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Whistling shares a common tongue with speech: Bioacoustics from real-time MRI of the human vocal tract

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Data

It is a condition of publication that data, code and materials supporting your paper are made publicly available. Does your paper present new data?:

Yes

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Data and code are available from the Dryad repository.

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M.B. conceived of the study, designed the study, analysed the data and drafted the manuscript; B.G.S and J.C. helped design the study and provided analytical support, D.B. contributed to drafting the manuscript. S.A.K. contributed to the design of the study. All authors contributed comments and critical revisions.

1 **Whistling shares a common tongue with speech: Bioacoustics from real-**
2 **time MRI of the human vocal tract**

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25

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34
35

Abstract

36 Most human communication is carried by modulations of the voice. However, a
37 wide range of cultures have developed alternate forms of communication that
38 make use of a whistled sound source. For example, whistling is used as a highly
39 salient signal for capturing attention, can have iconic cultural meanings such as
40 the wolf-whistle, enact a formal code as in boatswain's calls, or stand as a proxy
41 for speech in whistled languages. Despite the versatile role of whistling in human
42 communication, the bioacoustics of whistling remain unclear. We used real-time
43 magnetic resonance imaging to examine the muscular control of whistling. We
44 found strong associations between the shape of the tongue and the whistled
45 frequency. This bioacoustic profile parallels the use of the tongue in vowel
46 production. This is consistent with the role of whistled languages as proxies for
47 spoken languages, in which one of the acoustical features of speech sounds are
48 substituted with a frequency modulated whistle. Furthermore, previous evidence
49 that non-human apes may be capable of learning to whistle from humans
50 suggests that these animals may have similar sensorimotor abilities to those that
51 are used to support speech in humans.

52

53

54 **Introduction**

55 Whistling produces a loud-pitched sound that approximates a high-amplitude and
56 high-frequency sine-wave. These sounds travel well over large distances and are
57 easy to discern from other biological sounds by the rare occurrence of pure tone
58 sine waves in nature. Frequency modulated whistles are all-the-more salient for
59 being unlikely to result from geophysical phenomena, such as the wind whistling
60 over inanimate objects. These features have made whistling a viable alternative
61 sound source for human communication when signal fidelity may be more
62 important than signal complexity.

63 Whistling may be a more robust channel in contexts where the voice may be
64 unreliable, such as communication over long distances or in poor weather. For
65 example, naval vessels maintain a traditional code of boatswain's calls, in which
66 arbitrary combinations of whistles correspond to simple commands [1,2].
67 Furthermore, a number of cultures have developed whistled proxies of spoken
68 language [3]. In these languages, the whistled frequency stands in for one of
69 acoustical feature that would normally be carried by the voice [3–5]. Whistled
70 languages encode less information from which to identify the intended speech
71 sounds than voiced speech (Figure 1), but are more robust to long distance
72 communication. The narrow frequency band of the whistle gives it more power
73 per unit of spectral bandwidth, increasing its signal-to-noise ratio and the
74 effective range of communication [6–8].

75 Whistles are physical phenomena that occur when airflow interacts with objects
76 to produce a positive feedback loop. For example, the hole-tone whistle is
77 produced when air flowing through a constriction creates a jet of quick moving air
78 surrounded by comparatively still air [9–11]. Disturbances at the surface of the jet
79 form a ring-shaped vortex that propagates downstream. Pressure fluctuations
80 travel upstream back through the constriction that produced the jet of air. When
81 these pressure fluctuations reach a resonant cavity, wavelengths that match the
82 size of the resonator are selectively amplified. These amplified fluctuations pass
83 back through the constriction when they contribute to the ring-shaped vortex and
84 form a periodic wave. The perceptual property of this periodic waveform is the
85 pitch of the whistle.

86 In many cases, whistled codes are produced with the aid of the hands or an
87 instrument, but the most basic form of whistling is the bilabial whistle. Though
88 common knowledge suggests that whistling is primarily determined by the action
89 of the lips, the tongue may have an active role. Shadle [9] hypothesized that the
90 lips form a constriction through which a jet of air is forced and that a resonant
91 cavity behind the lips and bounded by the tongue determines the frequency that
92 is whistled.

