On Musical Hearts and Heart Music

Elaine Chew

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Department of Engineering, Faculty of Natural, Mathematical & Engineering Sciences

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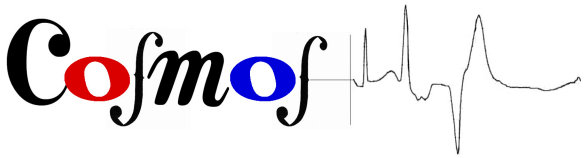


Agenda

- Background
- Heart Music
- Music~Heart
- Musical Hearts

International Series in Operations Research & Management Science ISOR 204

Elaine Chew

Mathematical and Computational Modeling of Tonality

Theory and Applications

I have watched with interest and appreciation as Elaine Chew's Spiral Array model has developed over the last 15 years. It is unique in representing pitches, intervals, chords, and keys in the same elegant geometric representation. In this way, the model addresses the fundamental problem of how to represent the hierarchical nature of tonal listening. The monograph presents in-depth analyses of a wide variety of interesting musical examples as well as large-scale, quantitative tests of algorithms for key-finding, pitch spelling, and musical segmentation. The reader will be amply rewarded with mathematical and musical insights – and intrigued by the power of mathematics to reveal the inner workings of music cognition.

– Carol Lynne Krumhansl, Professor of Psychology Cornell University

"What do you mean by key?" The seemingly innocent question asked once to the author by a student initiates a fascinating scientific journey into the concept of tonality addressed through its cognitive, mathematical and computational ramifications. This essential yet accessible and entertaining book results from years of research and experimentation by one of today's prominent minds in music science, with the right balance of formal modelling, experimentation and musical knowledge, always situated in the history of ideas. The student and the professional in computation and music related domains will benefit greatly from reading this book, as well as the music lover interested in reflecting on the way we apprehend tonality.

– Gerard Assayag, Research Director, Sciences and Technologies for Music and Sound Laboratory (IRCAM, CNRS, and Pierre et Marie Curie University)

From its imaginative opening pages to its rigorous appendices, Chew's book takes the reader on an engrossing tour through the theory and applications of her ingenious multiple-helix model of musical tonality. She approaches music theory and cognition from a fresh perspective inspired by operations research, to great advantage. One comes away with the clear sense that this approach will continue to bear fruit, whether through elaboration of the underlying model or through discovery of its applicability to new practical problems. No one interested in pitch representation, computational music analysis, or music visualization should miss this important volume.

– Douglas Keislar, Editor, Computer Music Journal (MIT Press)

Business/Economics

ISBN 978-1-4614-9474-4

▸ springer.com

Chew

Mathematical and Computational Modeling of Tonality

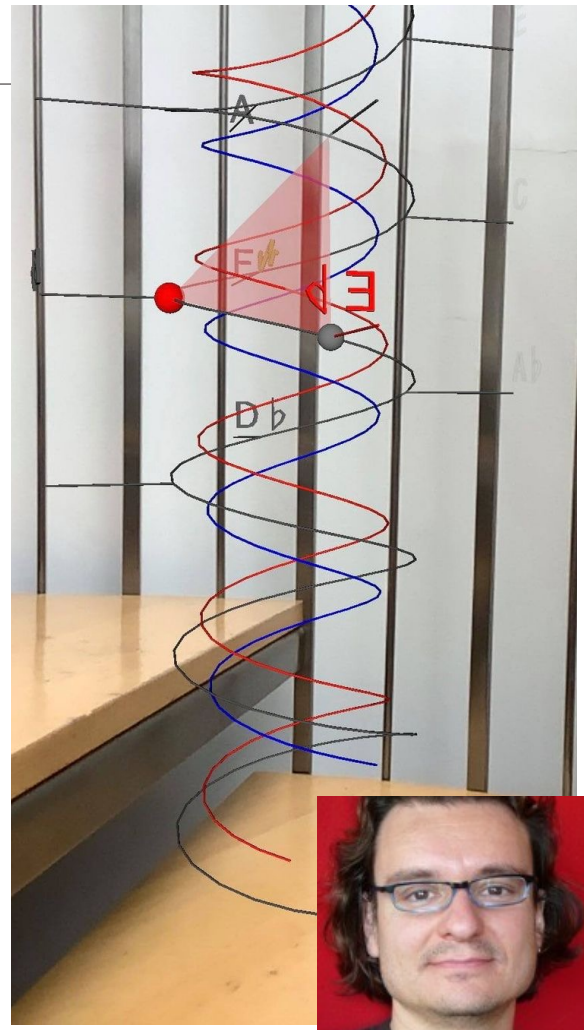
International Series in
Operations Research & Management Science

Elaine Chew

Mathematical and Computational Modeling of Tonality

Theory and Applications

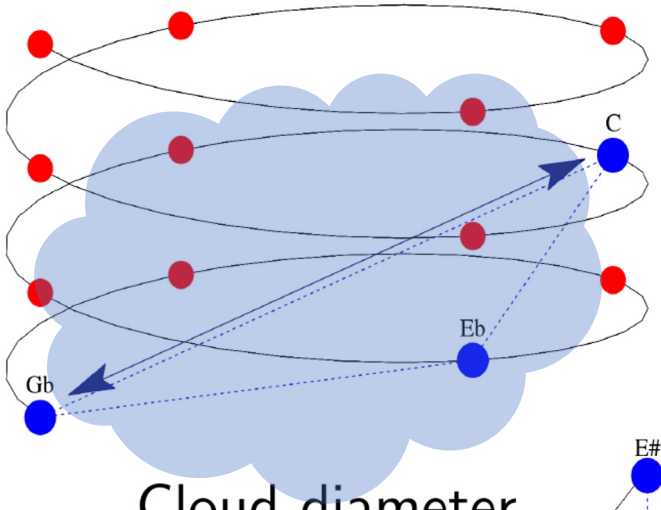
Springer



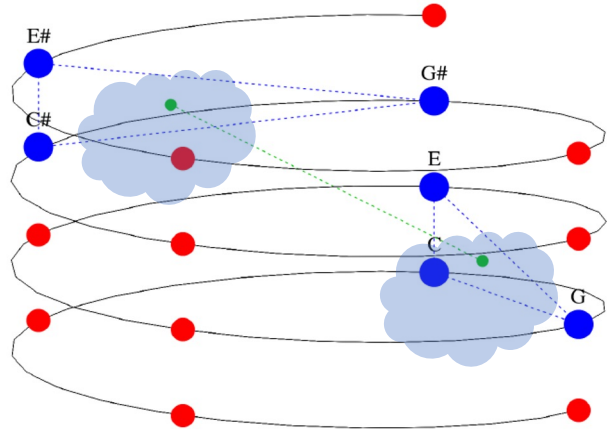
MuSA_RT 4+
Tonality 3D visualization
+ Augmented Reality
by Alexandre Francois

https://bit.ly/musa_rt

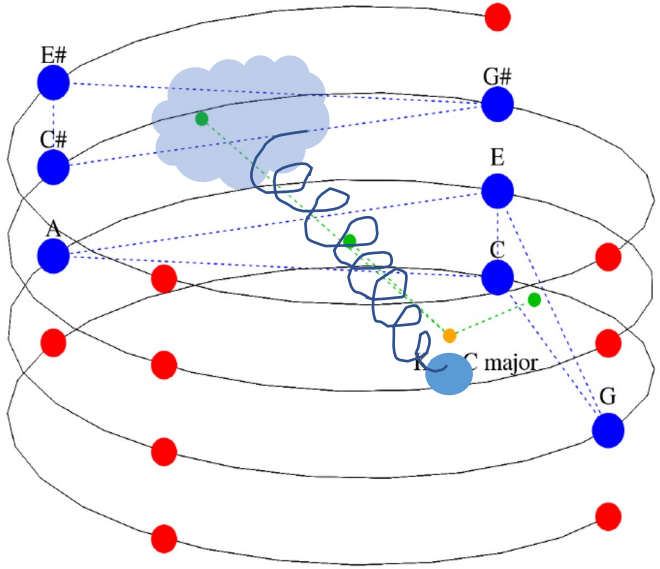
Tension



Cloud diameter
(dissonance)



