Energetic Consequences of Sonar Exposure

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What are the energetic consequences for cetaceans when exposed to sonar? The following model makes a first order approximation by estimating (1) the energy intake lost to foraging cessation and (2) the additional energy expenditure from increased swim speeds. We considered these two factors in four potential scenarios:

1. No response
2. Cessation of foraging without flight
3. Cessation of foraging with flight
4. Extreme response

The model will be paramterized using data and models from other sources (see table at the end of this document). Functional responses (e.g. displacement distance and duration) will come from the literature. The energy cost of lost feeding opportunities will be estimated with the scaling relationships in Jeremy's scaling paper. The energy cost of increased swim speeds during flight will be estimated using models from Williams et al. 2017. Thus:

$$E_{sonar} = P_{in} \times t_d + P_{out} \times t_f$$

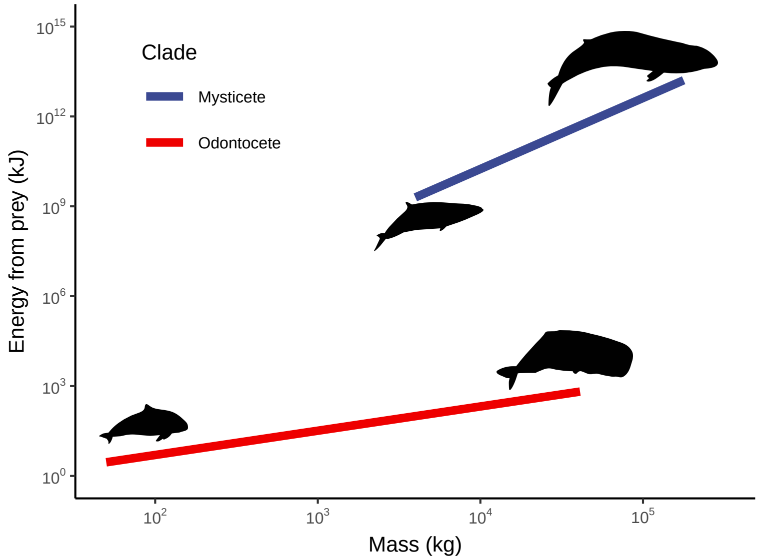
Where $\mathrm{E_{sonar}}$ is the energy cost of sonar exposure, $\mathrm{P_{in}}$ is the rate of energy intake when foraging, $\mathrm{t_d}$ is the displacement time, $\mathrm{P_{out}}$ is the increase in energy expenditure from locomotion due to the flight response, and $\mathrm{t_f}$ is the flight time.

Functional responses

In progress

Energetic parameters

I'm estimating $\mathrm{P_{in}}$ as the product of energy acquired per feeding event ($\mathrm{E_p}$) and feeding rate ($\mathrm{r_f}$). Broadly speaking, energy acquired from prey scales sublinearly among odontocetes [$\mathrm{E_p}$=$0.12\mathrm{M_c}^{0.81}$] but superlinearly among mysticetes [$\mathrm{E_p}$=$5.83\mathrm{M_c}^{2.37}$]. *Note: Jeremy's paper has a negative coefficient for mysticete E_p scaling (v8.3:115) but I think that's a mistake. Also, what are the units of E_p? kJ? Or is it scale invariant?*

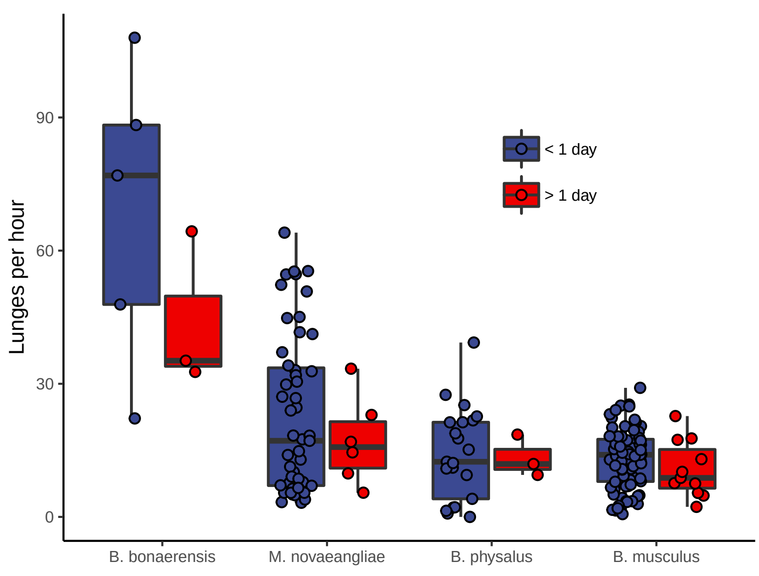


Empirical feeding rates

Prey data from "Cetacea model output BOUT_EXTANT_v2.csv".

