The phonology of sperm whale (*Physeter macrocephalus*) coda vowels

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OVERVIEW

- sperm whales (*Physeter macrocephalus, P.m.*) use **short series of clicks** (a. k. a. ***codas***) to communicate (Watkins and Schevill, 1977)
- little is known about how codas encode information

→ the structure of *P.m.* vocalizations remains one of the most intriguing questions in animal communication

sperm whale codas 🐳 show patterns *analogous* to **human phonologies** 🗣️

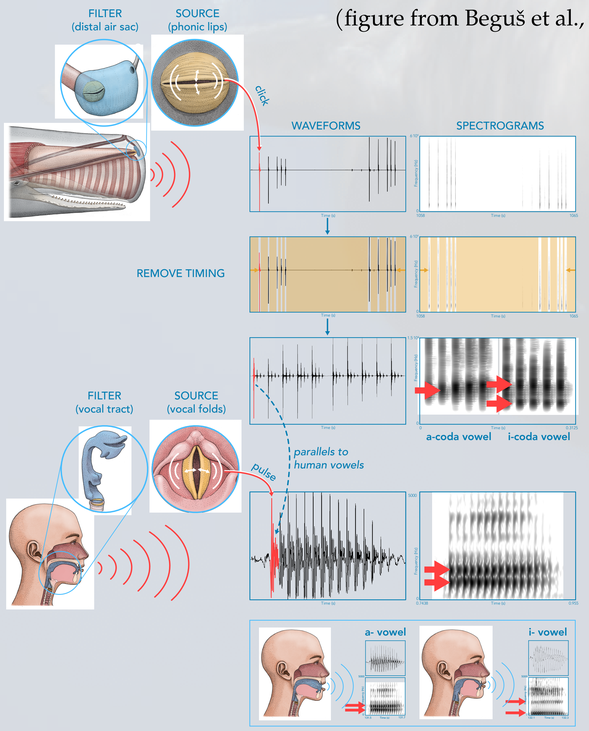
BACKGROUND

- *P.m.* codas traditionally are grouped into different *types* based on the number of clicks and duration of inter-click intervals (ICIs), e. g.:
  - $5R_1$ ("5 clicks, *regular* ICIs"), • 9i ("9 clicks, *increasing* ICIs"),
  - 1+1+3 (click... click... 3 fast clicks) (Weilgart and Whitehead, 1993)
- *P.m.* clicks have structured spectral properties that fall into one of two discrete, articulatorily-controlled categories (Beguš et al., t.a.):
  - 1-formant codas: ***"a*-vowels"** • 2-formant codas: ***"i*-vowels"**
- source-filter model (Fant, 1960) hypothesis:
  - sound source: **phonic lip vibrations** • acoustic filter: **distal air sac**

DATA

- 3948 temporally-ordered, speaker-associated, and labeled codas
  - produced by 15 members of the EC1 clan (Gero et al., 2014),
  - captured w/ DTAGs tags (Johnson and Tyack, 2003) between 2014–18
- analyzed: only *focal* codas (i. e. produced by DTAG-carrying whale)

(figure from Beguš et al., t.a.)



RESULTS

1 QUALITY–TYPE CORRELATION

- there is a correlation between coda quality (*a* vs. *i*) and coda type ($5R_1$, 9i, etc.)
- the distribution of *a* vs. *i* is not signf. different from 50% in the 1+1+3 type ($\beta = -0.20, z = -1.04, p = 0.3$), but the *i*-quality is less frequent on $5R_1$, $5R_2$, 6-UNCLASS., 6i, and 9i types (Figure 1)
- analogizing *P.m.* phonic lip vibrations to human glottal pulses, different coda types are like different tonal contours (and lengths)
- the observed interaction between coda type and quality is like the interaction between tone and vowel features in human languages:
  - e. g. in Slovenian, tense vowels (e. g. *e*) prefer H and lax vowels (*ɛ*) prefer L (Becker et al., 2017)

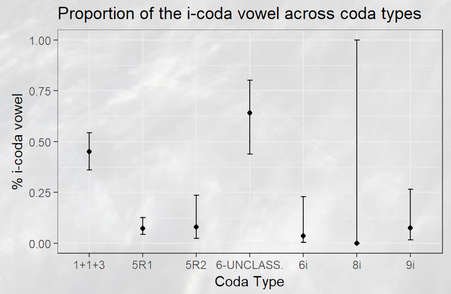


Figure 1: Proportion of the *i*-coda vowel across coda types

2 INTRINSIC CODA VOWEL DURATION

- the *a*-vowels are significantly longer than the *i*-vowels (Figure 2c)

