The production-based approach for the study of humpback whale songs. Overview and Perspectives

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Summary

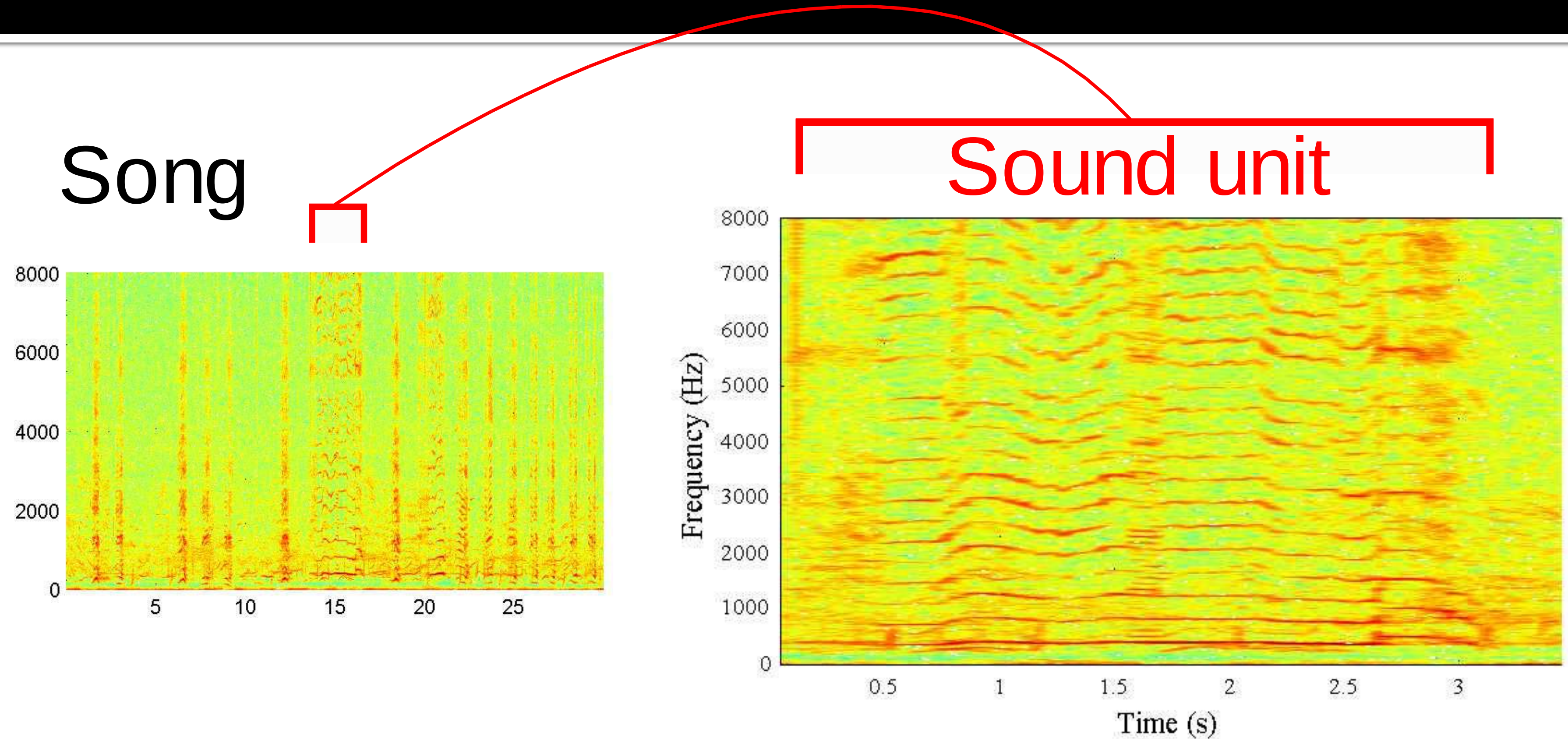
I. **Background** : Different approaches for classifying HW sound units
   1. Hierarchical approach
   2. Computational approach
   3. Production-based approach

II. **Presentation** of the production-based approach
   1. Anatomical review
   2. Biomechanical modeling
   3. Signal processing

III. **Perspectives**
   1. Potential applications
   2. Conclusion

I – Background on approaches to classify humpback whale sounds

Payne’s approach (1)

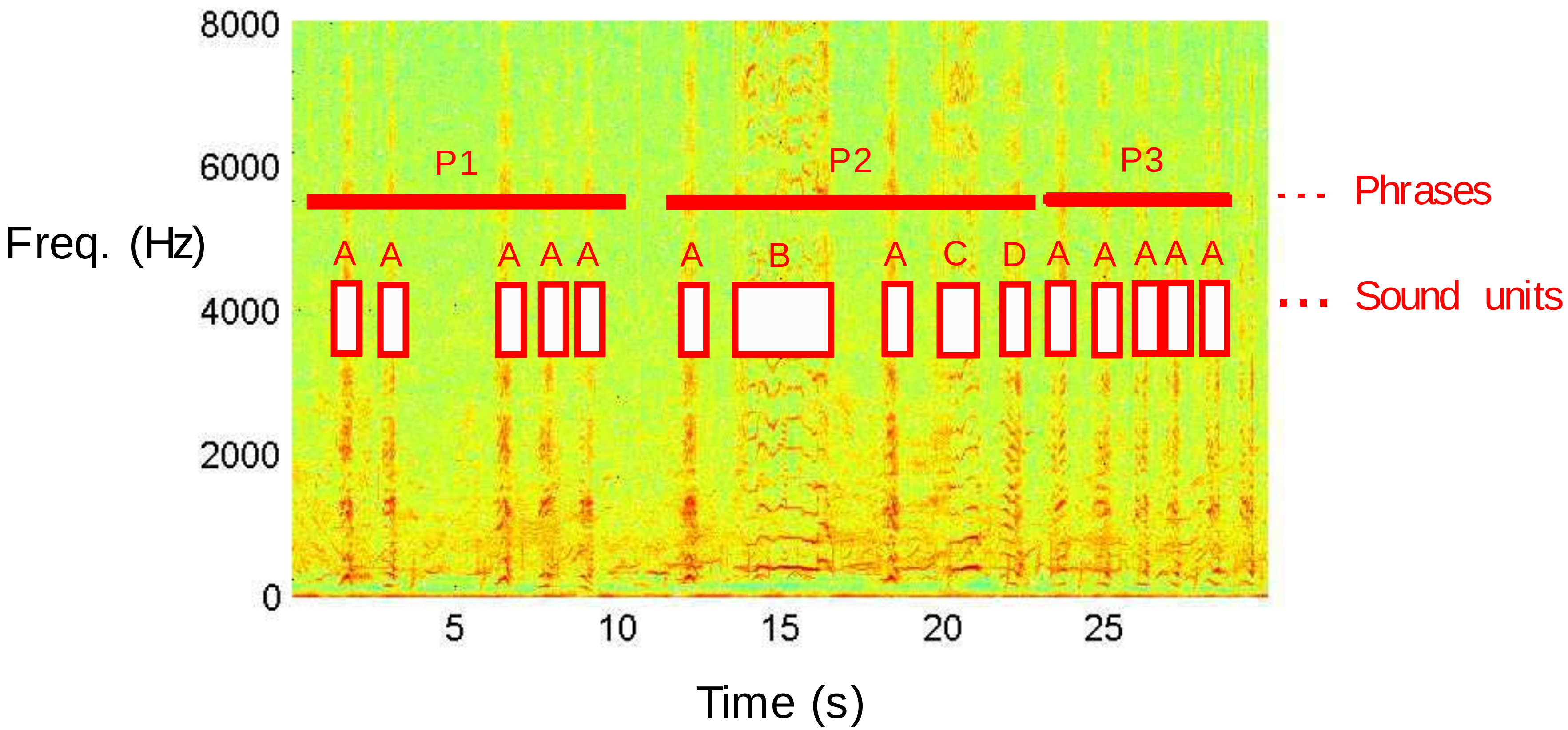


Definitions (Payne, 1971) :

*- **Sound unit** : minimal continuous sound ;*

*- **Song** : ordered sequences of individual sound units separated by gaps of silence*