Rorquals

How should lunge rate be calculated? Lunge rates from tags that lasted more than a day are lower because they capture night time. Should we use the mean lunge rate from <1 day tags because that's the opportunity cost? Or should we use the mean lunge rate from >1 day tags to be conservative? I'm going with the latter.



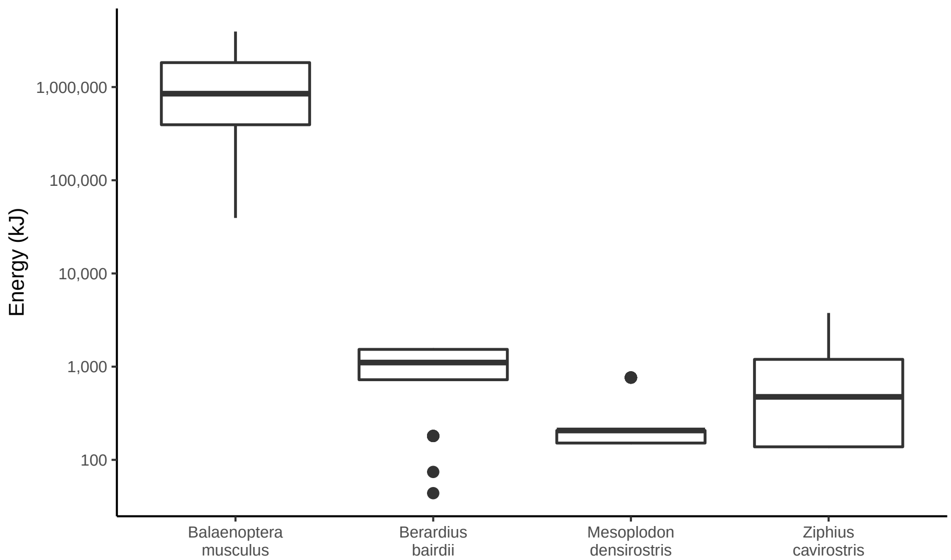
Beaked whales

We have limited beaked whale data. Mean hourly feeding rates are 4.6 for *Berardius* (but N = 1) and ~13 for *Mesoplodon* and *Ziphius*.

Species	N	Buzz rate (per hour)
Berardius bairdii	1	4.6
Globicephala macrorhynchus	2	2.5
Globicephala melas	9	7.9
Grampus griseus	17	17.7
Mesoplodon densirostris	14	13.0
Orcinus orca	10	9.7
Phocoena phocoena	8	96.8
Physeter macrocephalus	36	NA
Ziphius cavirostris	4	12.8

Empirical prey size distributions

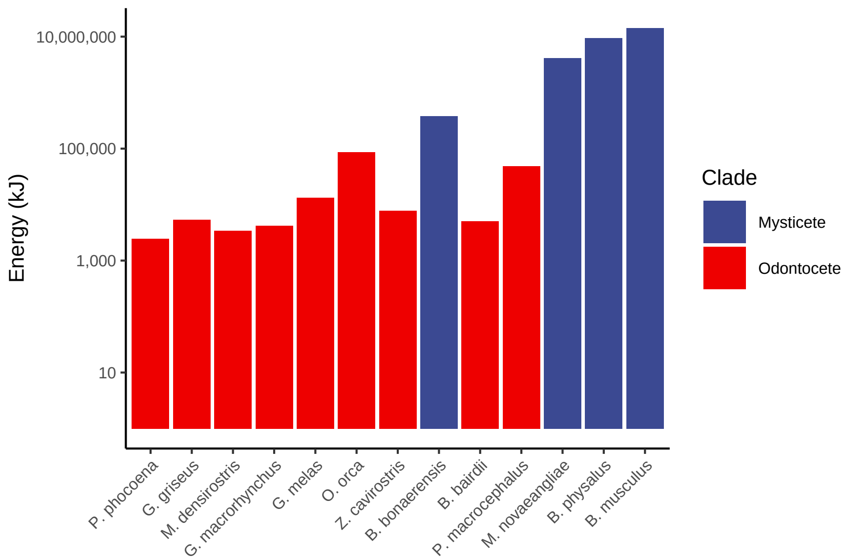
Blue whales engulf several orders of magnitude more energy per feeding event than beaked whales (no surprise there).