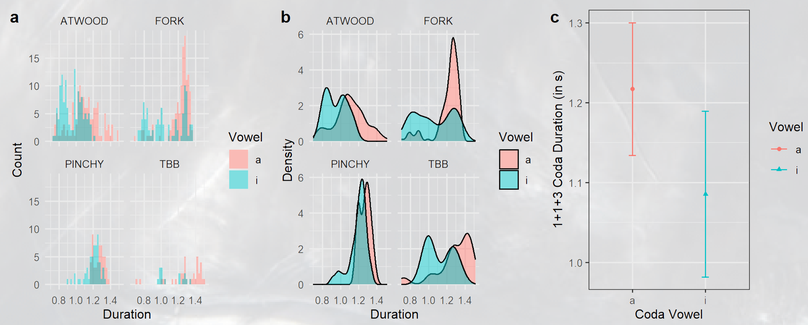


Figure 2: A histogram (**a**) and a density plot (**b**) of raw coda durations (in seconds) of the 1+1+3 coda on four whales. Estimates of the mixed effects linear regression model with 95% CIs (**c**)

- human vowels have intrinsic durational differences, too, e. g.:
  - low vowels such as *a* are longer than high vowels (e. g. *i* or *u*) (Heffner, 1937)

3 CONTRASTIVE CODA VOWEL LENGTH

- the *a*-vowel duration is unimodal for four whales, while the *i*-vowel duration is bimodal for at least 3 out of 4 whales (Figure 2)

→ this suggests a contrast between short *i*- and long *ī*-codas

- human languages often have vowel length contrasts (e. g. Latin, Xhosa, etc.)

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4 BASELINE CLICK RATE

- different whales differ in their baseline coda duration, e. g. the baseline duration of the *a*-vowel for Atwood is 1.11s, but 1.28s for Pinchy (Figure 3)
- humans also have different habitual speaking rates (Tsao and Weismer, 1997)

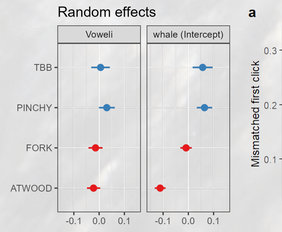

Figure 3: Intercepts and random slopes for each of the four whales

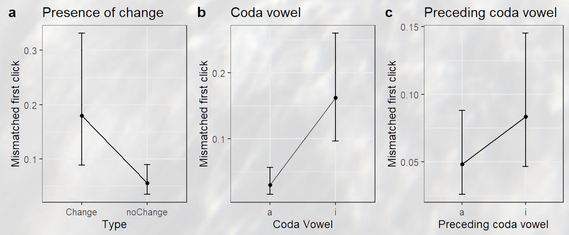

Figure 4: Effects of change, coda vowel, and preceding coda vowel on first-click mismatches

5 FIRST-CLICK MISMATCHES

- in most cases, all clicks within a coda match in quality (all *i* or all *a*)
- however, 1st click is significantly more often mismatched when the whale makes a transition between vowels of two different qualities (*a*-*i* or *i*-*a*), compared to when no change occurs ($\beta = 1.31, z = 3.07, p = 0.002$) (Figure 4)

DISCUSSION

- coda types vary with *P.m.* clan → acquired, not innate (Rendell et al., 2012)
- we provide further evidence that the *P.m.* communication system is complex, and parallels aspects of human phonetics and phonology

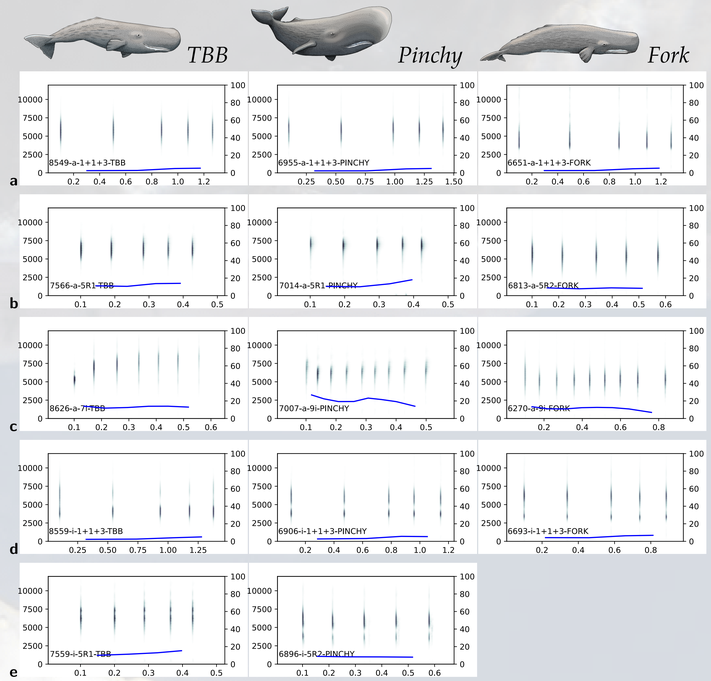

Figure 5: Different coda vowel quality and type combinations as produced by three different whales, including *a*-quality codas of the 1+1+3 type (**a**), 5R type (**b**), and i-class ("increasing" ICI) types (**c**), as well as *i*-quality codas of the 1+1+3 type (**d**) and 5R type (**e**). Pitch plots are given as blue lines. Whale drawings CC BY 4.0 © Alex Boersma.