Cloud momentum
(chord change)



Tensile strain (distance to key)

[Herremans & Chew TENOR 2016]

MorpheuS: generating structured music with constrained patterns and tension

Dorien Herremans, *Senior Member, IEEE,* and Elaine Chew, *Member, IEEE,*

Abstract—Automatic music generation systems have gained in popularity and sophistication as advances in cloud computing have enabled large-scale complex computations such as deep models and optimization algorithms on personal devices. Yet, they still face an important challenge, that of long-term structure, which is key to conveying a sense of musical coherence. We present the MorpheuS music generation system designed to tackle this problem. MorpheuS' novel framework has the ability to generate polyphonic pieces with a given tension profile and long- and short-term repeated pattern structures. A mathematical model for tonal tension quantifies the tension profile and state-of-the-art pattern detection algorithms extract repeated patterns in a template piece. An efficient optimization metaheuristic, variable neighborhood search, generates music by assigning pitches that best fit the prescribed tension profile to the template rhythm while hard constraining long-term structure through the detected patterns. This ability to generate affective music with specific tension profile and long-term structure is particularly useful in a game or film music context. Music generated by the MorpheuS system has been performed live in concerts.

Index Terms—Affective Computing, Music, Music retrieval and generation, Affective computing applications, Sound and Music Computing, Entertainment, Variable Neighborhood Search, Pattern Recognition

1 Introduction

Technologies for digital music have become increasingly important, bolstered by rising global expenditures in digital music in excess of 64 billion USD in 2014 alone [1]. The popularity and relevance of automatic *music generation* has recently been underscored by the launch of Google's Magenta project[1], "a research project to advance the state of the art in machine intelligence for music and art generation". In this research, we develop a music generation system, called Morpheus [2], that tackles one of

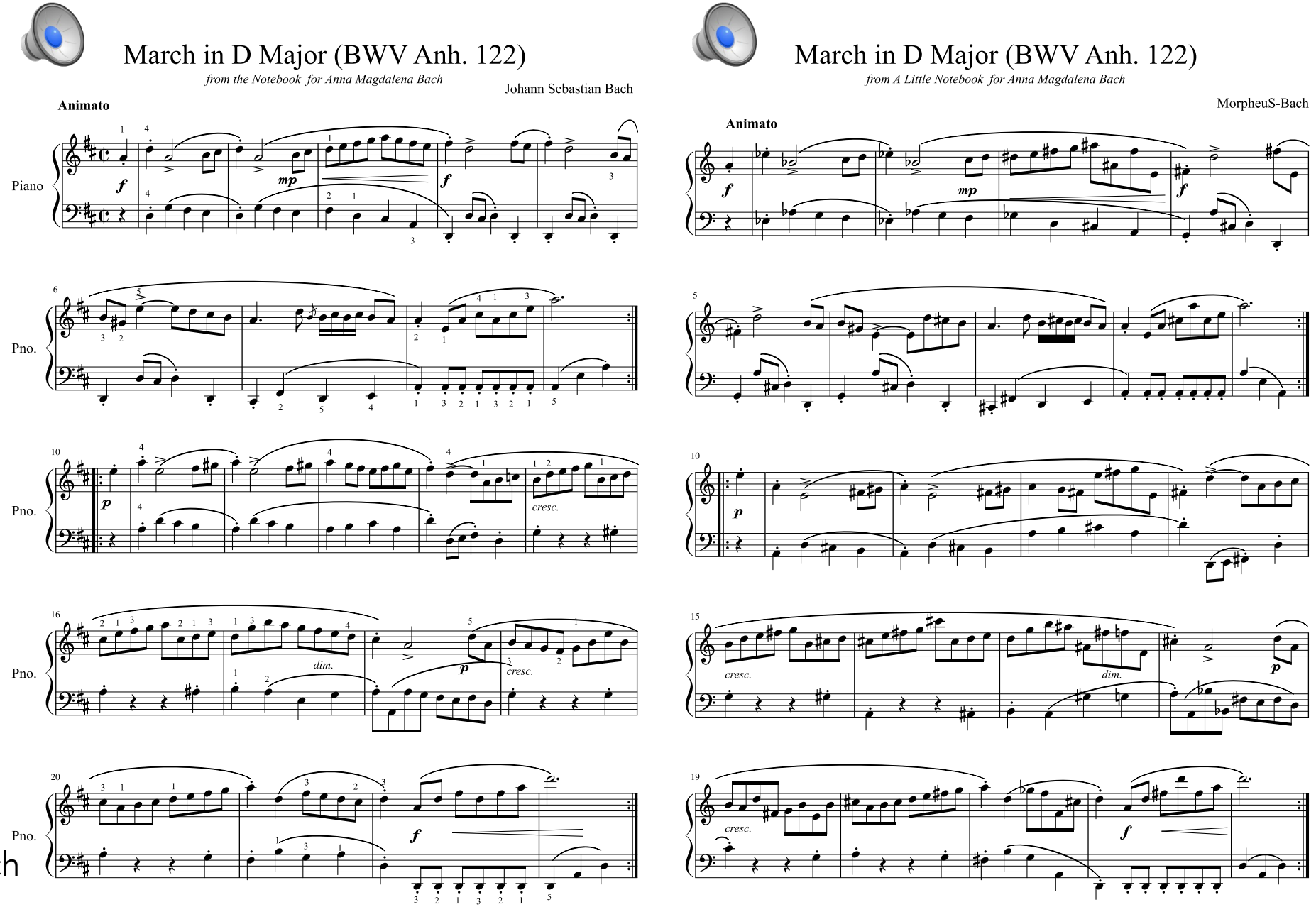
force constraints (e.g. long-term structure) in music generation systems based on machine learning methods such as Markov models [3]. In previous research, the first author therefore developed a novel method for constraining long-term structure through an optimization-based approach, combined with machine learning. The proposed framework consisted of an efficient variable neighborhood search (VNS) optimization algorithm that is able to generate melodies (or monophonic music) with a fixed semiotic structure (e.g.