Power in

$$P_{in} = E_p \times r_f$$

Where P_{in} is the rate of energy intake (kJ/hour), E_{p} is the energy from in one feeding event (kJ), and r_{f} is the feeding rate (feeding events/hour). The following figure shows estimates of P_{in}. *Note: there's a Pm with NA for buzz count.*



Power out

$$P_{out} = (f_{max} - f_{pref}) \times m \times C_L$$

Where f_{max} is the fluking frequency at maximum speed , f_{pref} is the fluking frequency at the preferred cruising speed, m is the mass of the animal, C_L is the mass-specific cost of locomotion. Williams et al. 2017 calculated C_L for cruising speeds:

$$C_L = 1.46 + 0.0005m$$

(see equations 6)

Fluking frequencies

1. Cruising speed (U_{pref}) is 1.5 m/s (Sato et al. 2007)
2. Max speed (U_{max}) from Hirt et al. 2017

$$U_{max} = aM^b(1 - e^{-hM^i})$$

- For swimming, a = 11.2, b = 0.36, h = 19.5, i = -0.56

3. Fluking frequency based on a fixed Strouhal number of 0.3

$$S_t = \frac{f}{U}A$$

A is about $\frac{L}{5}$

$$S_t = \frac{f}{U}\frac{L}{5}$$

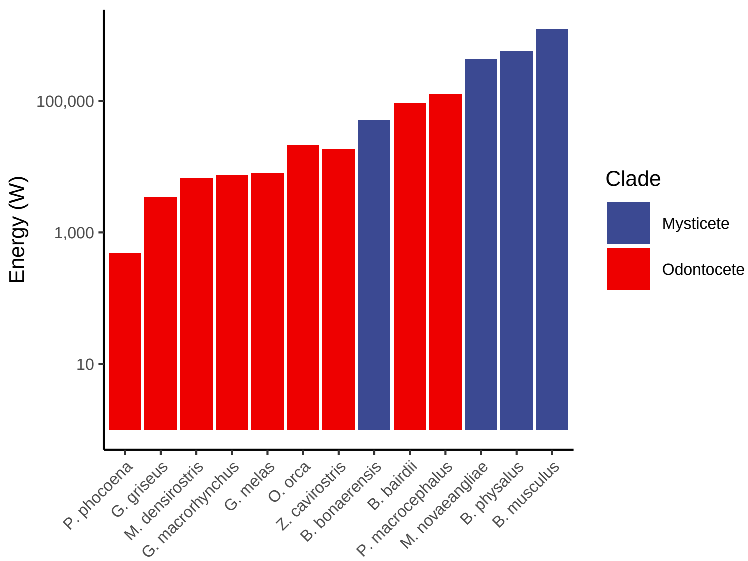
$$f = 5S_t\frac{U}{L}$$

$$f = 1.5\frac{U}{L}$$

Given the equations for P_{out}, f, and C_L, the estimates for power expended from increased fluking are:

Species	Length (m)	Mass (kg)	Clade	$U_{max}(m/s)$	$f_{max}(Hz)$	$f_{pref1}(Hz)$	$f_{pref2}(Hz)$	C_L	P
B bonaerensis	7.8	6700	Mysticete	9.72	1.87	0.29	0.3	5	
B musculus	25.2	93000	Mysticete	6.06	0.36	0.09	0.1	48	1
B physalus	20.2	53000	Mysticete	6.74	0.50	0.11	0.2	28	
B bairdii	10.5	11900	Odontocete	8.83	1.26	0.21	0.2	7	
G macrorhynchus	4.3	980	Odontocete	12.54	4.37	0.52	0.5	2	
G melas	5.0	1200	Odontocete	12.29	3.69	0.45	0.5	2	
G griseus	3.0	350	Odontocete	13.32	6.66	0.75	0.7	2	
M novaeangliae	14.0	36000	Mysticete	7.24	0.78	0.16	0.2	19	
M densirostris	4.1	860	Odontocete	12.69	4.64	0.55	0.5	2	
O orca	6.0	3000	Odontocete	10.98	2.74	0.38	0.3	3	
P phocoena	1.2	31	Odontocete	10.09	12.41	1.84	1.3	1	
P macrocephalus	11.0	15000	Odontocete	8.48	1.16	0.20	0.2	9	
Z cavirostris	6.6	2900	Odontocete	11.03	2.51	0.34	0.4	3	

