value for each note complex as the sum of all resulting path
320 lengths divided by the sum of all resulting durations.

321 We tested for statistical differences between trilled and non-trilled song sequence
322 categories using a repeated-measures t-test. We predicted, as outlined in the
323 introduction, that the performance of trilled song sequences would exceed the
324 performance of non-trilled song sequences.

325

326 RESULTS

327 Frequency excursion versus vocal deviation

328 The three species examined here differed widely in vocal deviation, with chipping
329 sparrows achieving the highest performance (mean \pm SD vocal deviation scores = 1.54
330 \pm 0.76), followed by swamp sparrows (2.43 \pm 0.58) and then by song sparrows (3.42 \pm

331 1.26; ANOVA $F_{2,12} = 35.26$, $P < 0.001$, all Tukey HSD $P < 0.001$). By contrast, as
332 measured by frequency excursion, chipping and swamp sparrows achieved roughly the
333 same vocal performance levels, while song sparrows retained their lowest-performance
334 rank (chipping sparrows 146.0 ± 42.8 ; swamp sparrows 149.4 ± 47.0 ; song sparrows
335 83.0 ± 30.5 ; ANOVA $F_{2,12} = 12.73$, $P < 0.001$, Tukey HSD for chipping x song sparrow
336 and swamp x song sparrow $P < 0.001$, Tukey HSD for chipping x song sparrow $P > 0.5$).

337 For all three species, our two vocal performance indices correlated negatively with each
338 other, as expected (chipping sparrows, $r = -0.64$, $p < 0.001$; swamp sparrows, $r = -0.60$,
339 $p < 0.001$; song sparrows, $r = -0.65$, $p = 0.016$). The strength of the correlation in swamp
340 sparrows is lessened yet retains statistical significance when we remove one notable
341 high-performance outlier ($r = -0.43$, $p = 0.012$). In Figure 3 we present plots comparing
342 values generated by the two performance indices. Songs on this plot above the
343 regression lines tend to have features that we presume require high vocal performance.
344 Such features include rapid frequency modulations and large frequency jumps between
345 the end and start of successive notes (e.g., Figure 1A, C). By contrast, songs below the
346 regression lines tended to show more gradual frequency modulations both within and
347 between notes (e.g., Figure 1B, D).

348 Vocal performance variation and song type sharing

349 Our sample of swamp sparrows and their song types showed wide variation in
350 performance by both bird and song type (Table 1). Of the two performance indices,
351 frequency excursion proved better able to discern variation among the two factors

352 analyzed (birds and song types). This is shown in our results in two ways. First, an
353 ANOVA based on vocal deviation (Table 2A) failed to identify significant contributions by
354 either factor to sample-wide vocal performance variation, whereas an ANOVA based on
355 frequency excursion (Table 2B) revealed significant contributions of song type. Second,
356 inspection of effect sizes suggests that song type is a greater contributor than individual
357 bird to the overall sample variation in performance, with this difference being more
358 pronounced for frequency excursion (Table 2C). These outcomes are consistent with
359 the expectation that song types are more important than individual birds in defining a
360 population's overall vocal performance variation (Cardoso et al. 2009).

361 Frequency excursion also revealed greater differences among factors for our coefficient
362 of variation (CV) data: Vocal deviation identified similar ranges of performance variation
363 within birds (mean CV value of 22.10) and song types (mean CV value of 19.19, Table
364 1A). By contrast, frequency excursion identified substantially higher CV values within
365 birds (mean value of 27.21) than within song types (mean value of 16.69; Table 1B).
366 This provides another line of support for the hypothesis that vocal performance within-
367 types varies less than vocal performance within-birds.

368 Both performance indices covaried with song type sharing, yet in the direction opposite
369 to that predicted: song types shared by more birds were characterized by lower vocal
370 performance. When we measured song sharing within-sample only (Fig. 4 left panels),
371 the relationship approached statistical significance with the vocal deviation index
372 (Spearman rank correlation: $r_s = 0.543$, $F_{1,11} = 130.73$, $P = 0.068$), and achieved
373 statistical significance with the frequency excursion index ($r_s = -0.690$, $F_{1,11} = 483.32$, P

374 = 0.013). When we measured song sharing across the population at large (Fig. 4 right
375 panels), the relationship achieved statistical significance with both performance indices
376 (vocal deviation: $r_s = 0.465$, $F_{1,11} = 119.88$, $P = 0.048$; frequency excursion: $r_s = -0.508$,
377 $F_{1,11} = 455.19$, $P = 0.043$).

378 Trilled versus non-trilled song sequences

379 In Figure 5 we present, from our song sparrow sample, a summary of frequency
380 excursion values for both trilled and non-trilled song sequences. Frequency excursion
381 values in non-trilled song sequences exceeded those from trilled song sequences, as
382 predicted, although not at a level that was statistically significant (repeated measures t-
383 test, $df=11$, $t=1.131$, $p=0.282$).

384

385 DISCUSSION

386 Our two main goals in this paper were to introduce the frequency excursion index, and
387 to apply it to representative questions about vocal performance. A key attribute of our
388 frequency excursion index is that it characterizes not just frequency modulations within
389 notes, but also frequency transitions between notes, i.e. during the silent gaps in song.
390 As such, frequency excursion builds on the suggestion of Podos et al. (2009, their
391 Figure 1) and parallels a method developed by Geberzahn & Aubin (2014) to quantify
392 vocal performance in skylarks (*Alauda arvensis*). While we here apply the frequency
393 excursion method to songbird songs, we note that it could be applied readily to other
394 taxa and vocalizations of interest.

395 Before discussing our data and analyses it is worth emphasizing that frequency
396 excursion is not suited to capture all potentially significant aspects of vocal
397 performance. A first such example concerns modulations in amplitude, with broader
398 amplitude modulations or the ability to sing at consistently high amplitudes likely
399 indicating higher vocal performance (Forstmeier et al. 2002). Frequency excursion also
400 cannot be applied to the analysis of non-tonal sounds, in which peak frequencies cannot
401 be identified with confidence within each time bin. It thus cannot be applied readily to
402 analysis of buzzes, harmonic stacks, two-voiced sounds, or other complex vocal
403 phenomena that all likely challenge singers' performance limits (e.g., Fee et al. 1998).

404 The frequency excursion index also contains, in its construction, at least four implicit
405 assumptions about vocal mechanics: (i) more extensive frequency modulations both
406 within and between notes require higher levels of performance; (ii) frequency
407 modulations within and between notes can be scaled for performance equivalently,
408 using identical frequency by time parameters; (iii) frequency up-sweeps and down-
409 sweeps present equivalent (and thus directly comparable) production challenges; and
410 (iv) the performance required for frequency modulations varies linearly across the
411 frequency scale. These assumptions are likely oversimplified, and we welcome user-
412 guided adjustments and re-weightings in how FEX is calculated. As an illustration,
413 consider the fourth assumption above. Our decision to use a linear scale to code
414 frequency for our FEX calculations was motivated mainly by an interest in retaining a
415 common scale with spectrograms, which employ linear frequency scales and on which
416 visual descriptions of FEX calculations can be overlaid (Fig. 2). However, as was
417 recently argued by Cardoso (2013b), performance indices involving frequency

418 comparisons (including both FEX and VDEV) might also be conducted using frequency
419 data that is first log-transformed, in part because use of linear frequency scales might
420 overestimate vocal performance at higher frequencies. If, to illustrate, doubling a source
421 frequency requires similar performance across the frequency scale, then a bird
422 modulating its song from 2 kHz to 4 kHz would gain four times the performance “credit”
423 as compared to a transition from 0.5 kHz to 1 kHz. Ideally, decisions about whether to
424 log-transform frequency data before calculating performance values will be guided not
425 just by theory but also by empirical studies that explore relationships between vocal
426 mechanics and song frequency variation (e.g., Goller & Suthers 1996; Hoese et al.
427 2000; Nelson et al. 2005; Riede et al. 2006). In any case, to facilitate further exploration
428 of the outcomes of linear versus log-transformed frequency scaling, we offer users a
429 log-transformation option in FEX calculator.