93 The tongue is a muscular organ that is divided into extrinsic and intrinsic muscle
94 groups [12,13]. The extrinsic lingual muscles originate in osseous structures,
95 such as the mandible and hyoid bone, and insert in the body of the tongue with
96 the primary function of changing the tongue's position. The intrinsic lingual
97 muscles make up the body of the tongue itself and serve to reconfigure the

98 shape of the tongue to produce the dexterous movements required by both
99 swallowing and speaking. The human tongue in particular receives dense and
100 complex innervation, which may support fine motor-control [14–16]. The
101 changing shape of the tongue is used during speech to create narrow
102 constrictions in the oral cavity that divide the vocal tract into a series of resonant
103 cavities [17–19]. Together these cavities selectively amplify a combination of
104 frequency bands that encode the physical basis for the vowel sounds of speech
105 [20,21].

106 Two previous studies provide anecdotal support for the role of the tongue in
107 whistling. Kaburagi et al. [22] used magnetic resonance imaging to gather still
108 images of one individual whistling at four discrete frequencies. Qualitatively, it
109 appeared from these images that the configuration of the tongue varied by the
110 frequency being whistled in a manner that was grossly similar to the production
111 of vowels. Azola et al. [23] gathered dynamic cineradiographic images of bilabial
112 whistling in two individuals, providing further qualitative evidence that the space
113 between the tip of the tongue to the incisors forms a resonant cavity as with
114 speech.

115 We used real-time anatomical MRI to collect videographic data of whistling from
116 a continuous whistled-siren, a music-like discrete chromatic scale, and a complex
117 call with culturally imposed meaning. We produced data-driven models of tongue
118 shapes using functional principle components analysis to quantify the changing
119 shape of the tongue and provide an empirical test of the tongue's role in
120 whistling.

121

Methods122 *Participants*

123 Six participants (three male, including authors MB and BS) with no speech-motor
124 or auditory deficits were recruited from Maastricht University. Participants had
125 varied cultural backgrounds including German, Dutch, Canadian, Australian, and
126 American and ages ranging from 20 to 33.

127 *Procedure*

128 Each participant performed a battery of sound production tasks while undergoing
129 real-time magnetic resonance imaging (rtMRI). In separate runs, each participant
130 was instructed to 1) whistle a continuous siren spanning the range of frequencies
131 that they could reliably produce, 2) whistle a chromatic scale of discrete notes
132 over the same range, and 3) produce a whistle with conventionalized meaning (a
133 “cat call” was selected as it was familiar to all participants despite diverse cultural
134 backgrounds). Participants were instructed to produce sound as part of a breath
135 phrase of approximately eight seconds and to breathe normally.

136 *Real-time magnetic resonance imaging*

137 Real-time MRI collects a series of anatomical images from a mid-sagittal slice of
138 the head and neck. Images were collected on a Siemens 3T MAGNETOM
139 Prisma Fit at the Maastricht Brain Imaging Centre with the LiveView pulse
140 sequence [24]. Real-time MRI images were collected with an acquisition time of
141 60ms over a single mid-sagittal slice with thickness = 8 mm, in-plane resolution =
142 2 mm by 2 mm, field-of-view = 256 by 256 mm, repetition time = 2.58 ms, echo

143 time = 1.64 ms, and flip angle = 8°. K-space was sampled over 125 radial
144 spokes. Scan durations were controlled manually and ranged from 88 to 98
145 seconds per run. Two scans from one participant were discarded due to scanner
146 malfunction or poor signal-to-noise ratio in imaging data. A third run from a
147 separate participant was discarded due to poor audio recording quality.

148 *Acoustical measurement*

149 Audio recordings were collected continuously throughout the scanning session
150 using an MRI compatible microphone attached to the side of the head coil. Audio
151 and rtMRI data were synchronized by aligning the onset of acoustical artefacts
152 associated with MRI acquisition with the first image volume.