Dorien Herremans
MSCA Fellow 2015-2017
Now Assistant Prof, SUTD

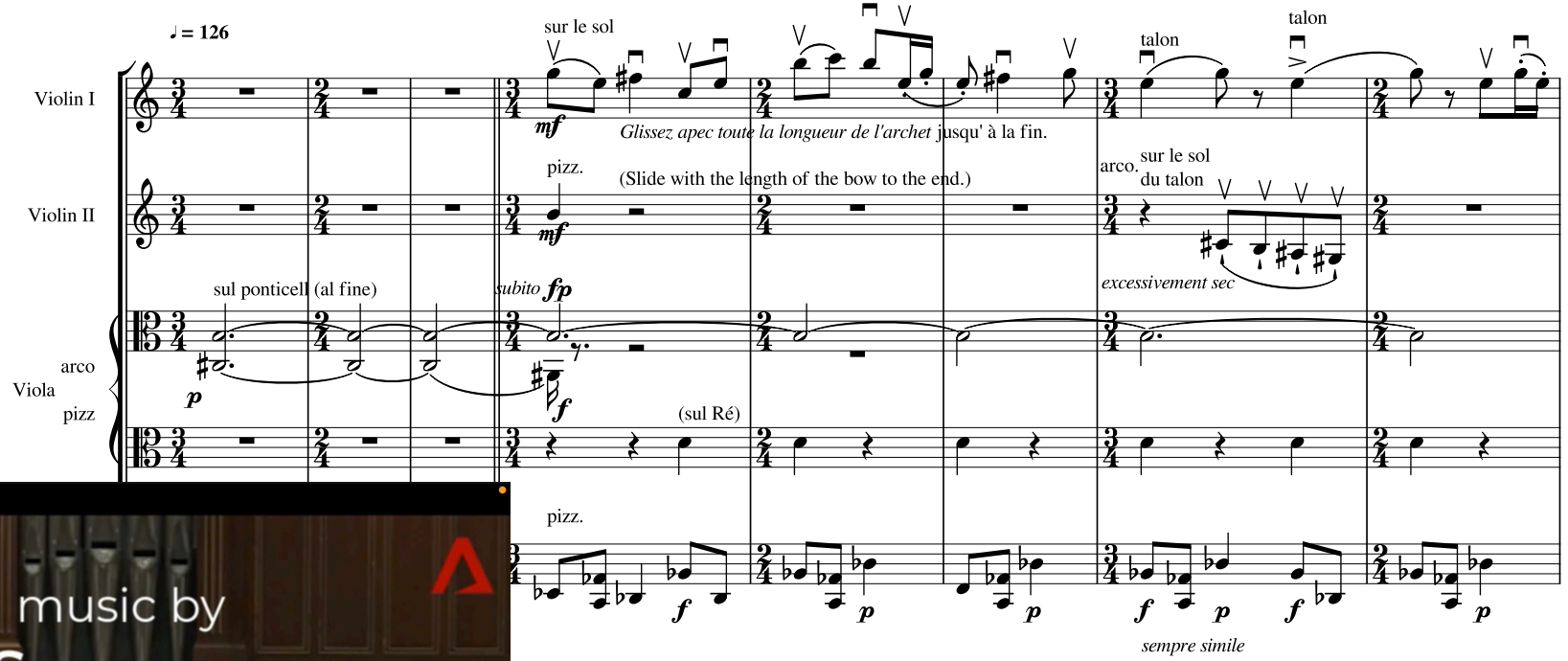
MorpheuS
Notes random start

Constraints
Rhythm
Repeated patterns
Harmonic tension profile

Meta heuristic
Variable neighborhood search



dorienherremans.com/morpheus



MorpheuS

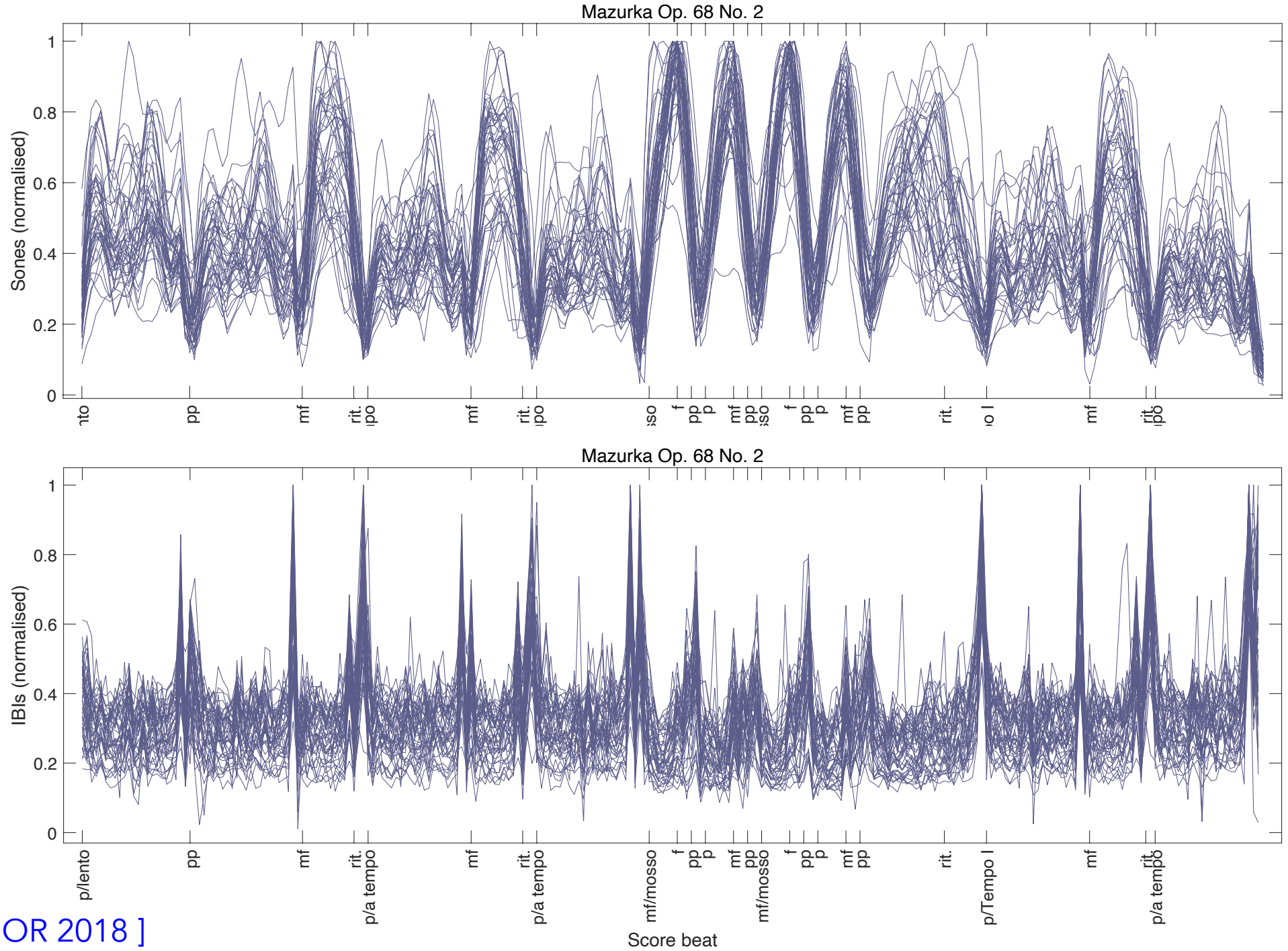
8PM, Monday, 8 October 2018
Channel News Asia Algorithms (Part 1):
Rage Against the Machine:
Man vs. Machine

MazurkaBL

Score-aligned
Beat and Loudness
With expression markings

2000 Mazurka recordings

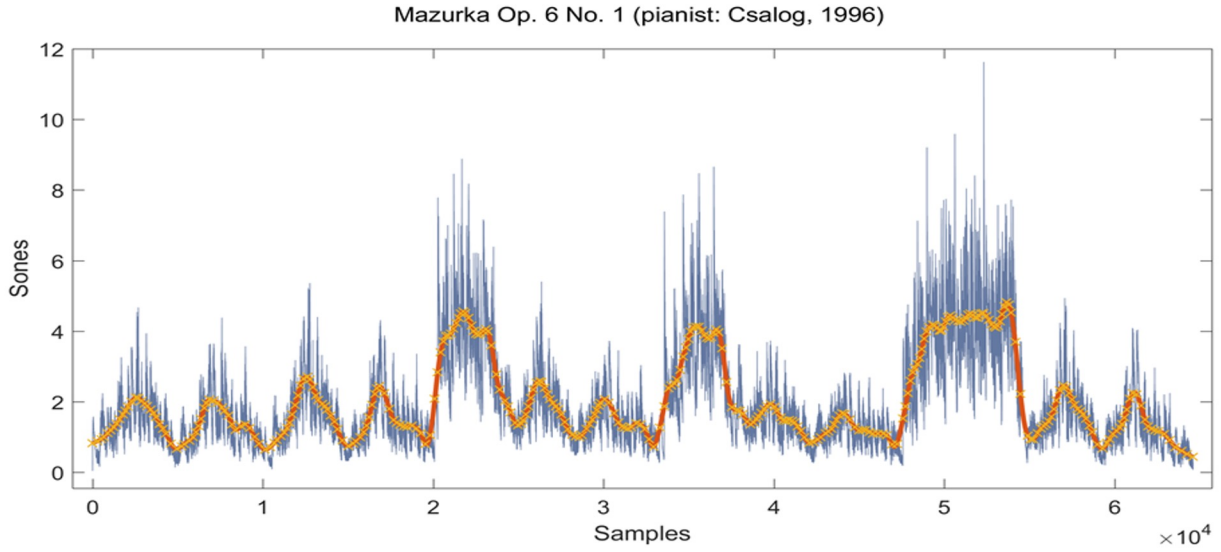
Katerina Kosta
Now Senior Machine Learning Researcher, ByteDance/TikTok