430 Returning the present analyses: The first main question we asked was how the
431 frequency excursion and vocal deviation indices compare as measures of vocal
432 performance. The generally strong relationships between the two performance indices
433 indicates that they overlap in aspects of vocal performance that they capture. However,
434 inspection of the phonological structure of songs, with reference to regression plots (Fig.
435 3), illustrates how frequency excursion indeed captures additional, finer-scale aspects of
436 vocal performance. In particular, songs that map above the regression lines tend to
437 have relatively rapid frequency modulations and large frequency jumps between notes,
438 features that are overlooked by vocal deviation (e.g., Fig. 1A and C). By contrast,
439 songs with slower, more gradual frequency modulations and less abrupt frequency
440 transitions between notes map comparatively low in frequency excursion (Fig. 1B & D).

441 Both of our indices revealed species differences in vocal performance. Following vocal
442 deviation, chipping sparrows sang with the highest performance, swamp sparrows with
443 intermediate performance, and song sparrows with the lowest performance. Frequency
444 excursion also places song sparrows as the poorer performers, but lumps chipping
445 sparrows and swamp sparrows as equivalent performers. These results correspond
446 roughly to body size, with the largest-bodied species achieving the lowest performance.
447 This contrasts the results of a larger analysis of multiple sparrow species, which failed
448 to identify a body-size effect on vocal deviation (Podos 2001). Species difference in
449 vocal performance might also arise from varying strengths of sexual selection on vocal
450 performance. Consistent with this possibility are data showing that both chipping and
451 swamp sparrows attend to inter-male variation in vocal performance (as measured by
452 trill rate or vocal deviation, Moseley et al. 2013; Goodwin & Podos 2014), whereas in
453 song sparrows, song assessment seems based mainly on non-performance features
454 such as song type matching and soft song (Searcy et al 2014). With this latter point, we
455 acknowledge that further work would be needed with song sparrows to test directly the
456 potential salience of vocal performance features in song assessment in this species.

457 The next set of questions focused on song repertoires and song type sharing in swamp
458 sparrows. Swamp sparrows learn to sing by imitation, copying adults on their natal
459 grounds (Marler & Peters 1982). Birds who share song types likely learn those types
460 from different tutors, yet the structure of notes and song types tends to be conserved
461 across the species range (Marler & Pickert 1984). For this reason, song performance
462 would seem more likely to be more restricted within type than across types (within
463 birds). Indeed, our results here parallel those of Cardoso et al (2009) for dark-eyed

464 juncos: the frequency excursion index varied significantly by song type but not by bird,
465 with the effect size of song type being notably larger. Notably, these distinctions were
466 not detected by the vocal deviation metric. To the extent that song types are less
467 variable than individuals in vocal performance, the value of individual songs as
468 indicators of signaler attributes related to vocal capacity should be compromised
469 (Cardoso et al. 2009). However, our analysis did not take into account song type use,
470 i.e., whether birds tend to use songs with different performance levels in different
471 singing contexts.

472 We also detected relationships between song sharing and vocal performance, in the
473 direction opposite to that expected (and again with stronger effects for frequency
474 excursion). Overall, songs that were shared tended to be lower performance, and our
475 initial assumption that song sharing would promote the evolution of higher performance
476 (Logue & Forstmeier 2008; see also Poesel & Nelson 2015) is thus unsupported.
477 Perhaps the unshared, higher performance songs are used rarely, and reserved for the
478 most critical social interactions. Moreover, if young birds are unable to produce high-
479 performance song types with accuracy, then perhaps they preferentially crystallize
480 lower-performance songs, which would increase the prevalence of low-performance
481 songs in a population and, correspondingly, the likelihood that they would be shared. Of
482 particular interest in future work will be attention to the interplay of song performance
483 and song use in species like swamp sparrows that have song repertoires (as in DuBois
484 et al. 2011; Cardoso et al. 2012).

485 In a final sample application, we asked whether frequency excursion values were
486 greater for trilled than non-trill components of song sparrow songs. While frequency

487 excursion values were greater for trilled as compared to non-trilled song segments, in
488 the predicted direction, this difference was not statistically significant. It thus seems that
489 song sparrows do not achieve higher performance in trills, at least as measured by
490 frequency excursion. One possible explanation for this outcome is that selection on trill
491 performance in song sparrows might be comparatively weak, at least as compared to
492 our other two study species for which available data suggests that trills are both
493 mechanically limited and scrutinized in field contexts. Further studies comparing the
494 performance of trilled versus non-trilled songs or song segments should include
495 additional species, particularly those with evidence for relying on performance variation
496 in vocal communication. Nightingales (*Luscinia megarhychos*) would seem like a
497 particularly good candidate species, given that they seem to sing with high performance
498 and also produce both trilled and non-trilled song segments (Kunc et al. 2006)

499 Overall, we envision frequency excursion being applied to these and other questions
500 about vocal performance, including questions previously addressed using other
501 performance measures such as trill rate and vocal deviation. Some such questions
502 concern the relationship between ecology, morphology, and vocal signal structure (e.g.,
503 Slabbekoorn & Smith 2000; Podos 2001; Seddon 2005; Derryberry et al. 2012;
504 Ballentine et al. 2013); whether vocal performance offers a reliable indicator of signaler
505 attributes (e.g., Juola and Searcy 2011; Moseley et al. 2013; Goodwin & Podos 2014);
506 and the extent of vocal performance variation expressed in nature (Lambrechts 1997;
507 Podos 1997; Cardoso & Hu 2011; Wilson et al. 2014).

508

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721 Table 1. Song type x bird performance scores for our swamp sparrow sample (A=vocal deviation; B=frequency excursion). Descriptive statistics (mean,
 722 standard deviation, and coefficients of variation) are shown in the final 3 columns and rows. Mean CVs are as follows: Vocal deviation x bird, 22.10,
 723 Vocal deviation x song type, 19.19, Frequency excursion x bird, 27.21, Frequency excursion x song type, 16.69.