153 Acoustical MRI artefacts were then removed using the noise reduction algorithm
154 in Audacity (v2.1.3) [25]. The noise profile of the MRI acoustical artefact was
155 estimated from a rest period between the onset of the MRI related noise and the
156 onset of whistling for each run. The frequency bands containing these sources of
157 noise were then selectively attenuated (noise reduction = 48 dB, sensitivity = 1.5,
158 frequency smoothing = 3 bands). Two iterations of this procedure sufficiently
159 filtered the acoustical waveform. Recordings were visually inspected in Praat
160 (v6.0.36) [26] by an experienced acoustical analyst (MB) to remove remaining
161 artefacts.

162 Whistling frequency measurements were extracted semi-automatically with an in-
163 house Praat script. The script extracted the mean fundamental frequency from a
164 window equal to half the rtMRI sampling rate centered at each image acquisition.

165 *Tongue shape measurement*

166 The edge of the tongue was detected in each frame automatically using a custom
167 MATLAB [27,28] script. A trace was then computed from tongue-edge maps
168 using the tongue root as a reliably identifiable point of origin. This produced a
169 continuous function of Y (anterior-posterior) and Z (ventral-dorsal) coordinates
170 that capture the shape of the tongue. The coordinate values were centered to
171 create an image space with the origin at the center of mass of the tongue for
172 analytical purposes. Figures are plotted with origins at the tongue root to facilitate
173 visualization.

174 *Functional data analysis*

175 Spatially smooth representations of the tongue contour were created by modeling
176 each tongue trace with a B-spline with a basis set of cubic polynomials placed at
177 every second sample along the trace using the *fda* package implemented in R
178 (v3.4.1) [29,30]. Smoothing parameters were chosen by generalized cross
179 validation. The length of each trace was normalized to the mean to remove the
180 confounding influence of the cross-sectional size of the tongue, and to ensure
181 that tongue splines were modeled with a consistent number of knots.

182 Variation in tongue shape was explored using functional principal components
183 analysis (fPCA) [31]. Functional PCA explores patterns of variation in the shapes
184 of functions around a mean shape. Much like discrete PCA, fPCA seeks principal
185 components that maximize variation between observations [32–34]. The principal
186 components of discrete PCA are eigenvectors that map each component back

187 onto a set of discrete variables. The principal components of functional PCA are
188 eigenfunctions that map each component back onto variations in shape. fPCA
189 was conducted simultaneously on functions of Y and Z coordinates to produce a
190 two-dimensional description of the tongue. This approach has the benefit of
191 assessing the relative contribution of tongue shape variation along the anterior-
192 posterior (Y) and dorsal-ventral (Z) axes.

193 A separate examination of the functional principal components for each
194 participant and each whistling task confirmed that the components were highly
195 consistent across participants and tasks. The data were therefore combined and
196 fitted to a linear mixed-effects model with the dependent variable of whistled
197 frequency, with Y and Z-subscores as regressors. The model accounted for
198 random factors of Participant and Condition with random slopes for the effects Y
199 and Z-subscores at each level of the random factors. [35]. This approaches the
200 maximal random effects structure [36], though random effects of Condition were
201 not nested within Participant due to a failure of this more complex model to
202 converge. Significance was assessed by *F*-tests with degrees of freedom
203 determined by Satterthwaite's approximation for degrees of freedom, at an alpha
204 level of 0.05.

205 **Results**

206 The first two functional principal components (fPC) accounted for 62% and 17%
207 of the total variance in tongue contour. These functional components describe a
208 dimension from 1) low-forward to high-back tongue position, and 2) high-forward

209 to low-back tongue position (Figures 2a and 3a). As each fPC describes a distinct
210 dimension of tongue shapes, we report separate models for each principal
211 component.

212 Y-subscores on the first functional principal component predicted the frequency
213 that was being whistled ($F(1, 8.5) = 6.5, p = 0.03, \beta = 399.1, CI = [92.9, 705.3]$).
214 Z-subscores were poor predictors of whistled frequency ($F(1, 5.5) = 2.1, p = 0.21,$
215 $\beta = -200.1, CI = [-473.5, 75.3]$), and no interaction was apparent between
216 subscores ($F(1, 8.4) = 0.01, p = 0.94, \beta = 4.5, CI = [-112.1, 121.0]$). An anterior-
217 ventral tongue position was associated with high-frequency whistling ($R^2 = 0.61;$
218 Figure 2).