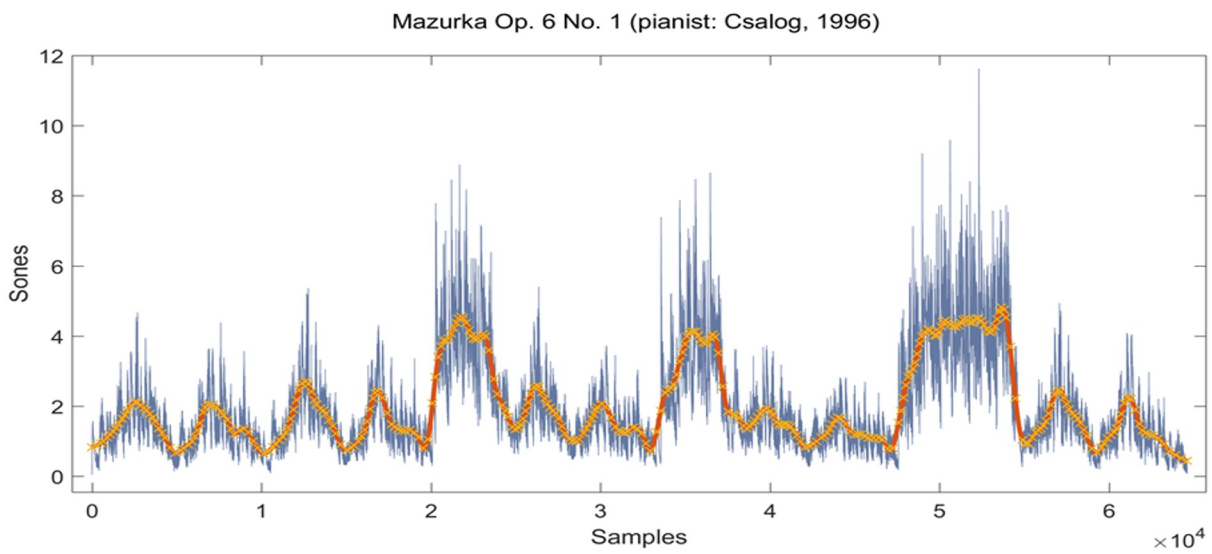


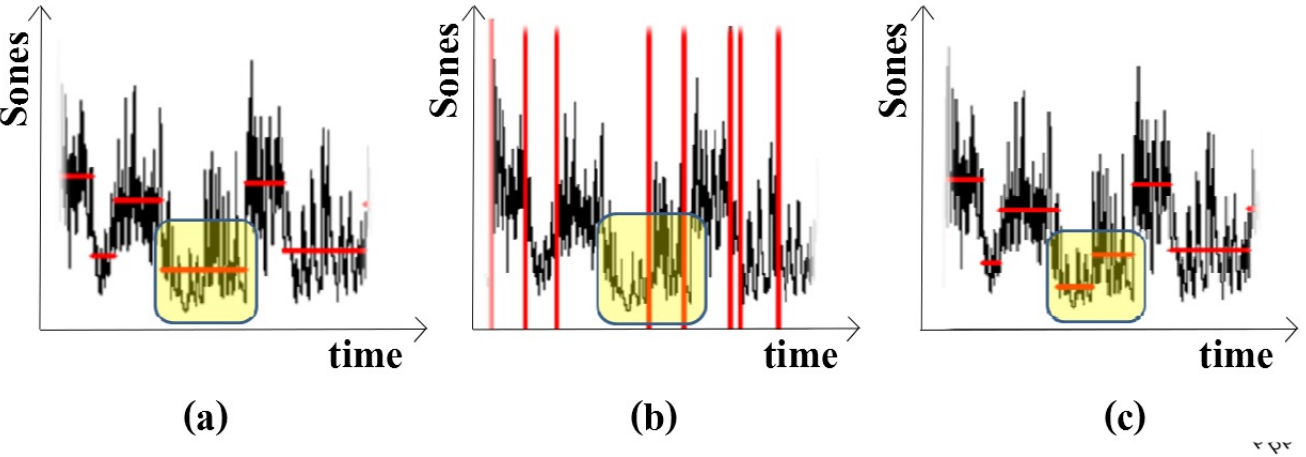
[Kosta, Bandtlow, Chew TENOR 2018]

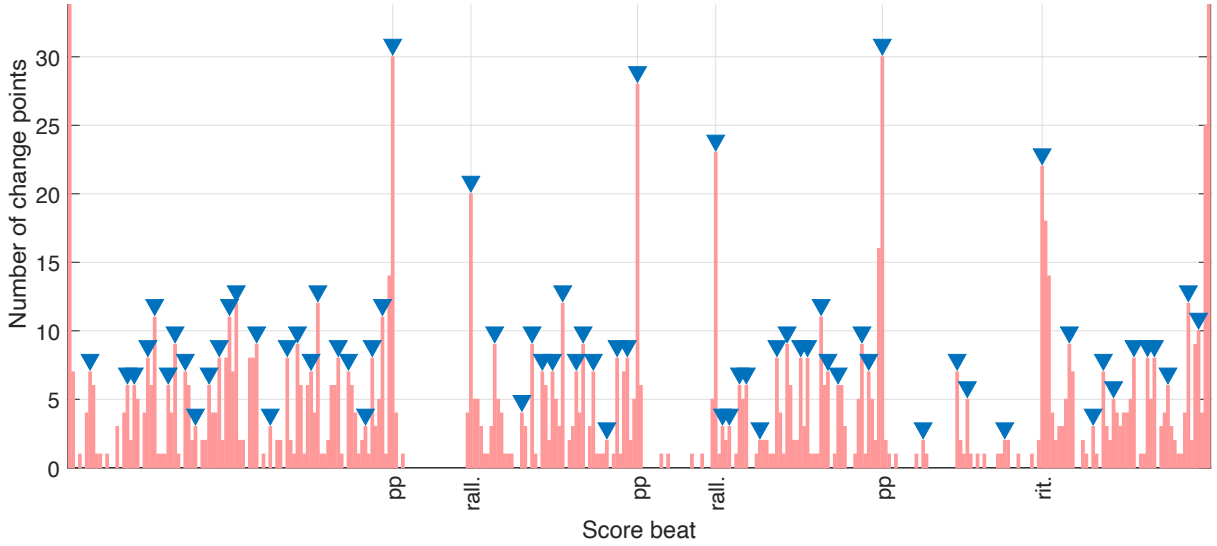
[Kosta, Killick, Bandtlow, Chew ISMIR 2017]