724

725 A. Vocal deviation:

726

	Bird ID														
Song Type	1	2	3	4	5	6	7	8	9	10	11	12	means:	stdev:	CV:
A	1.92												1.92		
B			2.52					2.02	2.86				2.47	0.42	17.1
C						2.2		3.42		2.02			2.55	0.76	29.9
D	2.67		2.54	2.15					2.69				2.51	0.25	10.0
E		1.78		2.35		3.15	1.94						2.31	0.61	26.6
F		2.01						2.64					2.33	0.45	19.2
G		2.15					2.98	3.42					2.85	0.64	22.6
H					2.12		2.45					2.16	2.24	0.18	8.0
I		2.49	2.92	3.32	1.93								2.67	0.60	22.4
J						1.63			2.27		2.84		2.25	0.61	26.9
K	2.49		2.46		2.89								2.61	0.24	9.2
L		0.64											0.64		
means:	2.36	1.81	2.61	2.61	2.31	2.33	2.46	2.88	2.61	2.02	2.84	2.16			
stdev:	0.39	0.70	0.21	0.63	0.51	0.77	0.52	0.68	0.30						
CV:	16.6	38.9	8.0	24.0	22.0	33.0	21.2	23.6	11.7						

727

728 Table 1 continued:

729

730 B. Frequency excursion:

731

Bird ID

Song type	1	2	3	4	5	6	7	8	9	10	11	12	means:	stdev:	CV:
A	211.2												211.24		
B			102.6					96.1	101				99.89	3.36	3.37
C						184.5		87.2		170.6			147.42	52.60	35.68
D	118.3		142.8	147.2					99.7				127.01	22.19	17.47
E		120.6		108.1		86.0	116.4						107.79	15.43	14.31
F		232.1						176.0					204.07	39.65	19.43
G		159.6					132.5	92.2					128.11	33.91	26.47
H					150.7		127.8					142.2	140.22	11.55	8.23
I		197.7	153.8	146.0	152.4								162.49	23.73	14.61
J						205.6			206.8		179.1		197.16	15.67	7.95
K	139.5		176.8		121.3								145.87	28.29	19.39
L		297.7											297.71		

means:	156.4	201.6	144.0	133.8	141.4	158.7	125.6	112.9	135.8	170.6	179.1	142.2
stdev:	48.7	68.0	31.0	22.2	17.5	63.9	8.3	42.2	61.4			
CV:	31.1	33.8	21.6	16.6	12.4	40.2	6.6	37.4	45.2			

732

733 Table 2. Two-way ANOVA (Type III) results and effect sizes for swamp sparrow data, for our two performance
 734 indices.

735 A. Vocal deviation

Factor	Df	SS	F value	<i>p</i> -value
bird	11	3.174	1.191	0.388
song type	11	4.347	1.631	0.215
residuals	11	2.665		

736

737 B. Frequency excursion

Factor	Df	SS	F value	<i>p</i> -value
bird	11	10321	1.931	0.145
song type	11	43586	8.155	<0.001
residuals	11	5345		

738

739 C. Effect sizes

Factor	Eta-sq vocal deviation	Eta-sq frequency excursion
bird	0.302	0.142
song type	0.413	0.597

740 FIGURE LEGENDS

741 Figure 1. Spectrograms of two songs for each of our three study species. Chipping sparrow songs (A & B)
 742 and swamp sparrow songs (C & D) are entirely trilled, whereas song sparrow songs (E & F) feature
 743 trilled sequences interspersed with "note complexes" (groups of notes produced in a non-trilled
 744 organization, Marler & Peters 1987; transitions between trills and note complexes are marked with red
 745 arrows). Note that the swamp sparrow songs shown here include prominent background noise;
 746 syllables with prominent background noise are excluded from performance calculations. Scale: x-axis =
 747 0-3 seconds, y-axis = 0-10 kHz.

748

749 Figure 2. Plots illustrating how frequency excursion is calculated, for a single song clip, in FEX calculator.

750 (A) Greyscale spectrogram of song segment from a male Adelaide's warbler, recording courtesy of
 751 David Logue. The clip is 0.65 s in duration, and the y-axis shown (zoomed in here for illustration
 752 purposes) ranges from 2.05 to 8.03 kHz. (B) All points from this clip with energy above our dB threshold,
 753 and thus eligible to be included in the frequency excursion calculation. Note that most but not all
 754 background noise is excluded in this step; (C) The highest amplitude points per time bin, after manual
 755 de-selection of candidate highest-amplitude points that the user identified as having captured noise or
 756 inter-note intervals rather than actual vocal output; (D) Highest-amplitude points now connected by line
 757 segments. The cumulative length of the line segments divided by total time interval is the frequency
 758 excursion value. For this song segment, the cumulative path length is 45.17, segment duration (first to
 759 last highest-amplitude points) is 0.607 s, and the resulting frequency excursion value is 74.42.

760

761 Figure 3 . Frequency excursion as a function of vocal deviation for our three study species. Song types with
 762 open circles and labels (A – F) are those illustrated in Figure 1. For song types above the regression
 763 lines (e.g., A, C, and E), vocal performance as measured by frequency excursion exceeded that
 764 predicted by vocal deviation alone, whereas song types below the regression lines (e.g., B, D, and F) fell
 765 short of performance levels predicted by vocal deviation alone.

766

767 Figure 4. Average vocal performance of swamp sparrow song types plotted against the number of birds in
768 our sample who shared those types. Left panels show data when song sharing is calculated within the
769 sample only, and right panels show data when song sharing is calculated across the population at large.
770 In all cases, song performance declines as the incidence of song sharing increases. The relationship
771 approaches statistical significance for the upper left panel data, and achieves statistical significance for
772 the other three panels (see text). The direction of the observed relationship contradicts our expectation
773 that shared song types would tend to require higher performance.

774 Figure 5. Frequency excursion values for trilled and non-trilled song sequences from our song sparrow
775 sample. Values shown are medians, 1st and 3rd quartiles, non-outlying minima and maxima, and one -
776 outlier.

777

778

779

780

781 Appendix 1: FEX calculator

782 **Appendix 1: FEX Calculator**

783

784 **1 Installation**

785

786 FEX calculator is freely available and licensed under an open source license. Currently FEX calculator
 787 is designed to run on a linux system. Experienced Mac OSX (with X11) users may be able to run it as
 788 well, though this is not currently supported. The source code, along with up to date information on
 789 building, installing, configuring, and using FEX calculator can be retrieved from
 790 <http://behaviorenterprises.com/software.html?pkg=FEX>. After installation you may wish to add a
 791 shortcut to the desktop file provided with the program (installed as /usr/
 792 share/applications/fex.desktop) in your preferred dock, launcher, menu, or on the desktop.

793

794

795 **2 Configuration**

796

797 FEX calculator can be configured by editing a run-time configuration file in any plain-text editor. A
 798 default config-uration file is distributed as /usr/share/fex/config. This file should not be edited; it
 799 can be copied to \$XDG_CONFIG_HOME/fex/config or \$HOME/.config/fex/config and edits can be made
 800 to the local copy. Read the default configuration file for a complete and up-to-date description of the
 801 available options.

802

803

804

805

805 **2.1 One-time settings**

806

807 Each laboratory, or each project that uses FEX calculator, should select values for the following
 808 options that will be used for all data to be included in the project. Changes in these values can alter the
 809 resulting Frequency Excursion values reported, and sometimes substantially so.

810

811 **bandpass** bandpass filter applied to audio before any processing is done. The values are for the low
 812 and high cutoffs in KHz.

813

814 **threshold** value — in decibels below the peak amplitude of the recording — below which points will be
 815 excluded from the analysis. Points above this cutoff are only *candidates* for inclusion in the analysis
 816 and will be included if the point is the highest amplitude of the points remaining in the time bin
 817 after extraneous points have been *erased*.

818

819 **samples** number of samples per time bin for the FFT. It is recommended to set this relative to the sample
 820 rate of the audio recordings: for 44.1 KHz audio use 256; for 22.05 KHz use 128. More generally,
 821 this should be the sample rate (in KHz) times 5.805.