Payne's approach (2)



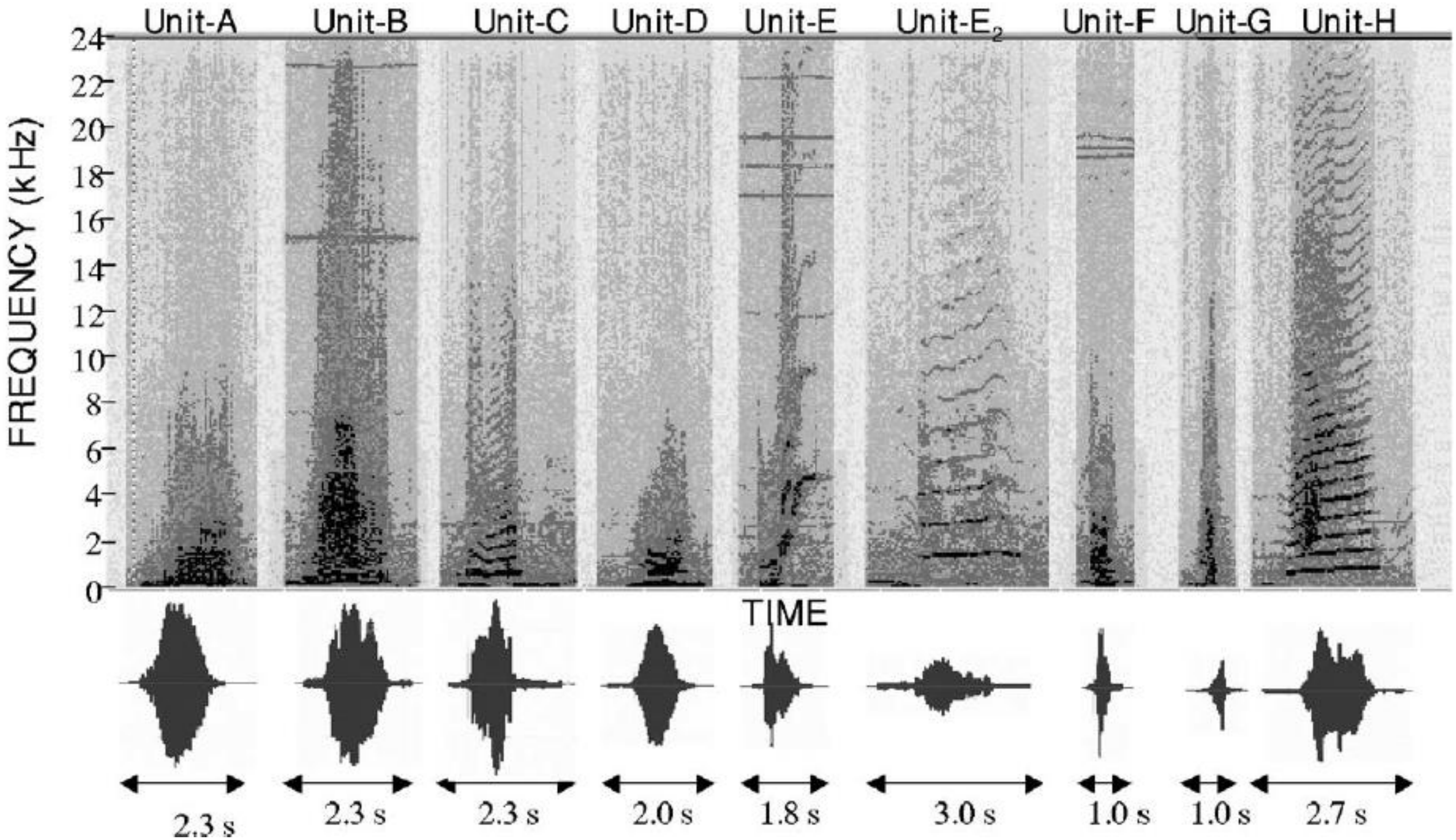
Definitions (Payne, 1971) :

*- **Phrase** : succession of few sound units ;*

*- **Leitmotiv** : repetition of same phrases in a song*

Payne's approach (3)

Exemple of a manual classification of sound units



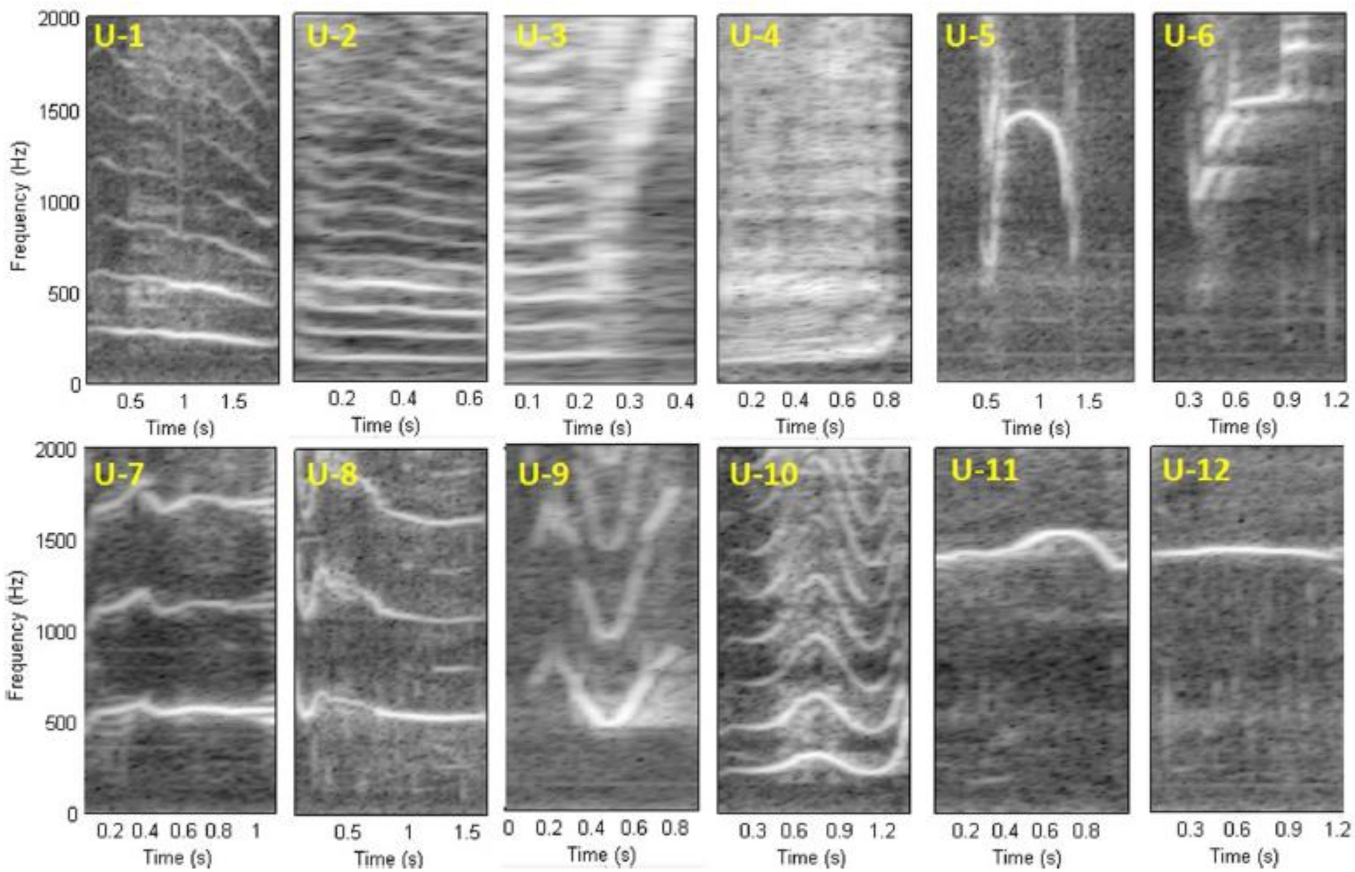
From Au et al. (2006)

Computational approach (1)