219 ***Insert Figure 1 about here***

220 Y-subscores on the second functional principal component also predicted the
221 frequency that was being whistled ($F(1, 8.8) = 5.8, p = 0.04, \beta = 297.0, CI =$
222 $[56.2, 537.8]$). Z-subscores were poor predictors of whistled frequency ($F(1, 5.6)$
223 $= 1.9, p = 0.22, \beta = 222.7, CI = [-96.5, 541.8]$) and no interaction was apparent
224 between subscores ($F(1, 8.6) = 0.04, p = 0.84, \beta = 13.8, CI = [-115.2, 142.8]$). An
225 anterior-dorsal tongue position was associated with high-frequency whistling (R^2
226 $= 0.60$; Figure 3).

227 ***Figure 2 about here***

228 Discussion

229 We used rtMRI to demonstrate that the shape of the tongue is strongly
230 associated with the frequency of bilabial whistling in humans, such that forward

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231 configuration of the tongue produced the highest frequencies regardless of
232 tongue height. This mechanism was consistent across contexts, including simple
233 but highly artificial siren sounds, music-like discrete chromatic scales, and
234 complex calls with culturally imposed meaning. This is consistent with Shadle's
235 hypothesis that the tongue shapes a resonant cavity behind the lips to determine
236 the whistled frequency [9]. Tongue configurations that reduce the size of the
237 resonant cavity between the lips and the tongue amplify pressure fluctuations
238 with shorter wavelengths (i.e., higher frequencies).

239 *A shared bioacoustical mechanism with speech*

240 The same mechanism determines the frequency of whistling and the identities of
241 spoken vowels. Vowel sounds are produced by shaping resonant cavities within
242 the vocal tract, primarily [18,19,31]. These resonant cavities selectively amplify
243 certain frequency bands of the voice, called formants, which together encode the
244 identity of spoken vowels [17,37] For, example a low-back tongue position
245 produces a high first formant (F1) and low second formant (F2), as in the sound
246 /a/ (odd). A high-forward tongue position produces a low F1 and high F2, as in
247 the sound /i/ (even). The most anterior of these resonant cavities, which
248 determines the second formant in the context of speech, is a strong driver of
249 whistled frequency. We observed whistled frequencies ranging from 600 Hz to
250 3100 Hz, which spans the values of the second formant that encode vowel
251 sounds in speech [38–40].

252 We observed two functional principal components of tongue shape: One
253 capturing variation from low-back to high-forward tongue configurations, and a
254 second capturing variation from high-back to low-forward tongue configurations.
255 Forward configurations of the tongue were associated with high frequencies
256 across components, suggesting that multiple tongue configurations may produce
257 similar bioacoustical effects.

258 The shared bioacoustics of whistling and vowel production may be in the case of
259 whistled languages. Twelve whistled languages have been documented, though
260 anecdotal reports suggest that they may be more abundant [3,7]. The most well
261 studied of these is Silbo Gomero of the Canary Islands, in which whistling is used
262 as a sound source in place of the voice [41]. Silbadors produce loud hand-
263 assisted whistles to communicate over long distances over mountainous terrain.
264 They describe producing Silba as whistling while moving ones tongue as though
265 to pronounce words in spoken Spanish [41]. The effect is to approximate spoken
266 Spanish with the whistled frequency standing in for the second formant (F2) of
267 Spanish vowels [3,4]. Similar whistled-proxies have been described of French
268 [42], Turkish [43], and Greek [44], among other languages [3,7]. Though the
269 simpler acoustical structure of whistling encodes less information than the voice,
270 even amateur whistlers are highly precise [45]. The common bioacoustical
271 mechanisms of speaking and whistling may explain the emergence of whistled
272 proxies across diverse languages and cultural groups.