822

823

823 **2.2 Adjustable settings**

824

825 The following settings can be adjusted at any time as desired. These settings will allow each user
 826 to customize the interface to their liking. Changes to these settings will not affect the calculation of
 827 Frequency Excursion values. The colors and fonts of various elements of the user interface can also
 828 be specified in the configuration file. Details on color and font settings can be found in the default
 829 configuration file.

830

831 **window** windowing function for the fft. This can be set to any of the following: hanning, hamming,
 832 blackman, nutall, blackman-nutall, blackman-harris, rectangular, or custom. If 'custom' is specified

833 it can be followed by up to 4 floating point numbers specifying the coefficients for a generalized
 834 cosine windowing function.

835
 836 **floor** sound floor for the spectrogram display, in dB below the maximum amplitude. Higher values are
 837 more inclusive and will produce a darker background spectrogram.

838
 839 **scale** number of graphical units per data unit. Higher values will provide a greater visual resolution
 840 making it easier to differentiate separate points. Higher values will, however, also use more system
 841 memory.

842
 843 **help** command executed to display the online help window — this should likely only be changed to select
 844 the default terminal emulator if xterm is not installed.

845
 846 **color** colors for the interface are specified with five floating point values from 0.00 to 1.00 specifying the
 847 red, green, and blue components of the color followed by the alpha (opacity) level and a width/size
 848 parameter.

849

850

851 3 Usage

852

853 3.1 Overview

854

855 The *FEX calculator* package contains two executable files: the compiled binary **fex** and a python script
 856 front-end **fex-gtk**. In most cases, only **fex-gtk** should be used directly. Details of **FEX calculator** are
 857 provided in the manual page distributed with the software.

858 **Fex-gtk** is a front-end of the program that facilitates batch processing of large numbers of wave files.
 859 **Fex-gtk** can be provided a list of file names, or can be run with no parameters to trigger a dialog window
 860 to select wave files. **FEX calculator** will be run on each input file, and the results can either be stored to a
 861 data file or displayed in a dialog window upon completion.

862 **Fex-gtk** is also the executable target of **fex.desktop** which is distributed with *Fex*. **fex.desktop**
 863 allows for drag-and-drop operation of *Fex*. The desktop file can accept any number of wave files as a
 864 drop target.

865

866

867 3.2 Starting FEX calculator

868

869 Assuming a shortcut to **fex.desktop** has been added to the desktop or your preferred launcher/dock,
 870 you can drag any number of wave files from your file manager and drop them on the icon. FEX calculator
 871 will process one file at a time.

872

873 3.3 Analysis: step-by-step

874

875 The steps below outline a recommended approach to analysing a song in *FEX calculator*. The key
 876 binding or controls for each step are listed as bullet points under that step. Many controls specify a
 877 direction which can be indicated with the keyboard arrow keys, home-row directional keys (h, j, k, l),
 878 or with a 2-axis mouse scroll-wheel. Many controls also specify a modifier key to be held down with the
 879 key or directional indicator. Press 'F1' at any time in *Fex* to open a help window outlining these and other
 880 controls.

881

882 1. **Crop** out the region of interest. Everything outside of the selected region will be ignored for the
 883 remainder of the calculation. Use this function to select the elements of interest: a set of repeated
 884 syllables, a note, or a full song.

885

886

887

888

889

- 'c' or "crop" button on the tool window
- right-click on the "crop" button to return to the original full signal

- 890 2. Optionally adjust the **floor** value as desired. This will only affect the display of the background
 891 spectrogram.
 892
- 893 • Control+Shift+Left for darker spectrogram
 - 894
 - 895 • Control+Shift+Right for lighter spectrogram
 - 896
- 897 3. Adjust the **threshold** if needed. *Caution:* this will affect the calculation of frequency excursion as
 898 it will make the calculation more or less inclusive. Most projects should select a standard threshold
 899 that will be held constant across all audio samples analyzed.
 900
- 901 • Control+Shift+Up for a higher more-exclusive threshold
 - 902
 - 903 • Control+Shift+Down for a lower threshold
 - 904
- 905 4. **Erase** extraneous points and/or noise. Any of the following may aid in differentiating signal from
 906 noise and may be used as needed in any order to clean up the signal.
 907
- 908 (a) **Zoom** in as needed.
 909
- 910 • Control+Up or Control+Down to zoom in/out
 - 911 • Up, Down, Left, or Right to pan while zoomed in
 - 912
- 913 (b) **Toggle** visibility of the points and lines overlay to view the regular spectrogram.
 914
- 915 • 't' to toggle
 - 916
- 917 (c) **Play** the signal. Note that this plays only what is in the current view. If you have zoomed in
 918 this will not play the full signal being analyzed, but only the portion zoomed in to.
- 919 • 'p' to play
 - 920 • Shift, Control, or Alt and 'p' to play at slower speeds
 - 921
- 922 (d) Adjust **point** or **line** sizes.
 923
- 924 • Shift+Up or Shift+Down for larger/smaller points
 - 925 • Shift+Left or Shift+Right for thinner/wider lines
 - 926
- 927 (e) **Erase**. Pay particular attention to reverberation between syllables, harmonics above the sig-
 928 nal, and any low-frequency noise not removed by the bandpass filter.
- 929 • 'e' or "Erase" button on the tool window toggle to the eraser
 - 930 • Alt+Up or Alt+Down for a larger/smaller eraser
 - 931 • Alt+Left or Alt+Right for a taller/wider eraser
 - 932 • Once in erase mode, the left mouse button will remove any points under the eraser cursor.
 933 You can drag while holding the mouse button to erase an area
- 934 (f) If you unintentionally erase, you can **undo** up to 7 steps.
 935
- 936 • 'u' to undo
 - 937
- 938 5. **Zoom out** for a full overview and **adjust** points and lines to ensure nothing was missed. Sometimes
 939 a stray point (often from a harmonic) might be easy to miss — substantially larger/heavier points
 940 and lines will make such points stand out.
 941
- 942 • Control+Down to zoom all the way out
 - 943
 - 944 • Shift+Up or Shift+Down for larger/smaller points
 - 945
 - 946 • Shift+Left or Shift+Right for thinner/wider lines
 - 947
- 948 6. **Exit**, the frequency excursion value displayed in the tool-window when the program exits will be
 949 recorded and optionally saved to a data file (see next section). You may also discard the value for
 950 the current signal and output an 'NA' instead — this is useful if you determine the recording was not
 951 of sufficient quality to get an accurate measure.
 952

- Control+q to exit normally saving the value
- Control+Shift+q to exit and discard the value (output an 'NA')

3.4 Saving data

If you selected multiple wave files for analysis (dropped multiple files on the icon, or selected multiple files from the file dialog) FEX calculator will prompt you to save the results as a tab-separated data sheet which can be imported into any data analysis program. If you selected only a single file, the resulting frequency excursion value will be displayed in a dialog box and will not be recorded in any data file.