- Characteristics
  - Built objective, automatic, time-saving methods

- Baseline surveys
  - Suzuki et al. (2006) used information theory techniques to study song structure ;
  - Mazhar et al. (2007) studied individual recognition of HW with SVM
  - Ou et al. (2013) developed a cluster-based learning to classify sound units ;

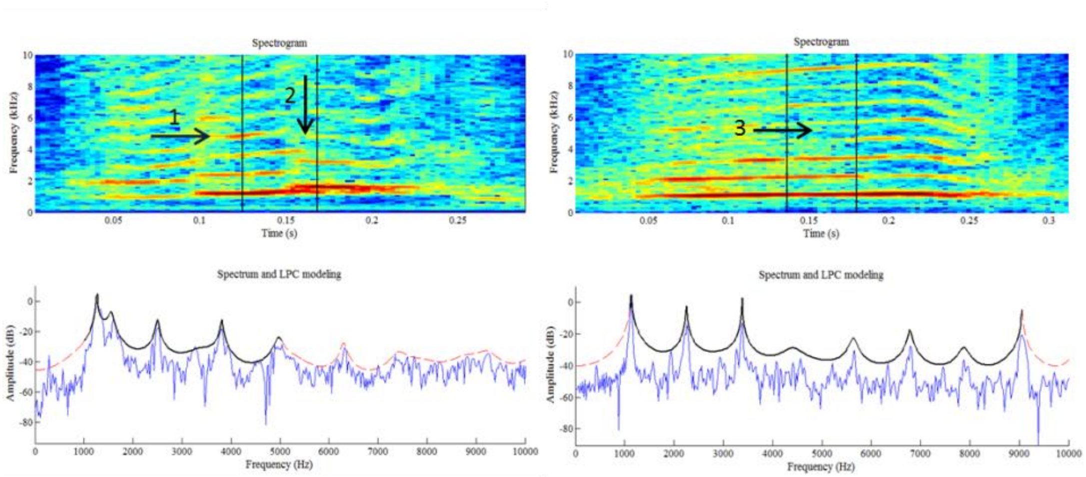
Computational approach (2)
Exemple of a clustering of sound units



From Ou et al. (2013)

Production-based approach (1)

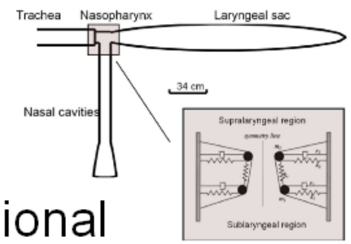
- Observations from data
  - Variable precary structure of sound units
  - Presence of singularities (e.g. vocal non-linearities)



Idea of a sound continuum (Mercado, 2010)

1 : Harmonic reinforcement
2 : Frequency jump
3 : Harmonic disapearing

Production-based approach (1)



Computational
MODELING

Understanding and analyzing how
Anatomy and Production are related ?

Sound-producing
ANATOMY

Which organs make sounds ?
How they function ?

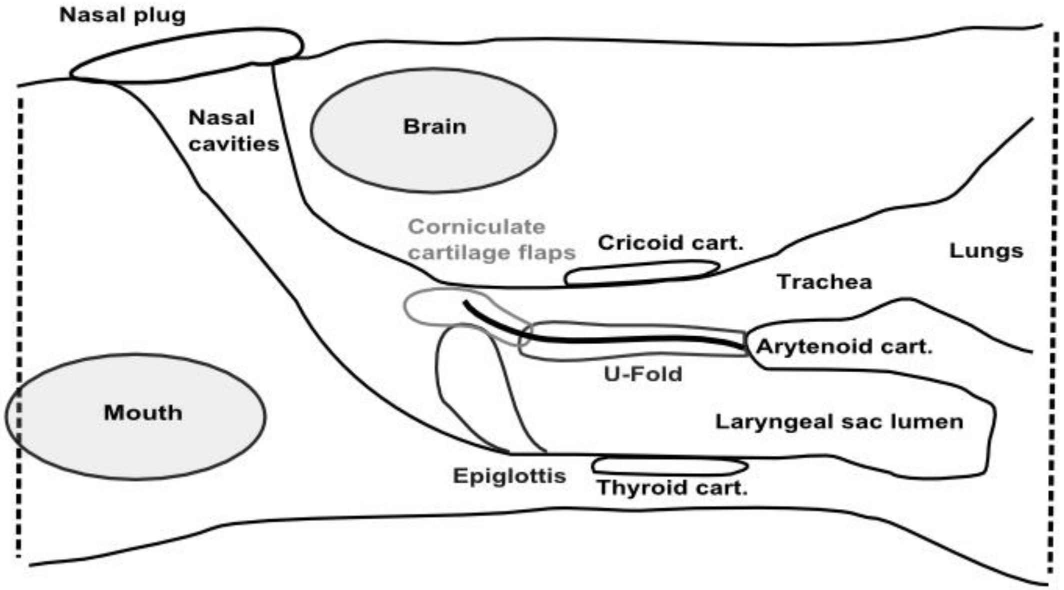
ACOUSTIC
Analysis

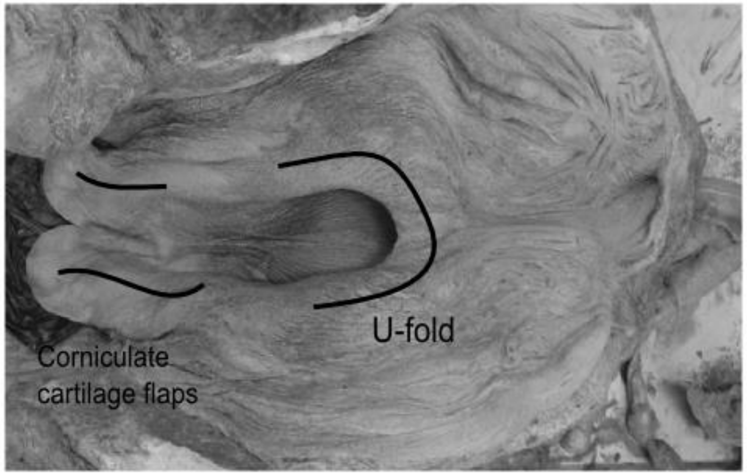
Which call types are used ? In
which behavioral context ?

II – Overview of the production-based approach

Anatomical view: from the outside

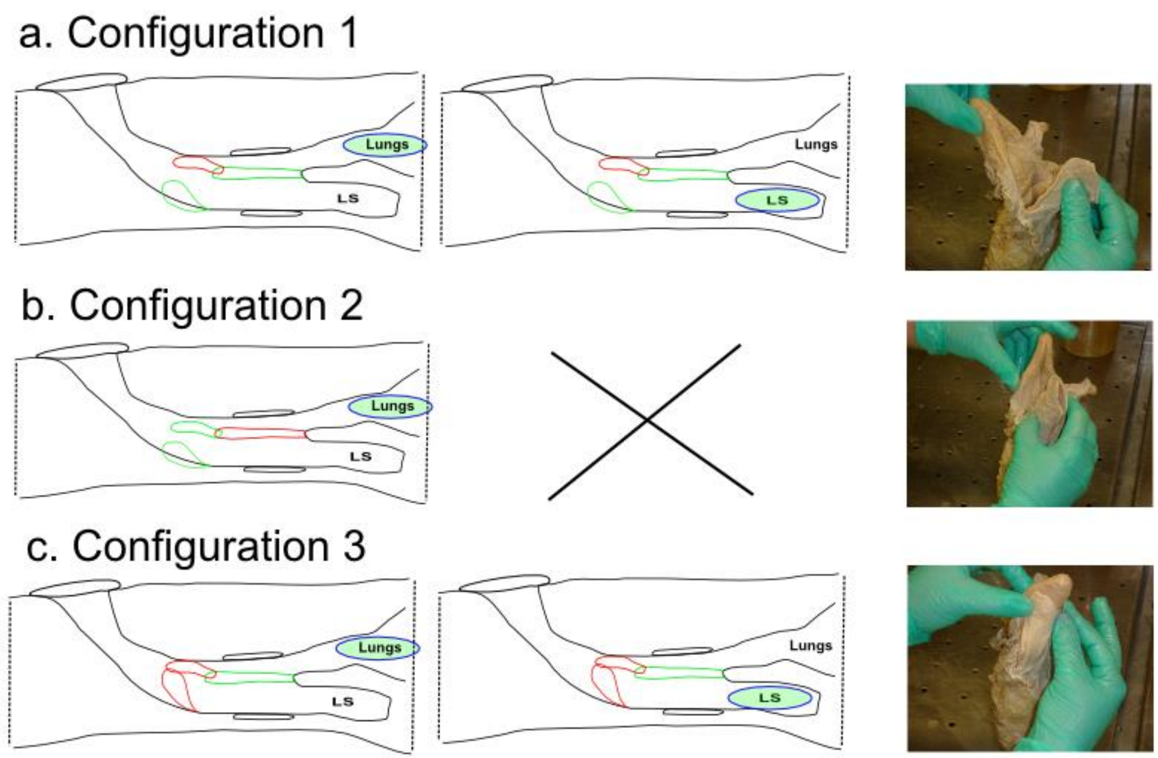
Anatomical view: from the inside





From Cazau et al. (2013)