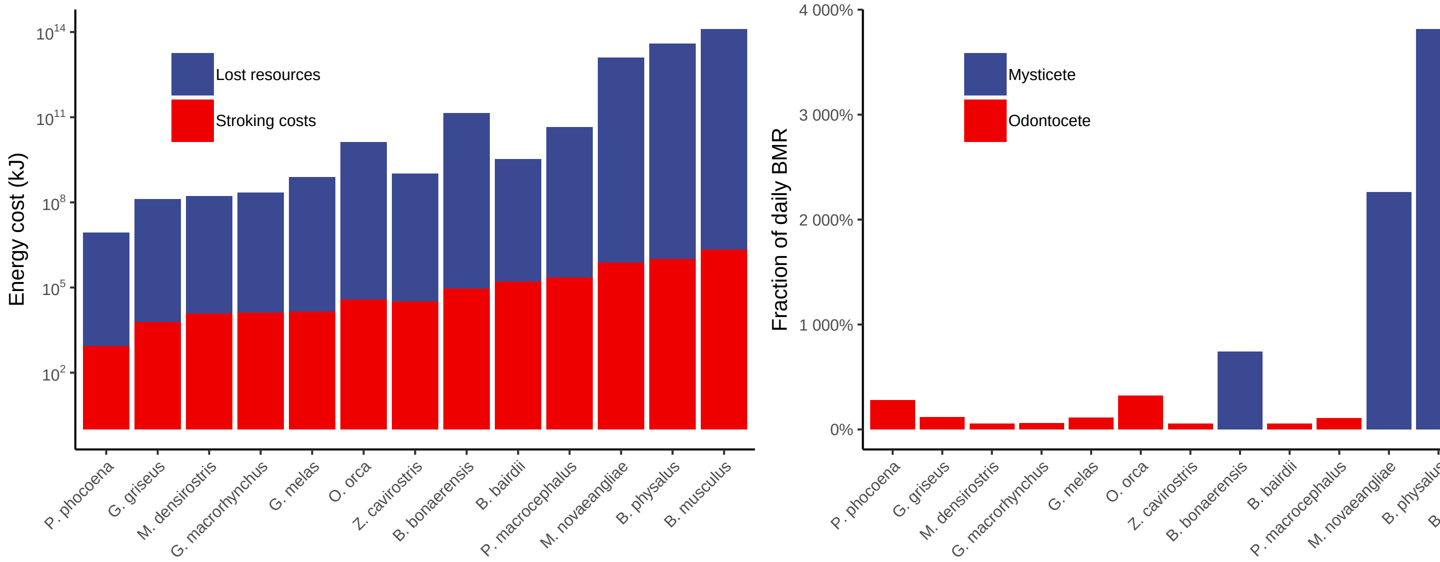
Note:
C_L is in units of $Jkg^{-1}stroke^{-1}$
f_{pref1} calculated using a Strouhal number of 0.3 at a cruising speed of 1.5 m/s
f_{pref2} calculated with the scaling relationship in Sato et al. 2007
P_{out} calculated with f_{pref1}



Mass-specific locomotor costs get huge for big animals! Going all the way to max speed is too much. Model it for 10%, 25%, 50% increases in speed? Or 10%, 25%, 50% to max speed?

Modeled E_{sonar}

TODO: finish functional response section and get good estimates for t_d and t_f. For now, let's say cetaceans are displaced for 4 hours and flee for 30 minutes. This figure isn't terribly meaningful, it's mostly to show the calculations work.



Literature

Reference	Species	Tags	Notes
Tyack et al. 2011	Mesoplodon densirostris	1	Only 1 tag, but other data from sonar array
DeRuiter et al. 2017	Balaenoptera musculus	37	How did the transition probability from deep feeding to other states change in CEEs?
DeRuiter et al. 2013	Ziphius cavirostris	2	Reduced time foraging in response to proximal sonar, but not distant
Friedlaender et al. 2016	Balaenoptera musculus	9	Includes prey data
Goldbogen et al. 2013	Balaenoptera musculus	17	Basis for Friedlaender et al. 2016 and DeRuiter et al. 2017
Kvadsheim et al. 2017	Balaenoptera acutorostrata	4	SoCal + Norway. 1 CEE + 1 control in each location
Southall et al. 2019	Ziphius cavirostris	0	Prey distribution in SoCal sonar array