273 *A bioacoustical clue to the evolution of speech*

274 Whistling may provide a novel avenue to understand the evolution of speech
275 motor abilities through the comparative study of human and non-human apes.
276 Though whistling has not been observed in non-human apes in the wild, at least
277 one species (*pongo* spp.) can learn to whistle in captivity [46,47]. In most
278 instances it has not been possible to determine whether these animals
279 spontaneously imitated their caretakers or were explicitly trained. In one case,
280 this behaviour was observed to transfer between cohabitating animals,
281 demonstrating the potential for cultural transmission [46]. This behaviour has
282 provided evidence that Orangutans have voluntary control over the upper lip,
283 lower-lip, and respiratory muscles, which are readily accessible to external
284 observation. Our study, along with that of Azola et al. [23], demonstrates the
285 strong involvement of the tongue in human bilabial whistling. Whistling in non-
286 human apes may provide a useful animal model for the study of sensorimotor
287 capacities that support speech. Medical imaging in non-human apes is needed to
288 confirm that the tongue is similarly involved when these species whistle, in line
289 with broad similarities in vocal tract anatomy [48].

290 **Conclusions**

291 The tongue is a strong determinant of the frequency of oral whistling, with
292 forward tongue configurations associated with higher frequencies. This lingual
293 component of whistling corresponds with the bioacoustical mechanism that
294 produces the second formant in vowel production. This finding is consistent with
295 the link between whistled languages and the spoken languages for which they
296 act as proxy. Comparative research with non-human apes that have learned to

297 whistle may provide further insights into the evolution of the lingual-motor skills
298 that support speech.

299

300

- 301 **Ethics**
302 This study was approved by the Ethical Review Committee for Psychology and Neuroscience at
303 Maastricht University.
- 304
- 305 **Data Accessibility**
306 Data and code are available from the Dryad repository.
- 307
- 308 **Author Contributions**
309 M.B. conceived of the study, designed the study, analysed the data and drafted the manuscript;
310 B.G.S and J.C. helped design the study and provided analytical support, D.B. contributed to
311 drafting the manuscript. S.A.K. contributed to the design of the study. All authors contributed
312 comments and critical revisions.
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314 The authors report no competing interests.
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323

324 **Figure Legends**

325

326 Figure 1: Waveform and spectrogram demonstrating the acoustics of speech
327 sounds and whistling. Insets show the complex waveform of the voice relative to
328 the simple waveform of whistling. Vowels are identified by a combination of
329 formant frequencies (F1, F2). Whistling is composed of a single sinusoidal wave
330 whose frequency corresponds to the heard pitch (f_0), but spans a range similar to
331 vowel formants.

332 Figure 2: Top) Mean shape of the tongue (black) framed by shapes marking the
333 first functional principle component (red to blue). Successive shades of red mark
334 tongue shapes with fPC1 scores of +1 to + 4. Successive shades of blue mark
335 tongue shapes with fPC1 scores of -1 to -4. Dashed lines continue each shaded
336 area where they would otherwise be obscured. Bottom) Scatterplot showing Y
337 and Z sub-component scores of fPC1 for each frame. Color hue indicates the
338 frequency being whistled at each frame. Symbols indicate the whistler that
339 contributed each point. Large background circles are fictive data points plotted
340 for the purpose of facilitating the interpretation of fPC scores only. Each fictive
341 point indicates the fPC1 score associated with the tongue shape of the same
342 colour in the top panel. The origin corresponds to the mean tongue shape.

343 Figure 3: Top) Mean shape of the tongue framed by shapes describing the
344 second functional principle component. Bottom) Scatterplot showing Y and Z
345 sub-component scores of fPC2 for each frame.