Four physiological configurations of the sound generator (*Cazau et al., 2013*)



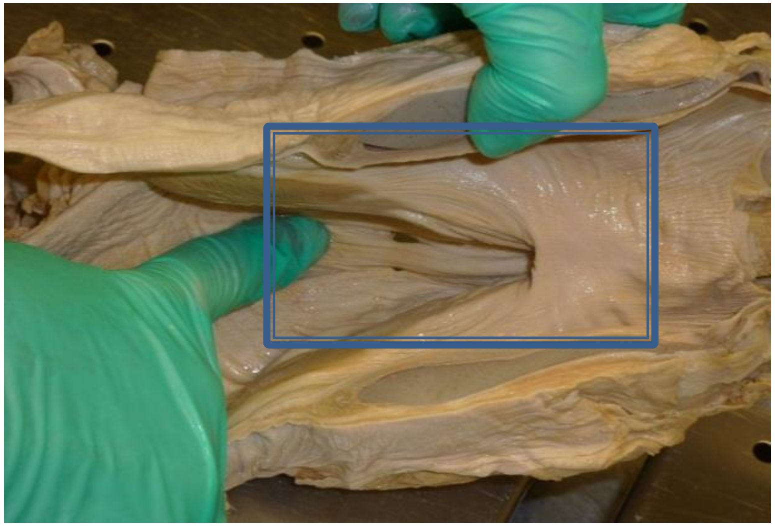
Config 1 : air source are the **lungs or the LS**, with opened nasal pipes

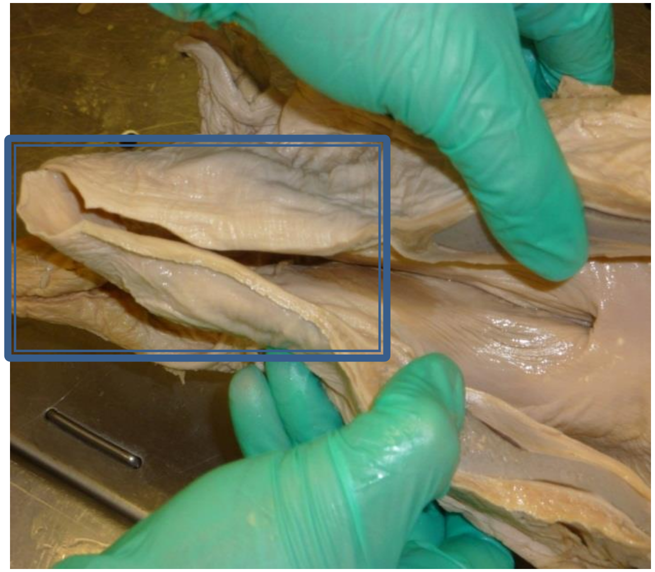
Config 2 : air source is the **lungs** , with sealed U-folds

Config 3 : air source are the **lungs or the LS**, with closed nasal pipes

Biomechanical measures

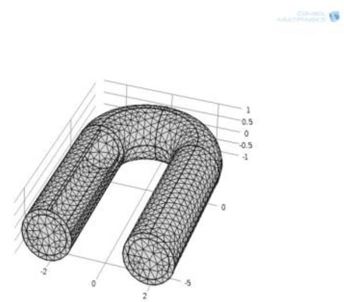
	L_0 (cm)	T_0 (cm)	D_c (cm)	E (kPa)	ν	ρ (kg.m^{-3})	η (Pa.s)
U-folds cover	6	1	0.2	20140	0.4	1020	1
U-folds body	6	1	1.8	33060	0.4	1020	1
CCF	4	10	0.6	20000	0.4	1020	1

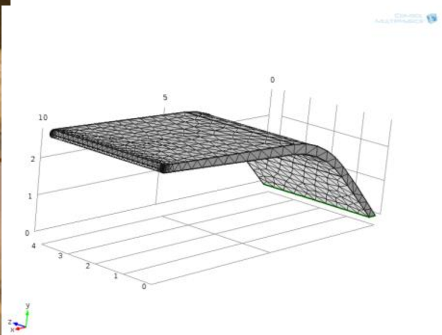


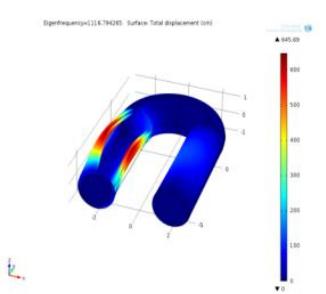


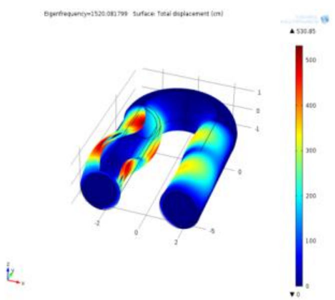
Static modal analysis

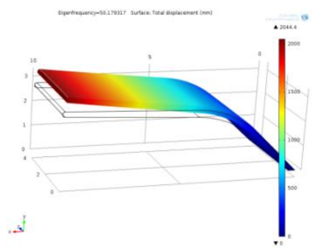
First two eigenmodes of the **UF** (left) and the **CCF**