Change-points Analysis of Loudness





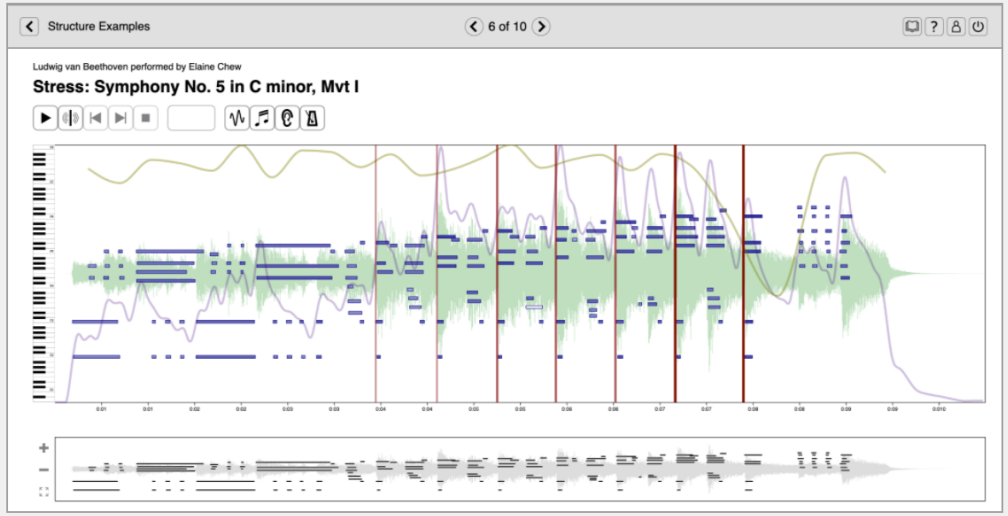




CosmoNote

https://cosmonote.ircam.fr

Listen for and annotate musical structures



CosmoNote is a web-based citizen science annotation platform

Learn more

Create an account

user@example.com

password

I am over 18 years old, have read the User Agreement, and agree to participate in the study

Keep me informed ?

Create Account

Already have an account?

Log In

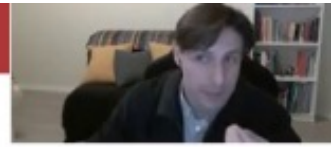
News

December 2021: CosmoNote unveils the Glenn Gould collection!

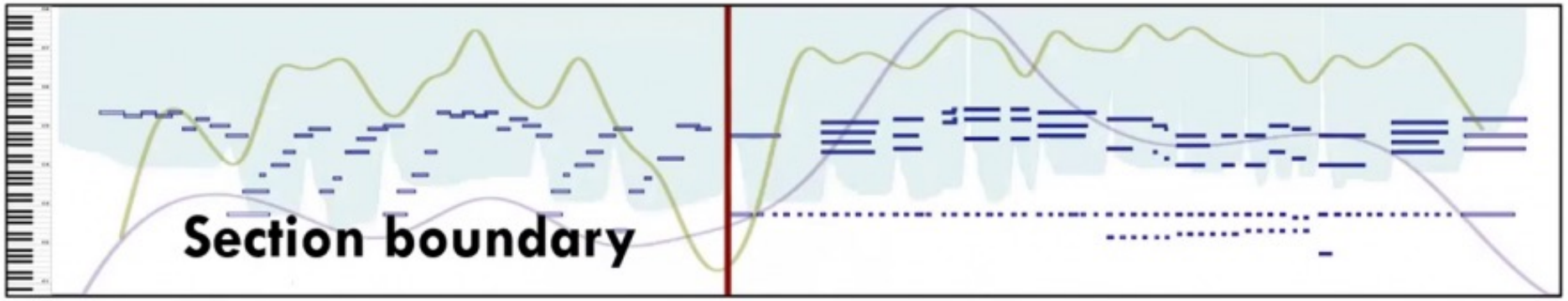
The new collection features Glenn Gould's original audio recordings of Bach's Goldberg Variations from 1955. CosmoNote features the individual notes and their timings as performed by Glenn Gould and meticulously derived, courtesy of Steinway, from the original recordings.

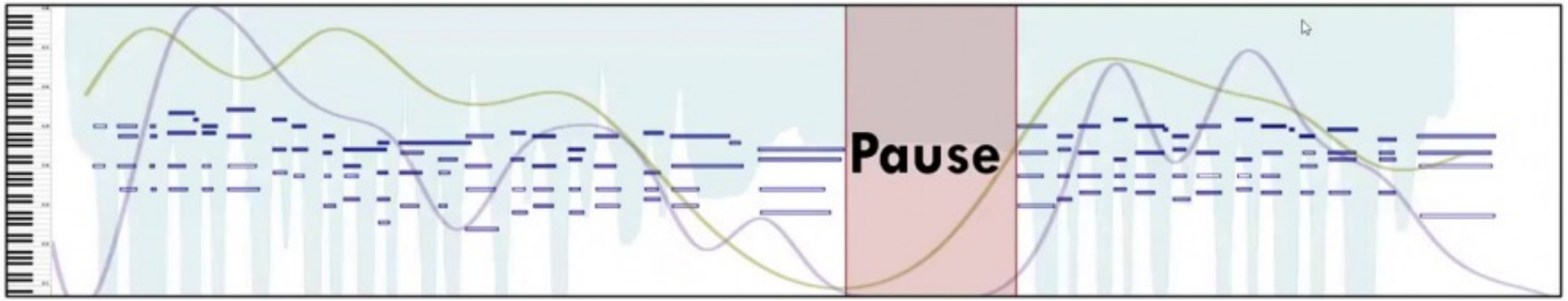
Fyfe, L., D. Bedoya, C. Guichaoua, E. Chew (2021). CosmoNote: A Web-based Citizen Science Tool for

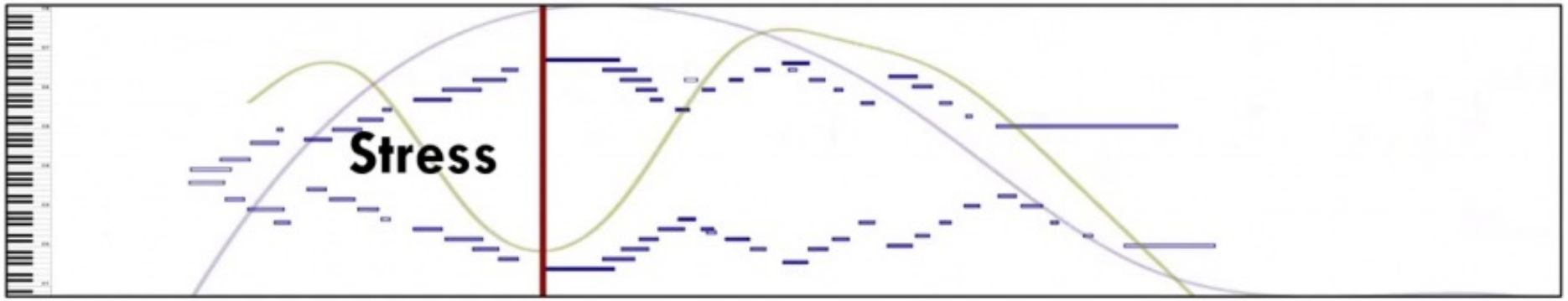
uestions or comments? cosmos@ircam.fr • Acknowledgments