346

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Sound

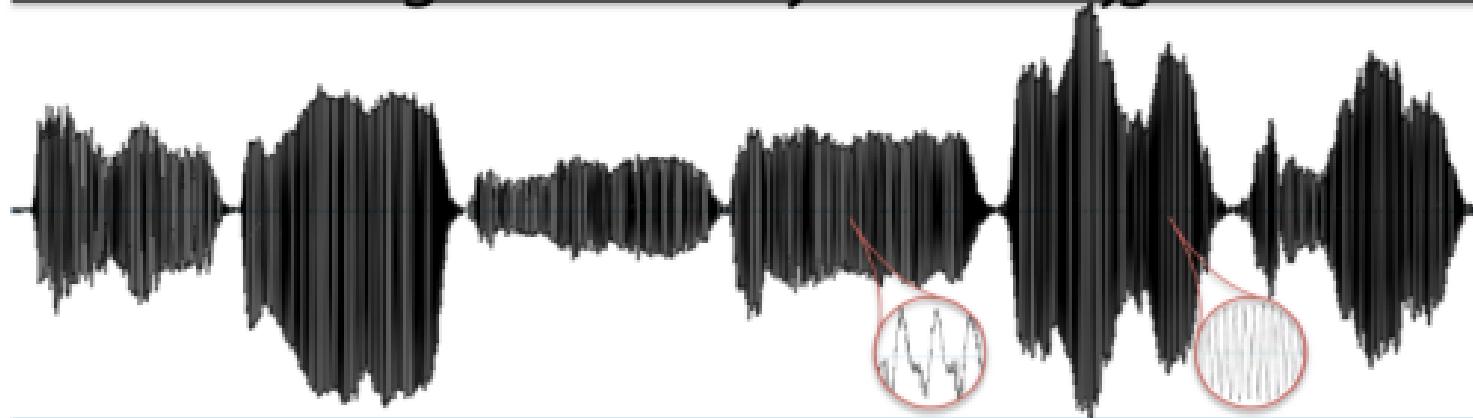
/a/ as in Odd

/i/ as in Even

Whistle

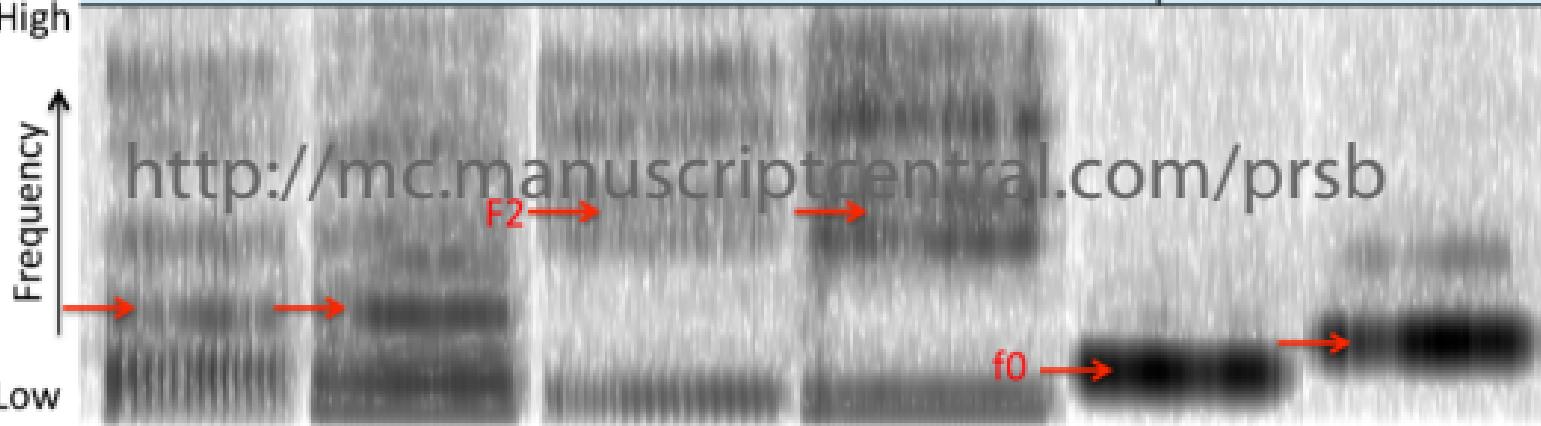
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Waveform