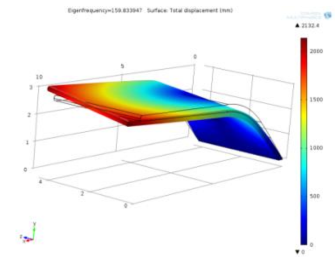








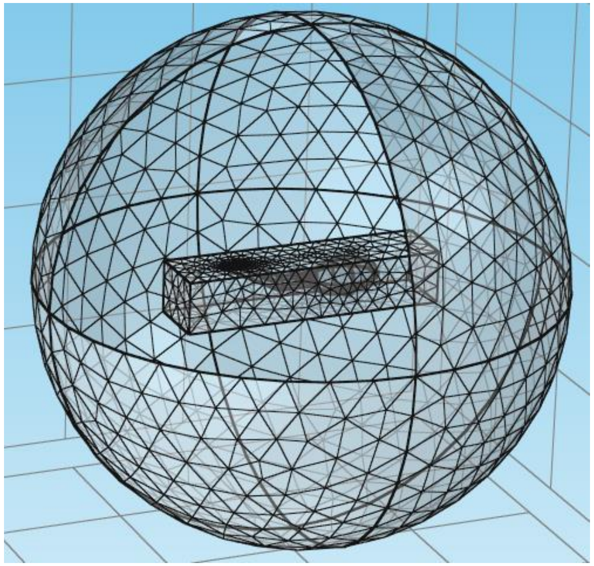




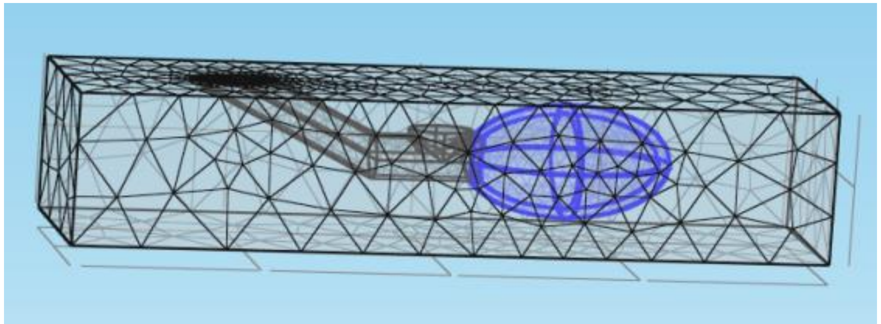
Determining fundamental frequency range

A 3D model of whale acoustic radiation for **formant analysis (1)**

The finite-element method



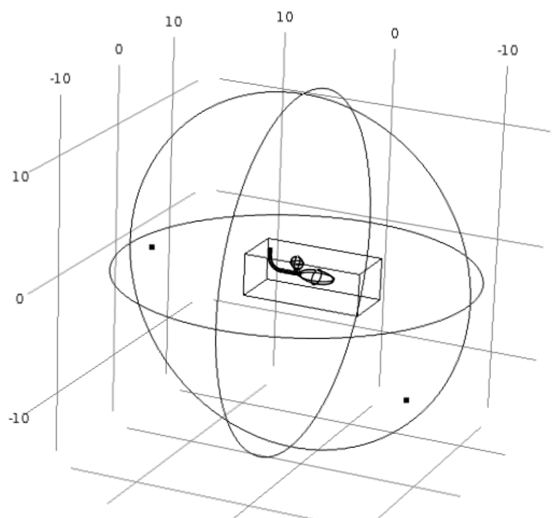
Supra-laryngeal system

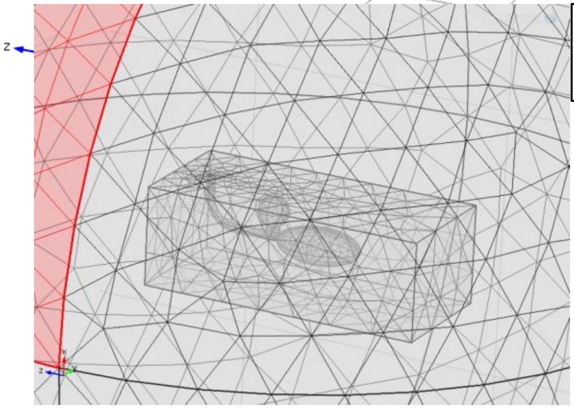


Use continuous equations projected on each finite element, with following advantages

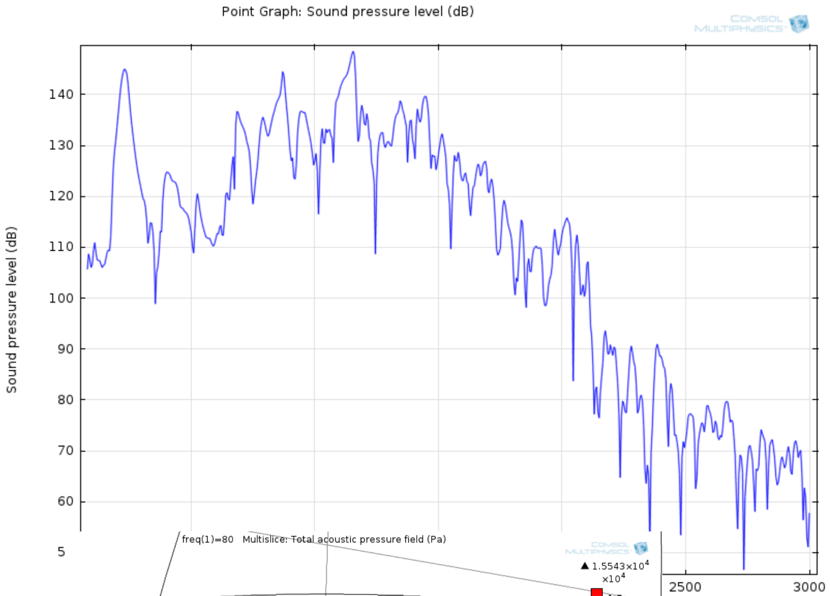
- Smooth, complex and unified geometry
- Can perform mesh generation based on CT-scans
- Complexity of simulations (fluid-structure interaction) adjusted with the mesh resolution

A 3D model of whale acoustic radiation for **formant analysis (2)**

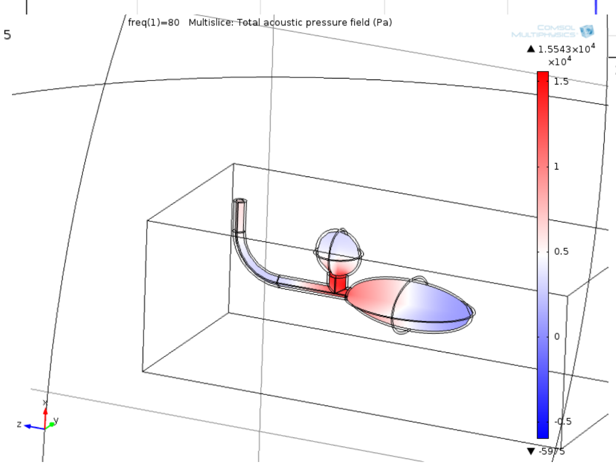




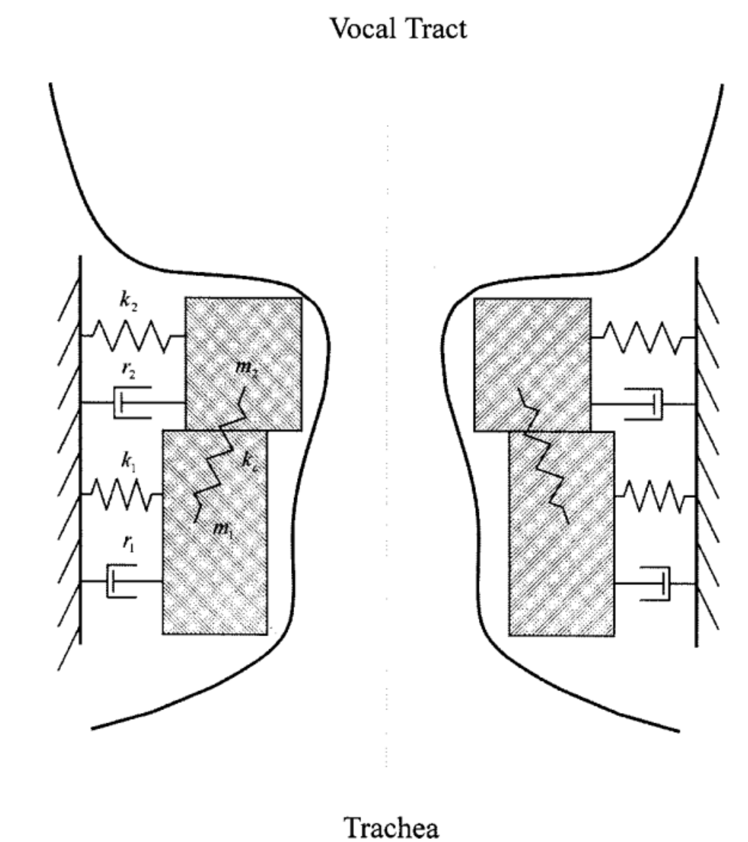
Model



Simulation



Biomechanical model with two-masses



After Steinecke 1995

Mechanical equations of motion

$$m_i \frac{d^2 x_i}{dt^2} + R \frac{dx_i}{dt} + K x_i = F_c$$

Aerodynamics relations

$$p_m = p_s - \frac{1}{2}\rho u^2 \left(\frac{1}{a_m^2} - \frac{1}{a_s^2}\right) \quad \text{(Bernouilli equation)}$$

$$p_m = p_2 \quad \text{(Jet regime)}$$

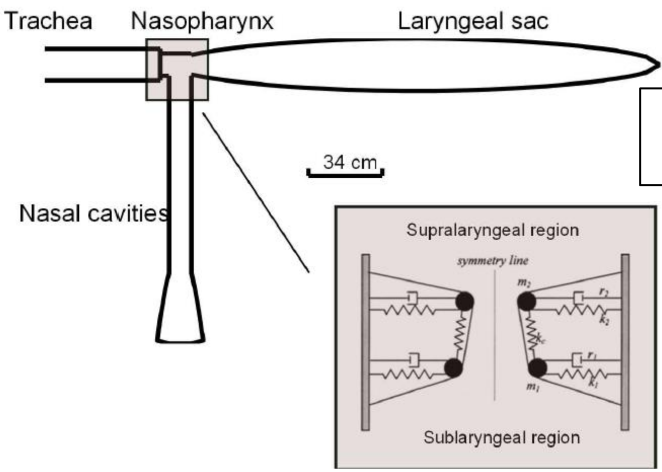
Glottal flow expression

$$u_g = \frac{c a_{\min}}{1-k_t}\left(-\frac{a_{\min}}{A^*} - [(\frac{a_{\min}}{A^*})^2 + \frac{4(1-k_t)}{c^2 \rho}(P_s^+ - P_e^-)]\text{^}0.5\right)$$