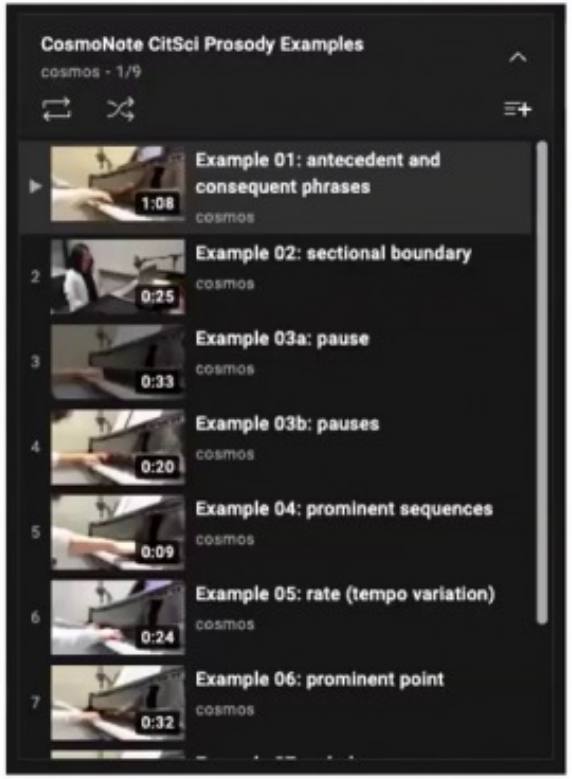


A growing library of examples





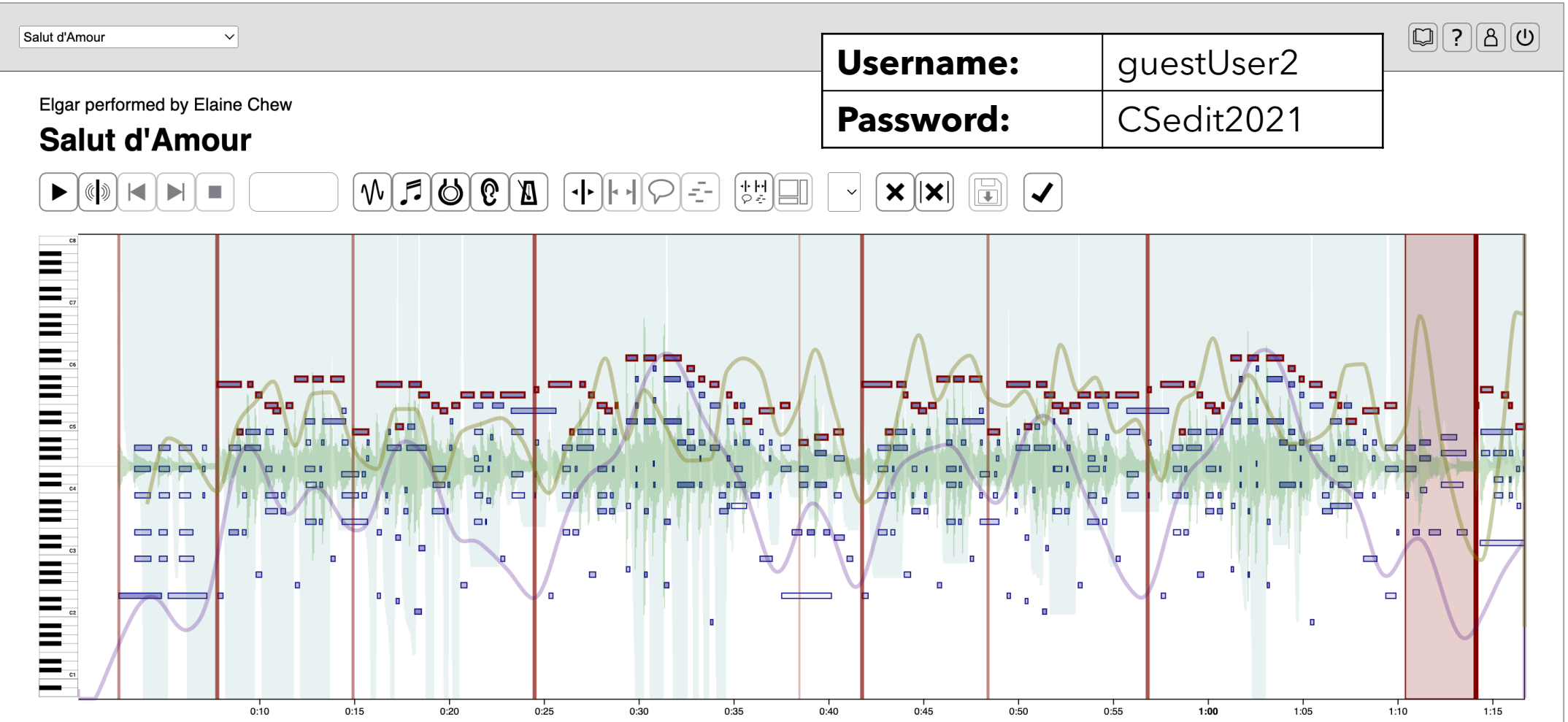




Annotation convention and growing library of examples

[Bedoya, Fyfe, Chew 2021 ISPS]

Art is not what you see but what you make others see ~ Degas



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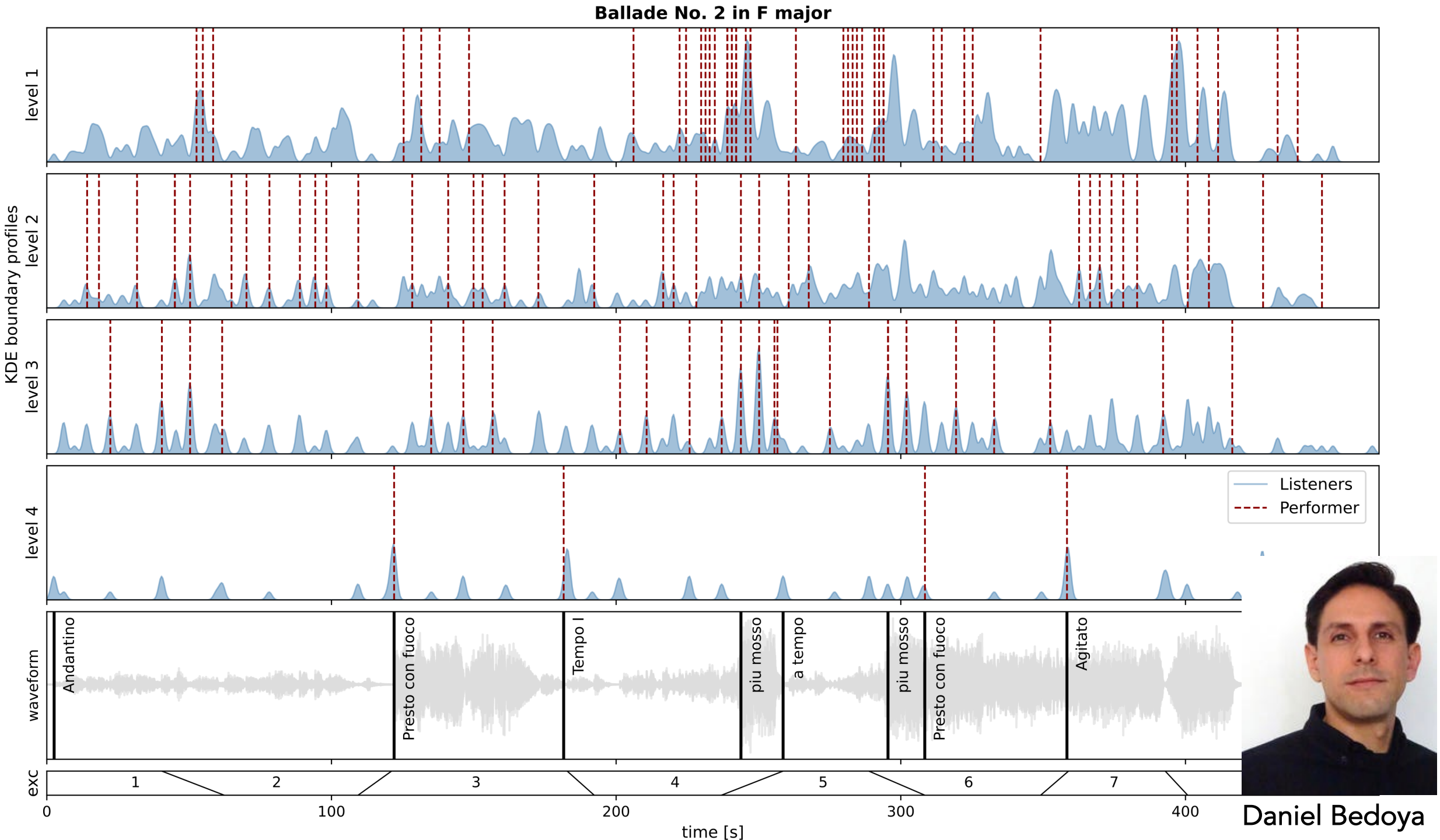
Lawrence Fyfe
Daniel Bedoya