4 Code excerpts

4.1 Fourier Transformation

4.1.1 Data Structures

The data structure for the Fourier transformation is defined in *fx.h* as shown below. The **freq** and **time** variables are arrays of length **nfreq** and **ntime** respectively. These arrays store the frequency in Hz of each frequency step and the time in seconds of each time bin. The two dimensional array **amp** stores the amplitude values in decibels relative to the signal peak for each time-frequency point. The simple variables **max** and **min** store the highest and lowest amplitude values for the full signal. The final two dimensional array **mask** records which points in **amp** have been erased (each time-frequency point is represented by an 8-bit mask allowing for up to 8 undo-levels in erasing).

```

981 typedef struct FFT {
982     double **amp;
983     double *time;
984     double *freq;
985     double max, min;
986     int nfreq, ntime;
987     char **mask;
988 } FFT;
989

```

This **FFT** data structure is filled via the **create_fft** function in *fft.c* as described below. First, memory is allocated for each of the data elements. The number of frequency bins (the frequency resolution) is directly dependent on the window length of the Fourier transformation as selected in the configuration file. The number of time bins depends on the number of samples in the audio file (the sample rate times the duration) and the configured hop size.

```

990 #define FFTW_FLAGS FFTW_FORWARD, FFTW_ESTIMATE
991
992 FFT *create_fft(Wave *wav) {
993     /* allocate memory */
994     FFT *fft = (FFT *) calloc(1, sizeof(FFT));
995     fft->nfreq = conf.winlen/2 + 1;
996     fft->ntime = wav->samples/conf.hop;
997     fft->amp = (double **) calloc(fft->ntime, sizeof(double *));
998     fft->time = (double *) calloc(fft->ntime, sizeof(double));
999     fft->freq = (double *) calloc(fft->nfreq, sizeof(double));
1000     fft->mask = (char **) calloc(fft->ntime, sizeof(char *));
1001

```

Next, the Nyquist frequency is calculated from the sample rate, and the step sizes for the **freq** and **time** arrays are calculated. These step sizes are used to fill the arrays.

```

1002 /* calculate step sizes and fill time/freq arrays */
1003 double nyquist = (double) wav->rate / 2000.0;
1004 double df = nyquist / fft->nfreq;
1005 double dt = (double)wav->samples / (double)(wav->rate * fft->ntime);
1006

```

```

1014     double f, t;
1015     int i, j;
1016     for (i = 0, f = 0.0; i < fft->nfreq; i++, f += df) fft->freq[i] = f;
1017
1018     for (i = 0, t = 0.0; i < fft->ntime; i++, t += dt) fft->time[i] = t;
1019
1020
1021

```

4.1.2 Calculation

The `create_fft` function next prepares the data for a call to the `fftw` library by allocating memory for the input and output data structures for `fftw`. In order to properly window the FFT data for `fftw` a multiplier array is filled based on the selected windowing function. Any 4-parameter cosine function can be used — the default is a *hanning* window with the values 0.5, 0.5, 0, 0.

```

1029     /* prepare fftw */
1030     fftw_complex *in, *out;
1031     fftw_plan p;
1032     in = (fftw_complex *)fftw_malloc(conf.winlen * sizeof(fftw_complex));
1033     out = (fftw_complex *)fftw_malloc(conf.winlen * sizeof(fftw_complex));
1034     p = fftw_plan_dft_1d(conf.winlen, in, out, FFTW_FLAGS);
1035     /* create windowing function */
1036     double window[conf.winlen];
1037     double *a = conf.win->a;
1038     double wl = conf.winlen;
1039     for (i = 0; i < conf.winlen; i++)
1040         window[i] = a[0] - a[1] * cos(2 * M_PI * (i / (wl - 1.0))) +
1041                 a[2] * cos(2 * M_PI * (i / (wl - 1.0))) -
1042                 a[3] * cos(2 * M_PI * (i / (wl - 1.0)));
1043

```

Calculation continues by looping over all the time bins and first allocating memory for the amplitudes (and mask values) for each time bin. The windowing function created above is used to copy a block of the signal data into the input for `fftw`. This windowed data is passed to `fftw` and the results are stored in one column of the amplitude matrix (as the absolute values of the complex-valued result).

```

1049     /* loop over signal */
1050     int pos;
1051     for (pos = 0, j = 0; pos < wav->samples; pos += conf.hop, j++) {
1052         fft->amp[j] = (double *) malloc(fft->nfreq * sizeof(double));
1053         fft->mask[j] = (char *) calloc(fft->nfreq, sizeof(char));
1054         /* copy windowed chunk to data */
1055         for (i = 0; i < conf.winlen; i++) {
1056             if (pos + i < wav->samples) {
1057                 in[i][0] = wav->d[pos + i] * window[i];
1058                 in[i][1] = 0.0;
1059             }
1060             else {
1061                 in[i][0] = 0.0;
1062                 in[i][1] = 0.0;
1063                 goto doublebreak;
1064             }
1065         }
1066         /* calculate fft & fill amp matrix */
1067         fftw_execute(p);
1068         for (i = 0; i < fft->nfreq; i++)
1069             fft->amp[j][i] = sqrt(out[i][0] * out[i][0] +
1070                               out[i][1] * out[i][1]);
1071     }
1072

```

After all time bins have been processed, any remaining time bins are zeroed out. Any values outside the hi and low pass filter settings are also zeroed out.

```

1075
1076
1077 doublebreak:
1078     fftw_destroy_plan(p);
1079     fftw_free(out);
1080     fftw_free(in);
1081     /* fill and zero unused bins */
1082     for ( ; j < fft->ntime; j++) {
1083         fft->amp[j] = (double *) calloc(fft->nfreq, sizeof(double));
1084         fft->mask[j] = (char *) calloc(fft->nfreq, sizeof(char));
1085     }
1086     /* band pass filter */
1087     for (i = 0; i < fft->ntime; i++) {
1088         for (j = 0; j < fft->nfreq && fft->freq[j] < conf.hipass; j++)
1089             fft->amp[i][j] = 0;
1090         for (j = fft->nfreq - 1; fft->freq[j] > conf.lopass; j--)
1091             fft->amp[i][j] = 0;
1092     }

```

Finally, the maximum amplitude is found, then all amplitude values are divided by this maximum and converted to decibels. The maximum (always zero) and minimum amplitudes relative to the peak are stored for later use in the spectrogram creation.

```

1096
1097     /* normalize, log transform, and scale to dB */
1098     fft->max = fft->min = 0.0;
1099     for (i = 0; i < fft->ntime; i++) for (j = 0; j < fft->nfreq; j++)
1100         if (fft->amp[i][j] > fft->max) fft->max = fft->amp[i][j];
1101     for (i = 0; i < fft->ntime; i++) for (j = 0; j < fft->nfreq; j++) {
1102         fft->amp[i][j] = 10.0 * log10(fft->amp[i][j] / fft->max);
1103         if (fft->amp[i][j] < fft->min && fft->amp[i][j] > -900)
1104             fft->min = fft->amp[i][j];
1105     }
1106     fft->max = 0.0;
1107     return fft;
1108 }
1109

```

4.2 Frequency Excursion Calculation

4.2.1 Data Structures

The data structure for the frequency excursion calculation is defined in the **Spectro** structure in *fex.h* as shown below. Several variables in this structure store spectrogram image data, as well as the points and lines overlays. Most relevant to the calculation are the variables **pex**, the path length of the lines, **text**, the time span of the lines, and **fex** which is the path length divided by the time span.

```

1122 typedef struct Spectro {
1123     const char *fname;
1124     char *name;
1125     unsigned char *a_spec, *a_thresh;
1126     cairo_surface_t *m_spec, *m_thresh, *s_points;
1127     FFT *fft;
1128     int fft_x, fft_y, fft_w, fft_h, fft_lo, fft_hi;
1129     double pex, tex, fex;
1130 } Spectro;
1131

```

This **Spectro** data structure is filled via the **spectro_points** function in *spectro.c* as described below. First, previous image data elements are reset as needed, then local variables **lt** and **lf** (representing “last” or previous time and “last” or previous frequency) are set to the first time bin and first frequency value at the start of the signal. Next **pex** and **tex** are zeroed.