VT coupling

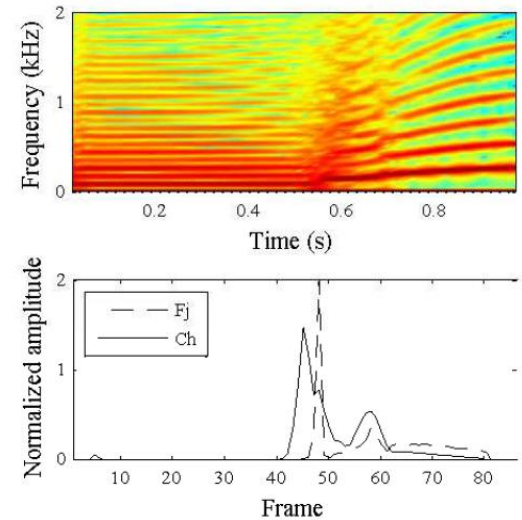
$$p_{s-} = p_{s+} - \frac{\rho c}{A_s} u \qquad p_{i-} = p_{i+} + \frac{\rho c}{A_i} u$$

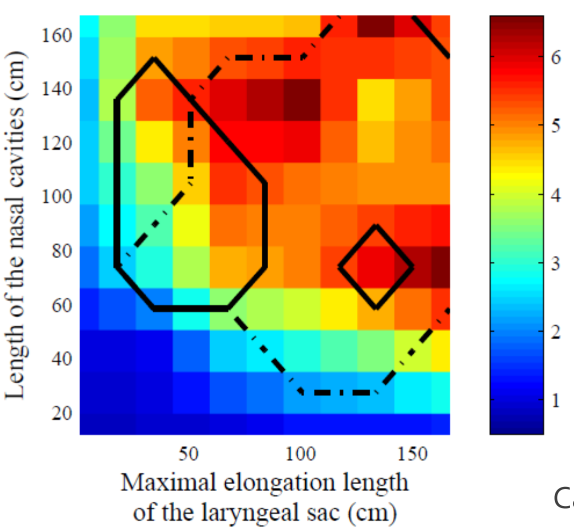
Time-domain wave reflection method for **vocal non-linearities**



Model

Simulation of vocalizations

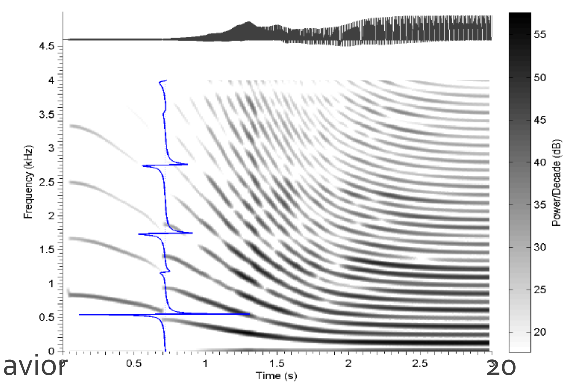




Simulation

Spatial distribution of vocal non-linearities in a geometrical map

Analyzing the physics

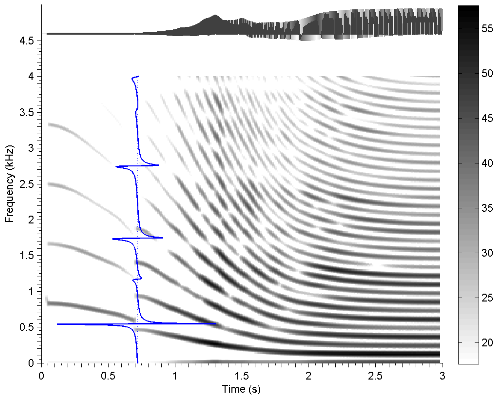


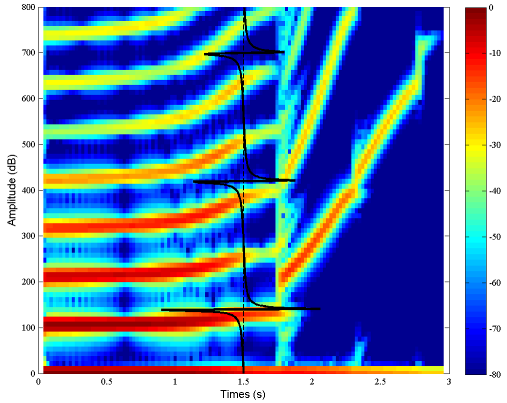
Understanding the physics behind frequency-jumps …

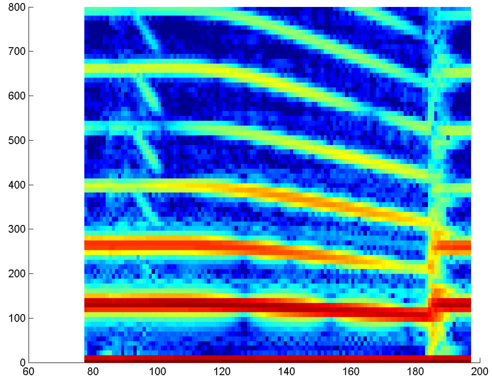
Frequency-jump may be caused by a crossing-over between a formant and the fundamental frequency