D. Bedoya, Fyfe, L., E. Chew (2022). A Perceiver-Centered Approach for Representing and Annotating Prosodic Functions in Performed Music. Front. Psychol., 21 July 2022 Sec. Performance Science https://doi.org/10.3389/fpsyg.2022.886570

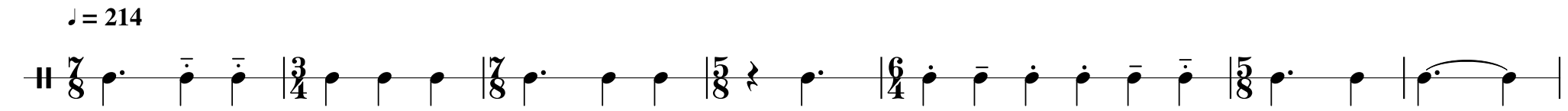

Ballade No. 2 in F major
KDE boundary profiles
level 1
level 2
level 3
level 4
Listeners
Performer
waveform
Andantino
Presto con fuoco
Tempo I
piu mosso
a tempo
piu mosso
Presto con fuoco
Agitato
exc
1
2
3
4
5
6
7
0
100
200
300
400
time [s]
Daniel Bedoya

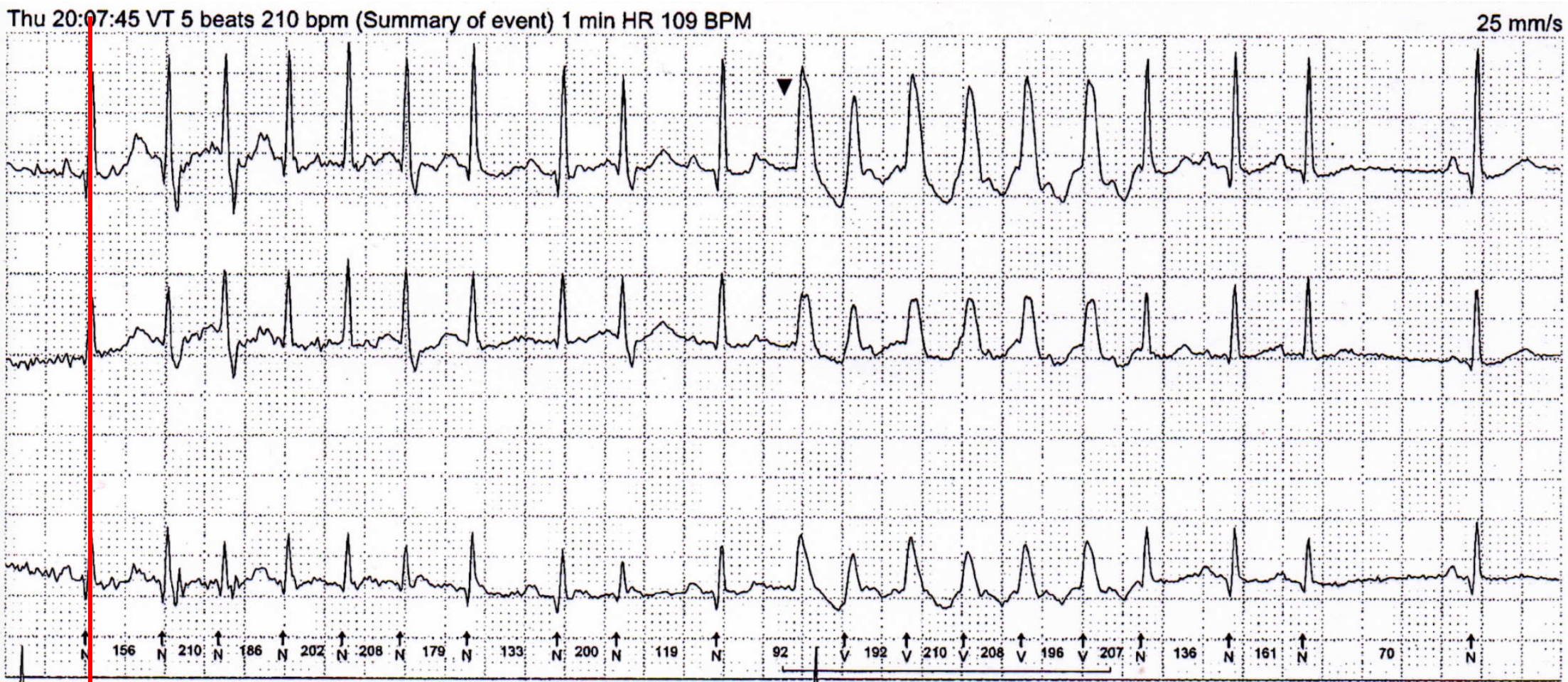
Agenda

- Background
- Heart Music
  - Putting One's Heart Into Music
- Music~Heart
- Musical Hearts

Thu 20-07-45 VT 5 beats 210 bpm (Summary of event) 1 min HR 109 BPM

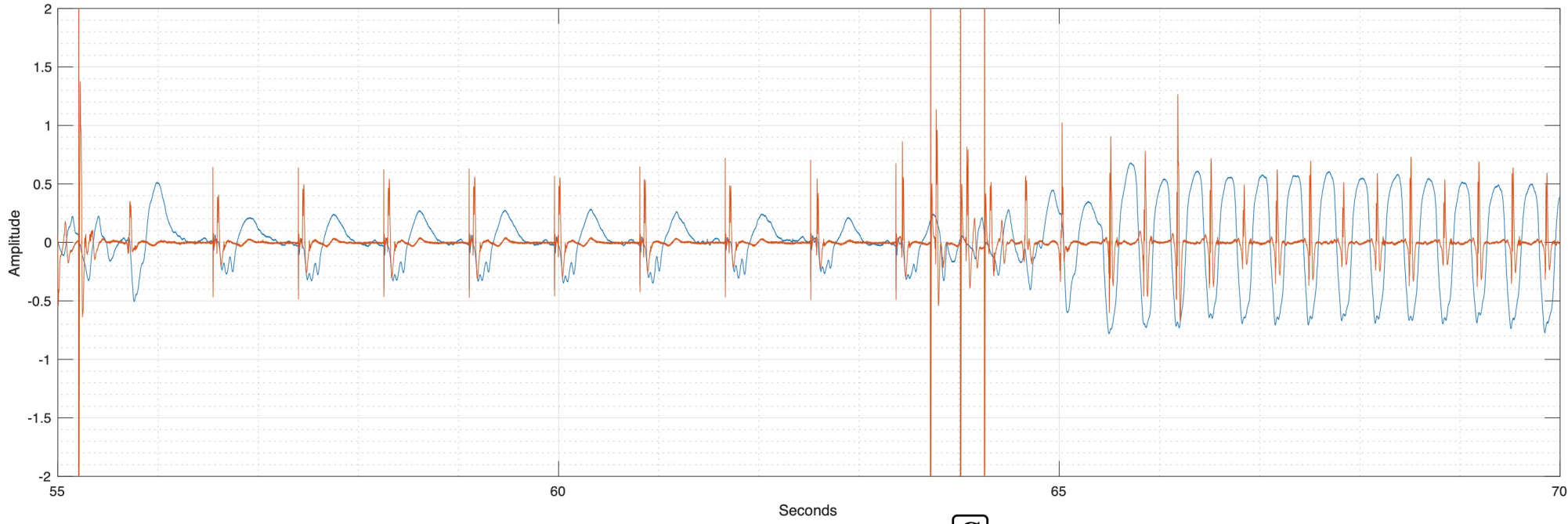
[10, 7, 8, 7.5, 7, 8.5, 11, 7, 12.5, 10, 7*, 8*, 7*, 7*, 8*, 7.5*, 11, 9, 21]