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```

126 int spectro_points() {
    if (spect->s_points) cairo_surface_destroy(spect->s_points);
128 spect->s_points = cairo_image_surface_create(CAIRO_FORMAT_ARGB32,
    spect->fft_w * conf.scale, spect->fft_h * conf.scale);
130 cairo_t *p = cairo_create(spect->s_points);
    cairo_t *l = cairo_create(spect->s_points);
132 set_color(p, RGBA_POINTS);
    set_color(l, RGBA_LINES);
134 int i, j, f;
    double lt = spect->fft->time[0], lf = spect->fft->freq[0];
136 spect->pex = 0.0;
    spect->tex = 0.0;
  
```

4.2.2 Calculation

The **spectro_points** function continues by looping through every time bin in the signal. In each time bin, point with the maximum amplitude that has not been erased (i.e. masked) is found. If this point is above the minimum threshold selected, this point is added to the calculation by finding the distance from the coordinate **lt**, **lf** to the current point's time-frequency coordinate. **lt** and **lf** are then set to this current point to be the starting point of the next line segment. Lastly, the cumulative **pex** value is divided by the cumulative **tex** value to get the **fex** or frequency excursion value. Function calls starting with **cairo_** are graphics functions for recreative the visual display but do not contribute to the calculation of frequency excursion.

```

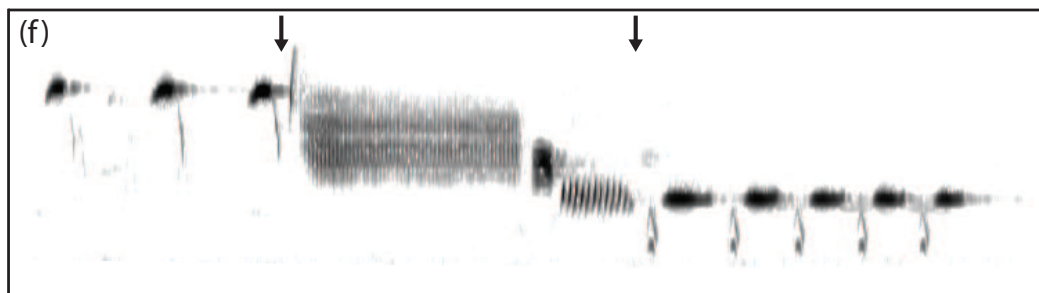
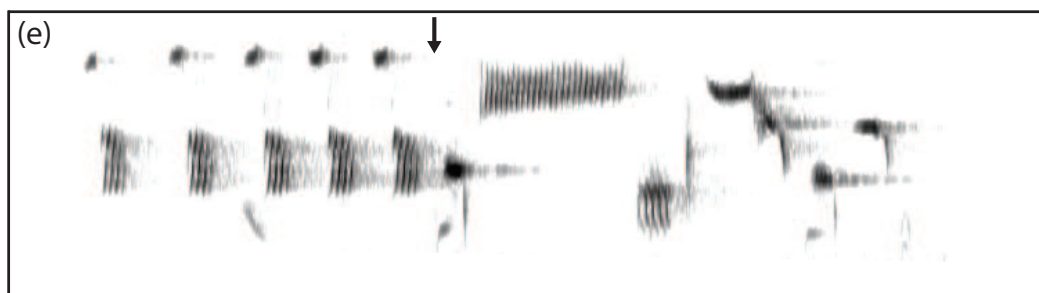
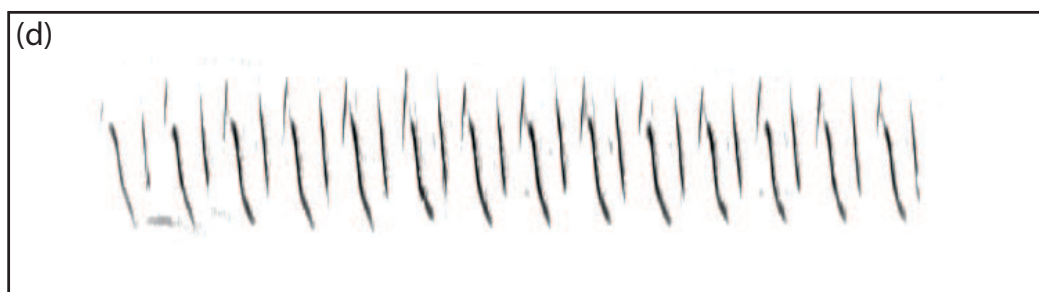
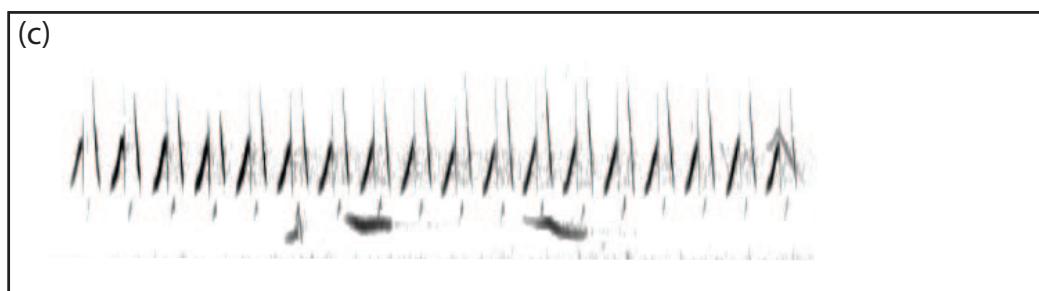
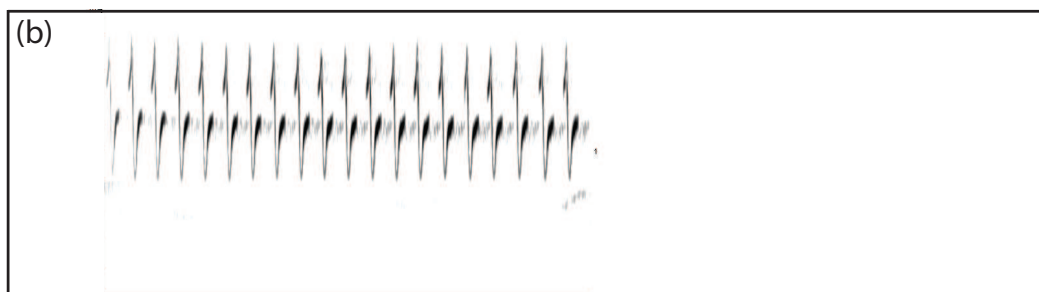
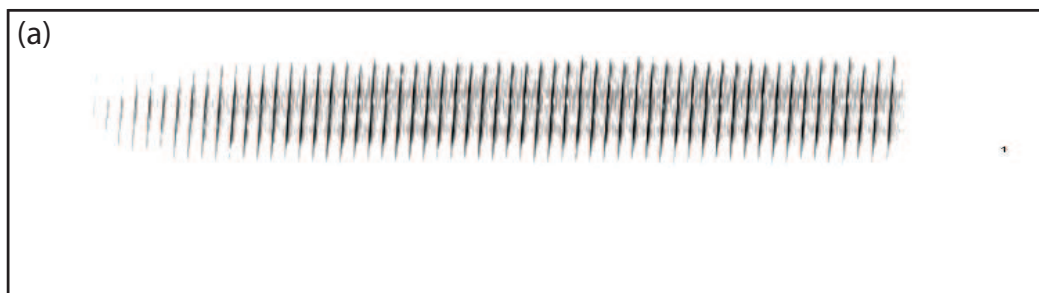
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1186
1187
1188
1189
1190
1191
1192
1193
1194
1195
1196
1197
1198
1199