Gliding fundamental frequency

The mysticetes whale
« singing into a tube » experiment

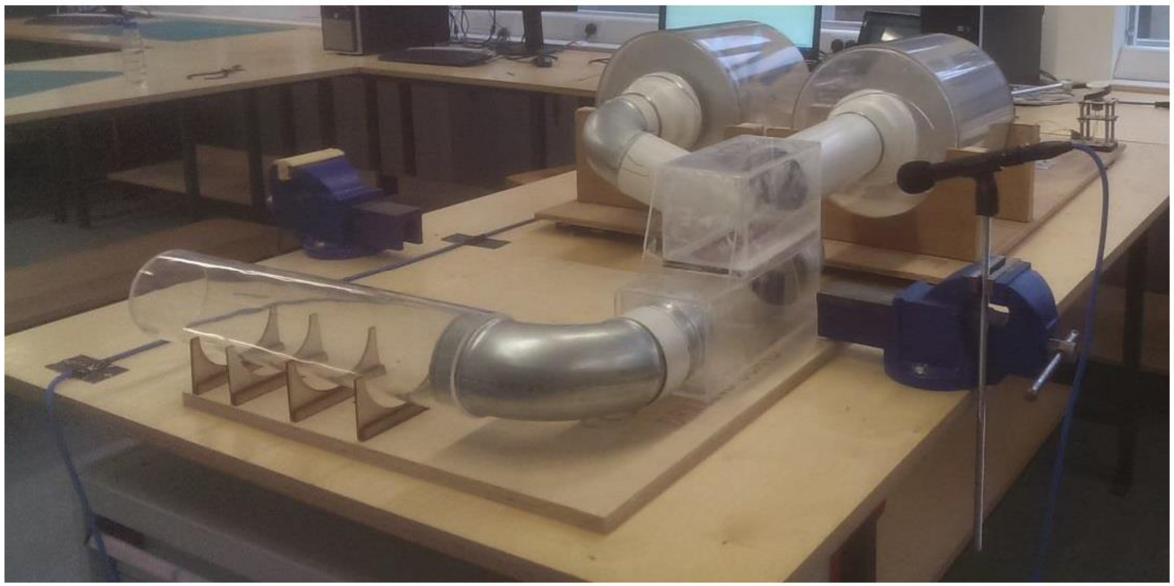






In blue, the inertance curve with positive values on the left

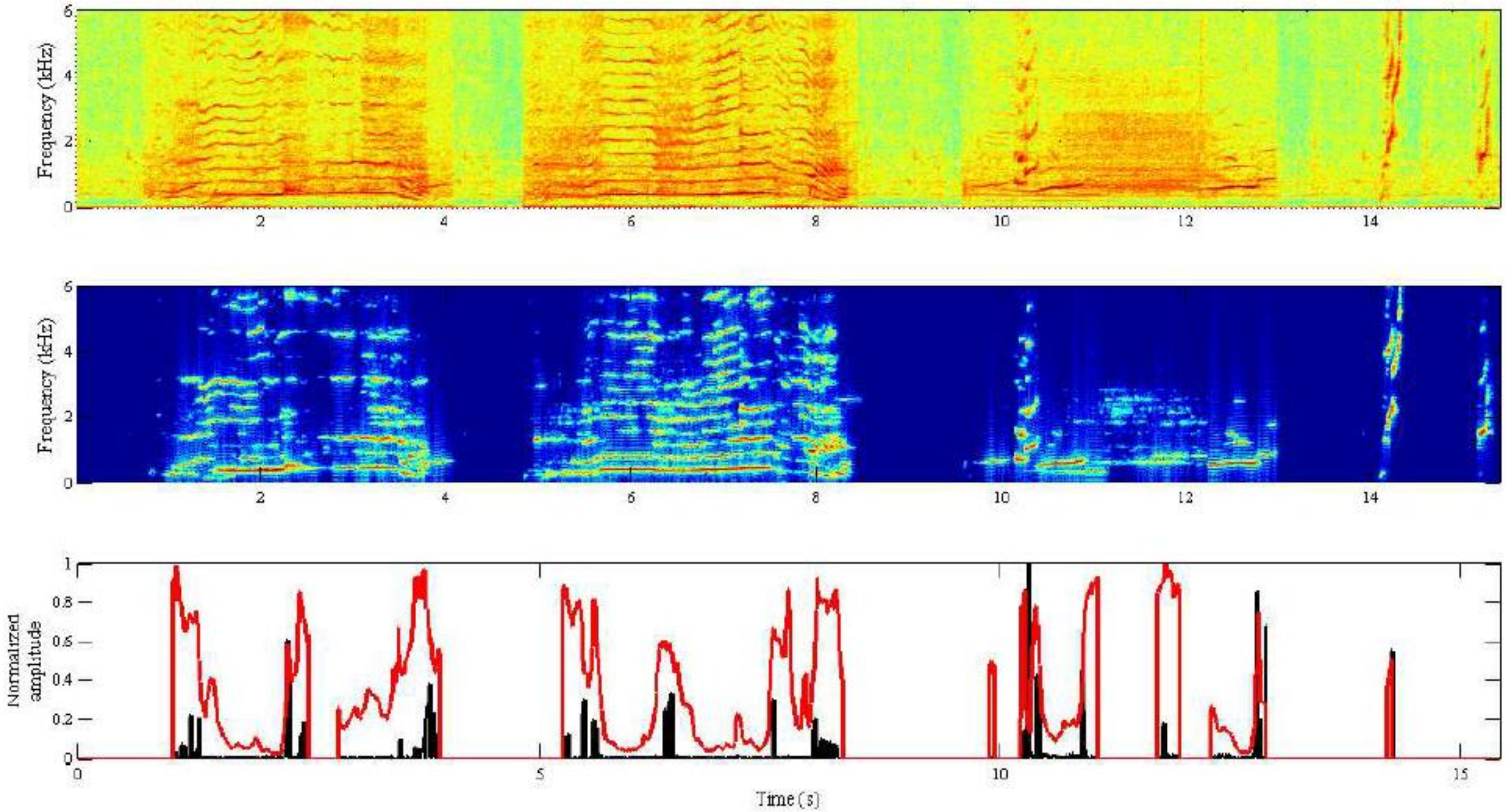
1-scale physical model (project at ISVR)



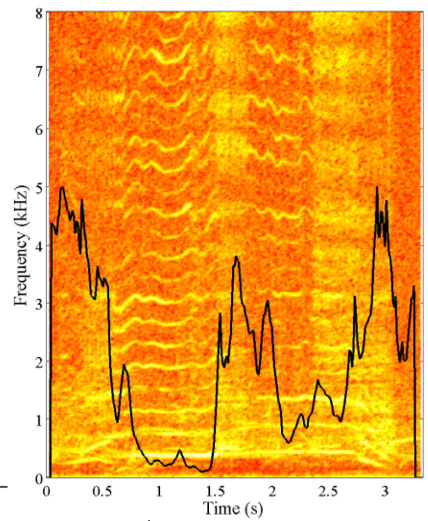
From Lallemand et al. (2014)

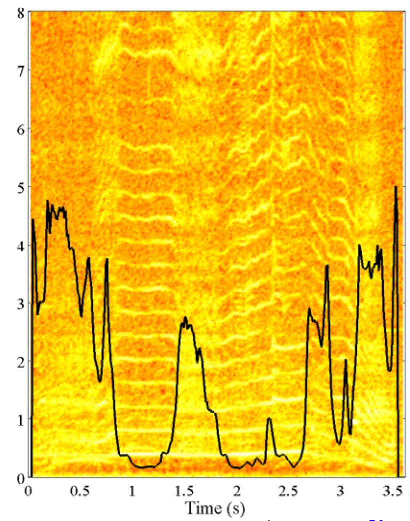
Detection of anatomy-related acoustic features

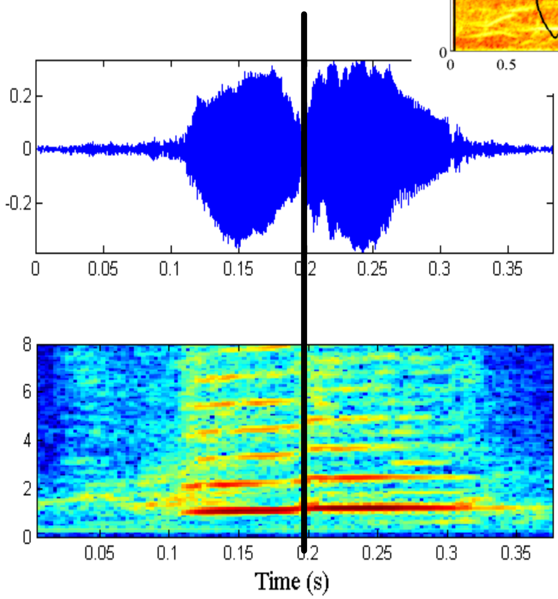
- Detection of chaos and frequency-jumps



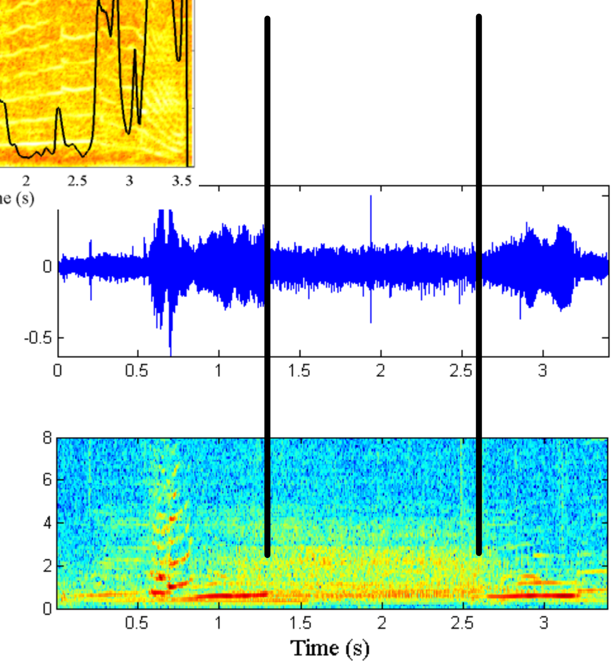
Acoustic analysis
Chaoticity in vocalizations





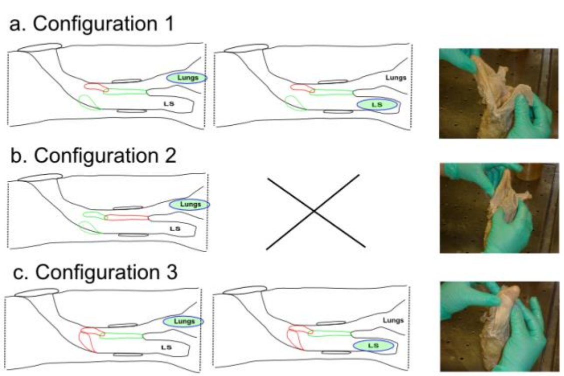


Structural function of vocal non linearities ?