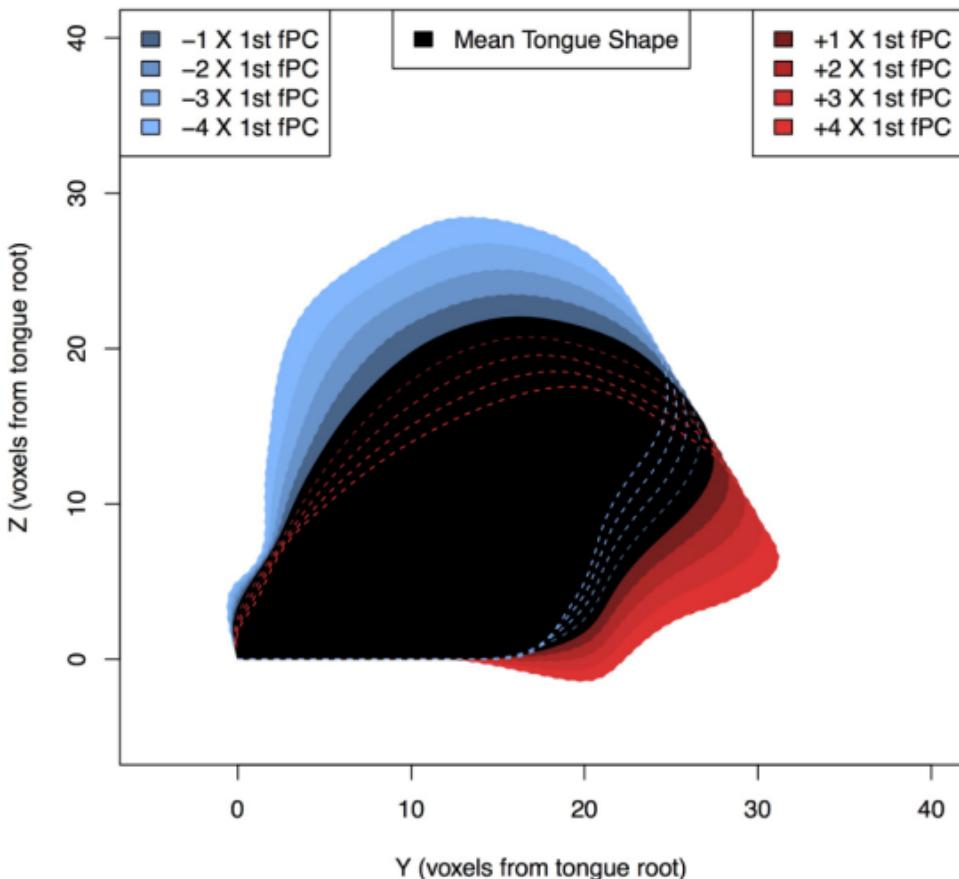


High

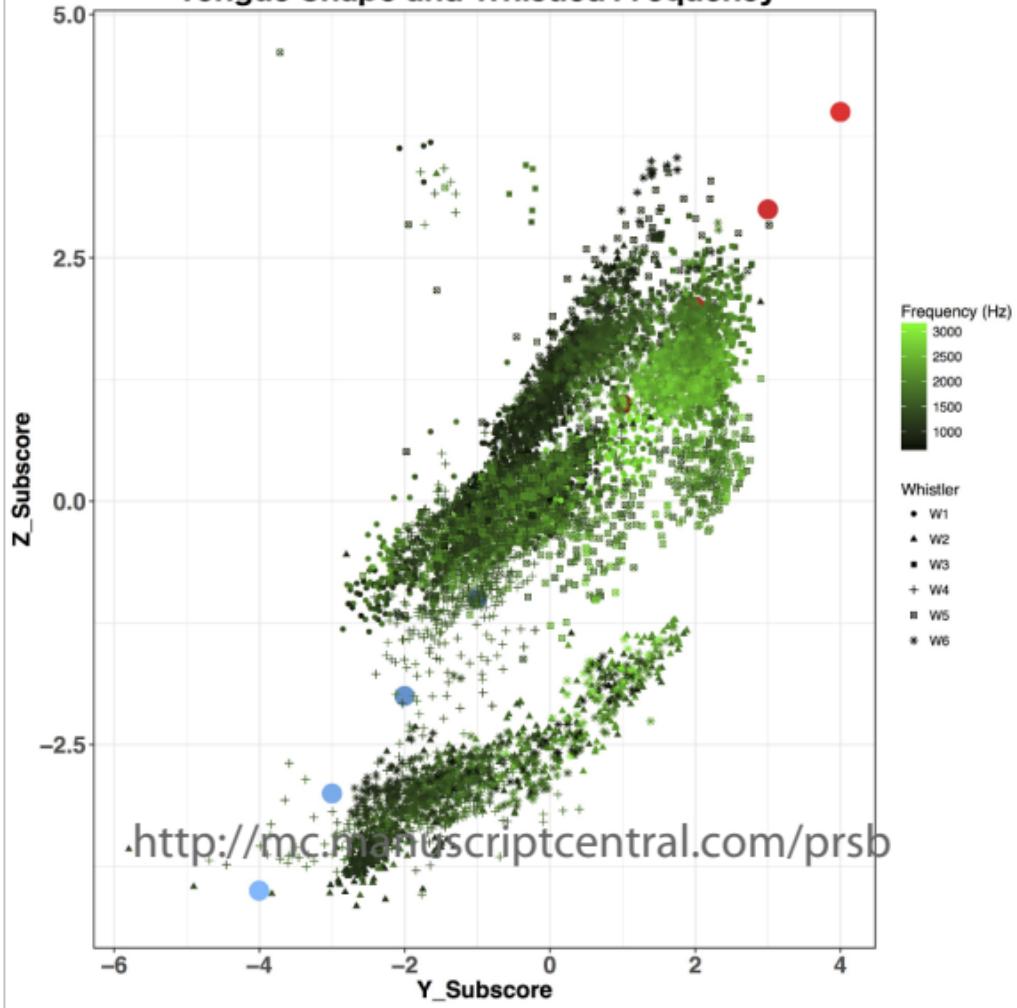
Spectrogram