138  /* loop through time bins */
139  for (i = spect->fft-x; i < spect->fft-w + spect->fft-x; i++) {
140      /* find maximum (non masked) frequency in time bin */
141      for (f = 0, j = spect->fft-y; j < spect->fft-h+spect->fft-y; j++) {
142          if (spect->fft->mask[i][j]) continue;
143          if (spect->fft->amp[i][j] > spect->fft->amp[i][f] || !f)
144              f = j;
145      }
146      /* add points and do calculations if f is above threshold */
147      if (f > 0 && spect->fft->amp[i][f] > conf.thresh) {
148          if (lt != spect->fft->time[0]) {
149              spect->pex += sqrt(
150                  (spect->fft->freq[f] - lf) * (spect->fft->freq[f] - lf) +
151                  (spect->fft->time[i] - lt) * (spect->fft->time[i] - lt) );
152              spect->tex += spect->fft->time[i] - lt;
153          }
154          lt = spect->fft->time[i];
155          lf = spect->fft->freq[f];
156          cairo_line_to(l,
157                      (i - spect->fft-x) * conf.scale + conf.scale / 2,
158                      (f - spect->fft-y) * conf.scale + conf.scale / 2);
159          cairo_new_sub_path(p);
160          cairo_arc(p,
161                  (i - spect->fft-x) * conf.scale + conf.scale / 2,
162                  (f - spect->fft-y) * conf.scale + conf.scale / 2,
163                  conf.col[RGBA_POINTS].w, 0, 2*M_PI);
164      }
165      spect->fex = spect->pex / spect->tex;
166  }
167  cairo_fill(p);
168  cairo_stroke(l);
169  cairo_destroy(p);
170  cairo_destroy(l);
171  return 0;
172 }

```

Figure 1 rev

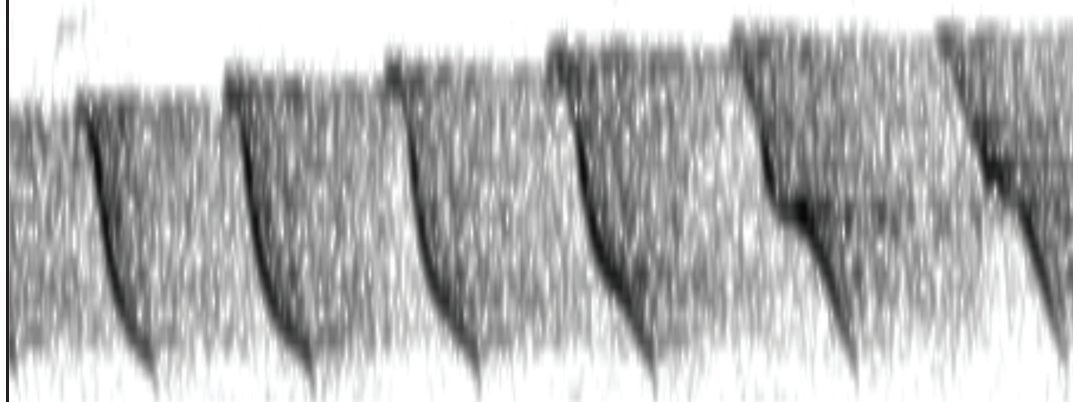
Frequency



Time

Figure 2

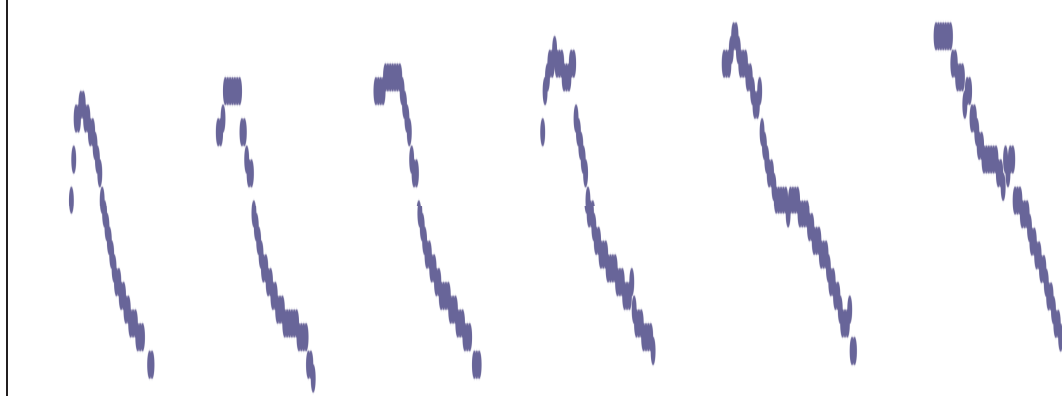
A



B

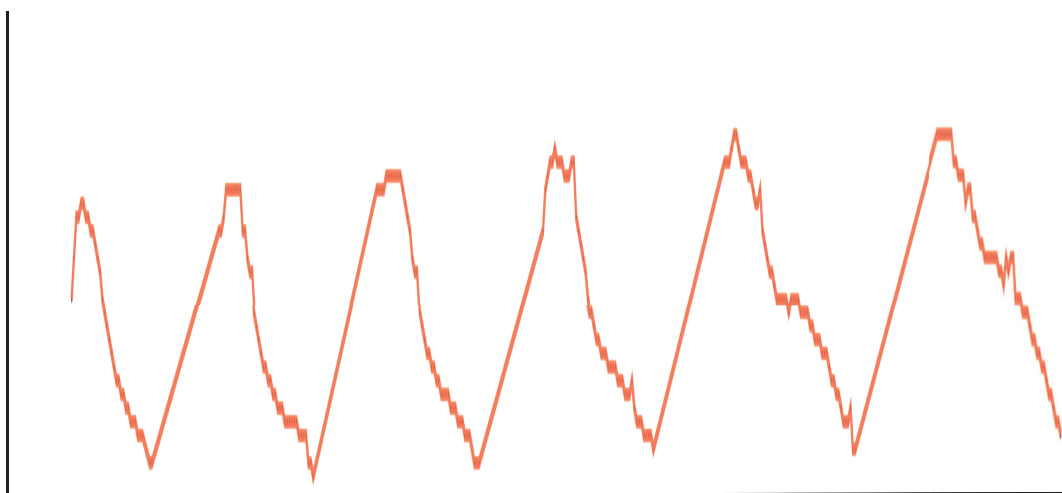


C



D

frequency



time

Figure 3

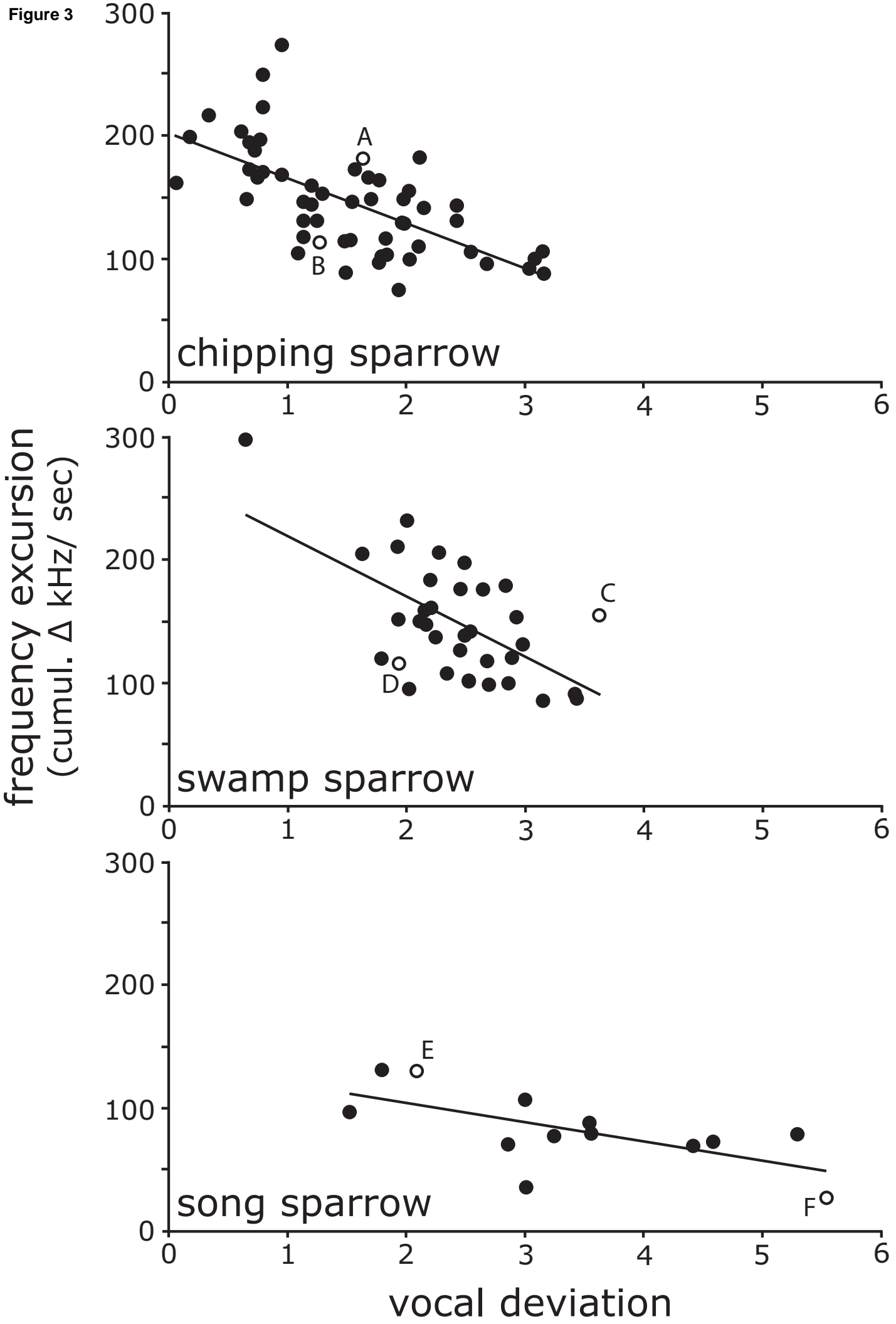


Figure 4

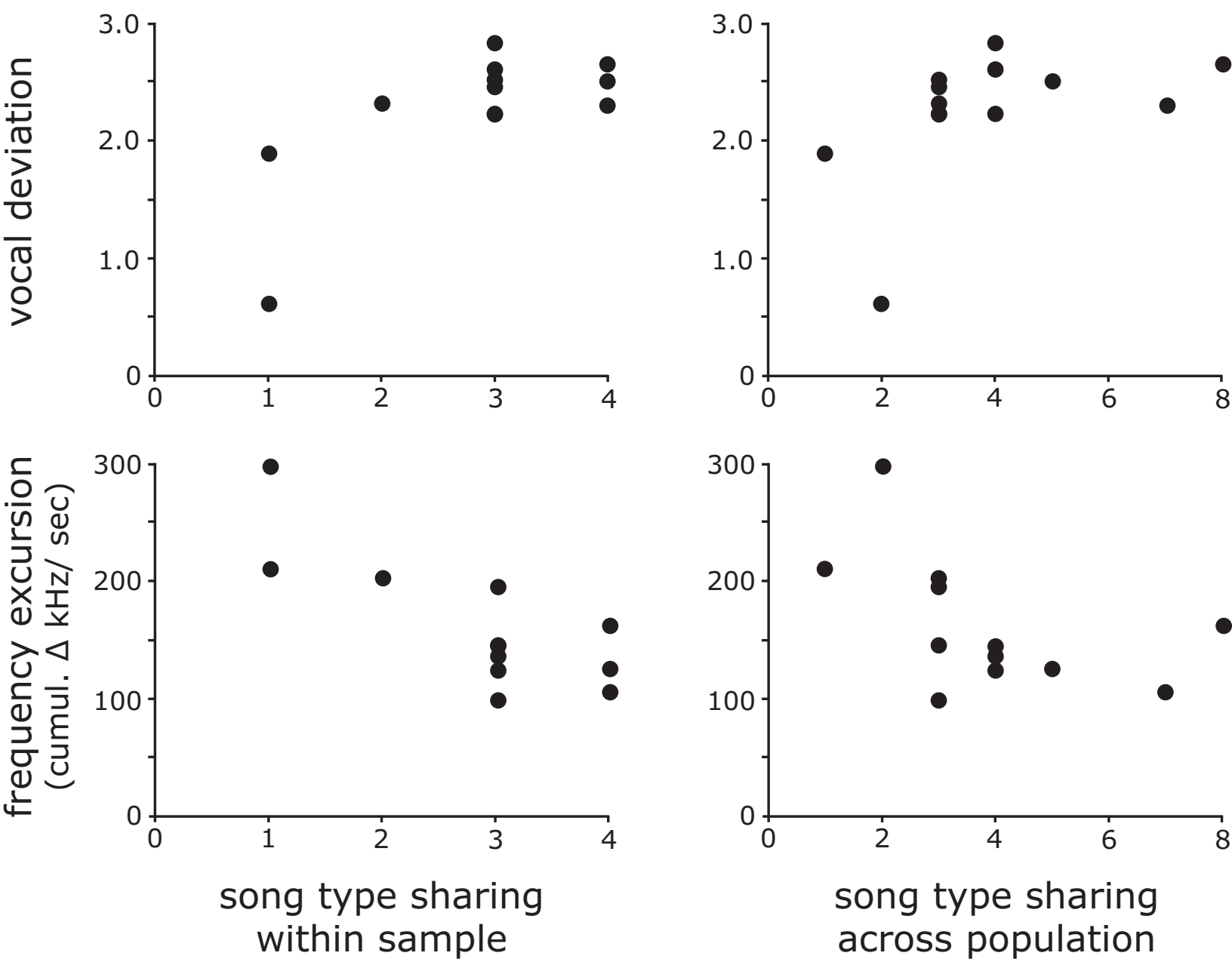


Figure 5