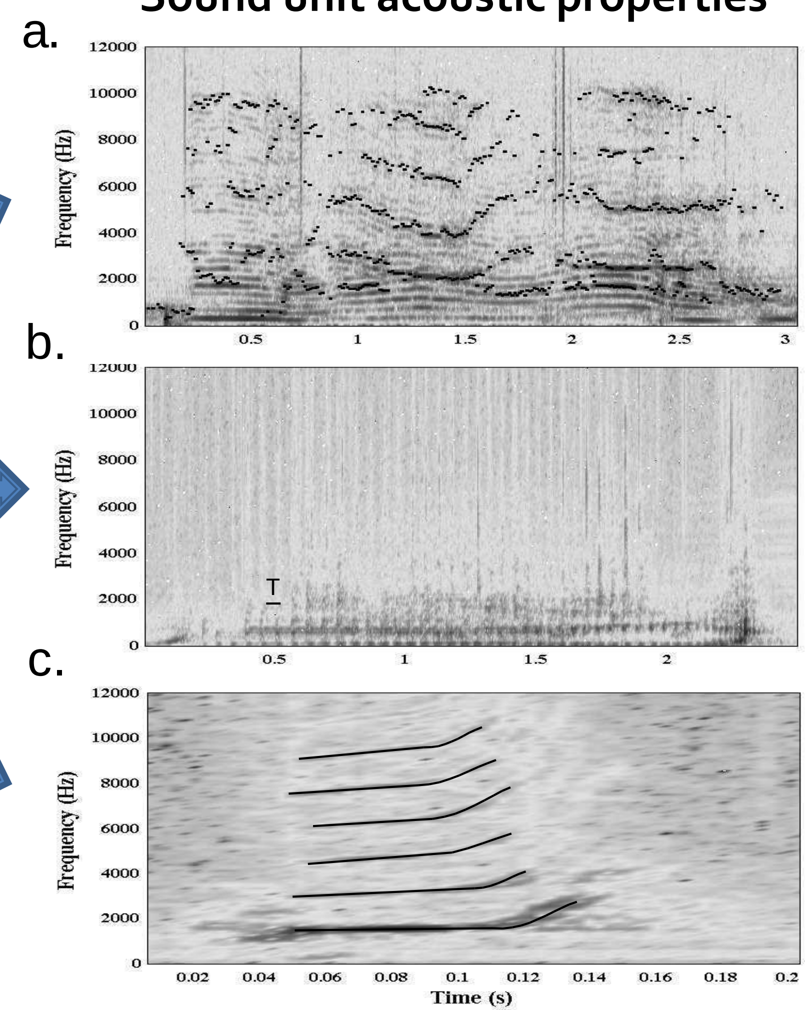


From functional anatomy to sound unit acoustic properties

Functional anatomy on sound production

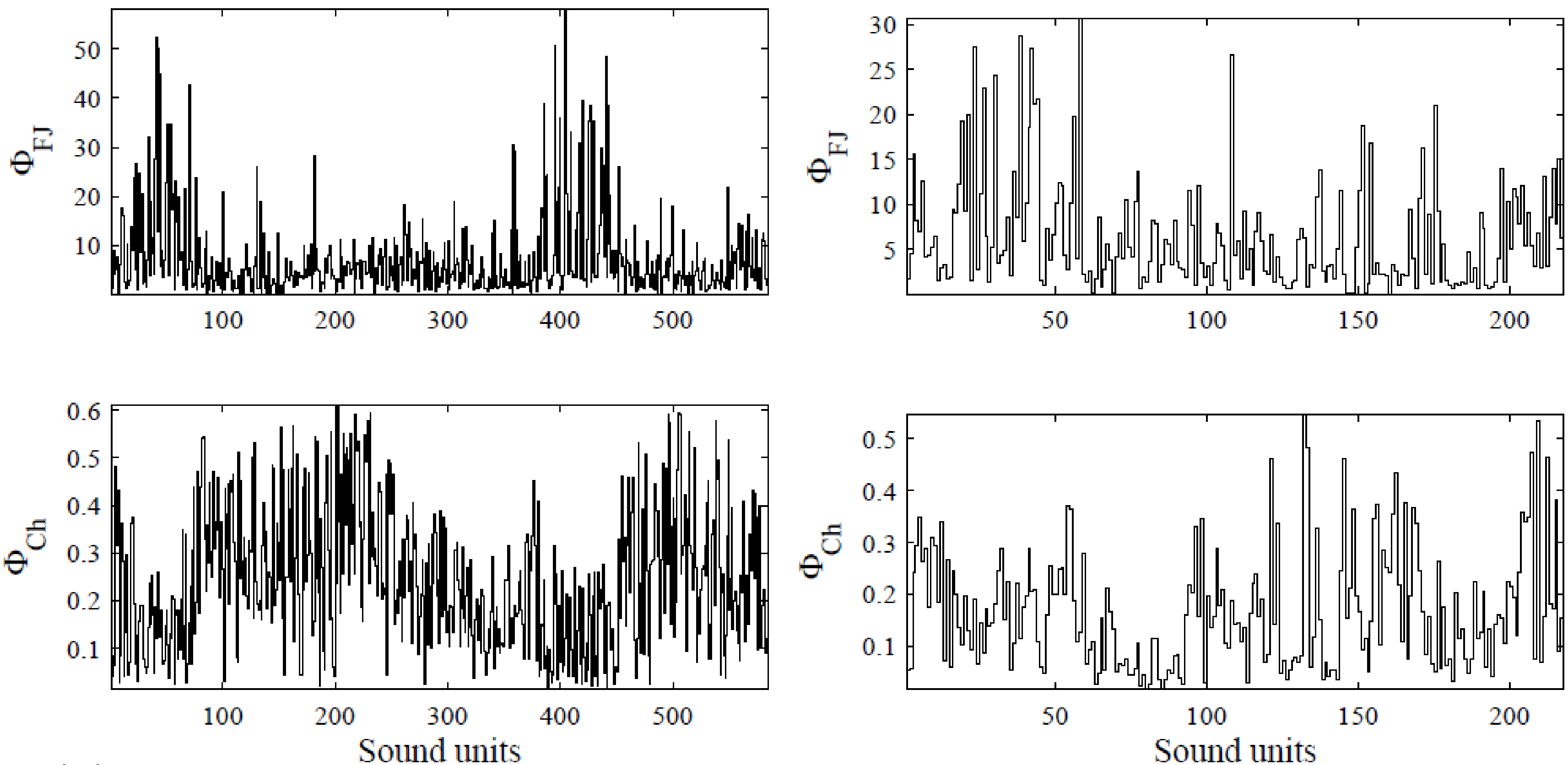


Sound unit acoustic properties



Time-dependent descriptors / identification of temporal events

- Temporal distributions of frequency jumps (on top) and chaos (on bottom) in two different songs



III – Conclusion & Perspectives

Conclusions and Perspectives

- Production-based approach to mysticete acoustic behavior ;
- Connection between Anatomy – Modelling – Acoustics ;
- No anatomy-informed dataset for the moment

Perspectives : relating acoustic analysis with behavioural hypothesis

- Statistic analysis of certain call type occurrences in reference to specific context of sound production (- social function)
- Temporal distribution of anatomy-related acoustic features (- energy cost and vocal skills)
- Calf/adult and female/male vocal repertoire differences (- vocal performance and learning)
- Towards an individual-specific acoustic signature?

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Thanks for your attention !