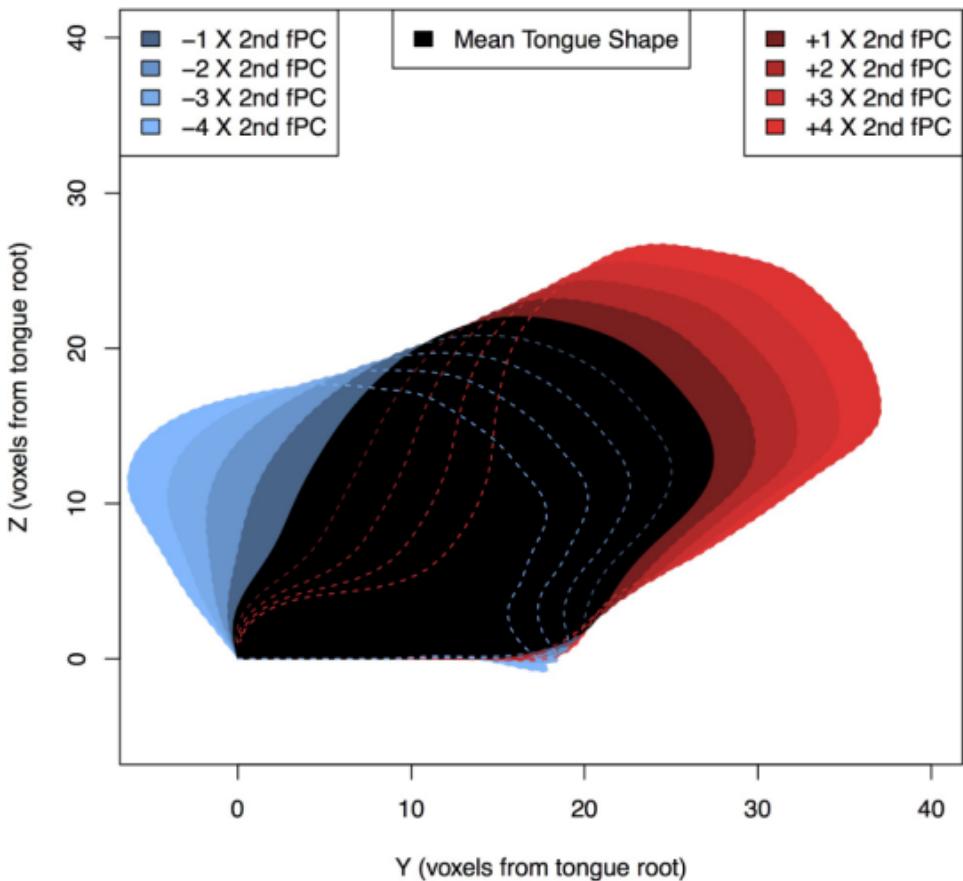


Low



Tongue Shape and Whistled Frequency





Tongue Shape and Whistled Frequency