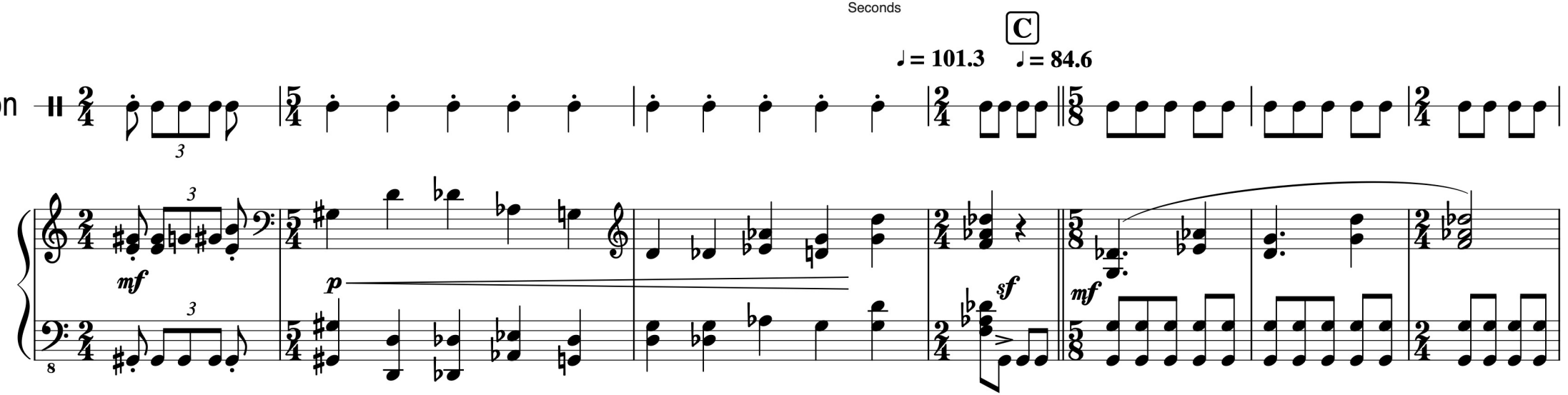
Chew (Music & Science 2018)

[EHJ Cardiopulse (2021) 42(28): 2721–2724]



Rhythm Transcription

Collage Music

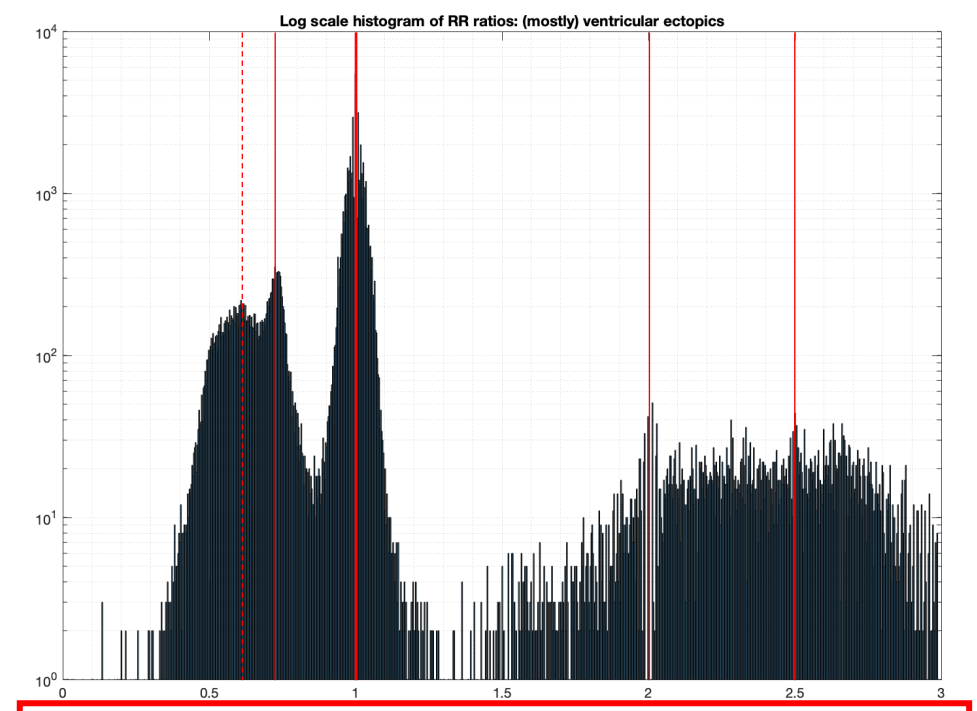


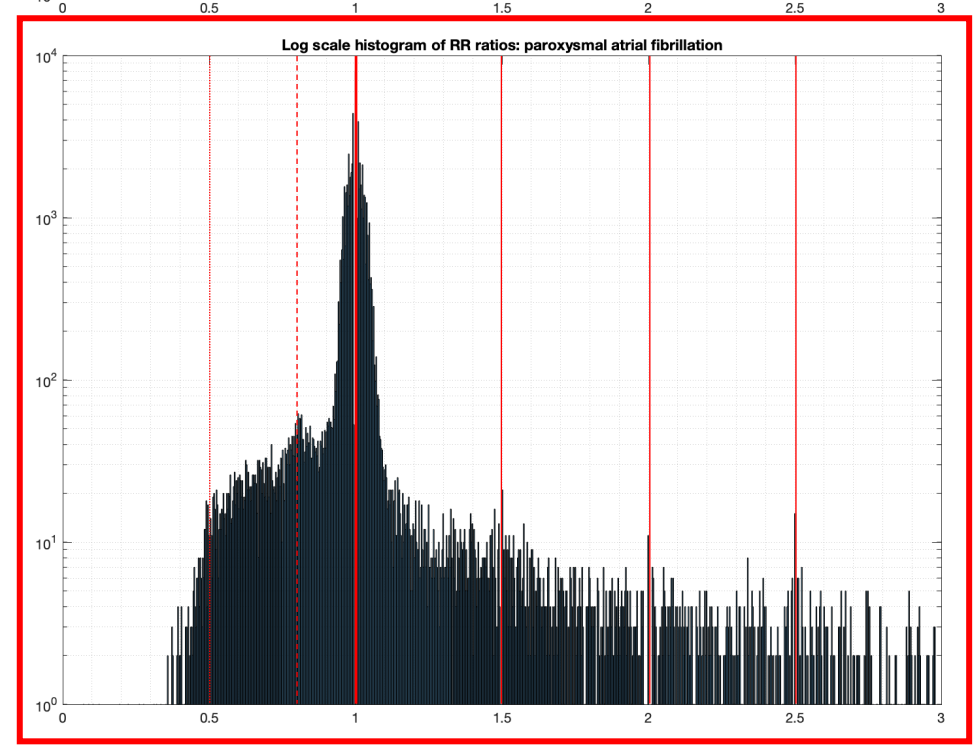

Allegro con brio. (♩ = 108)
Flauti 1, 2
Oboi 1, 2
Clarinetti 1, 2 in B♭
zu 2
ff
Fagotti 1, 2
Corni 1, 2 in E♭
Trombe 1, 2 in C
Timpani in C, G
Violino I
Violino II
Viola
Violoncello
Contrabasso
N 102 V 164 V 168 V 112 V 46 N 72 N
N 65 N 96 V 162 V 180 V 136 V 41 N 64 N

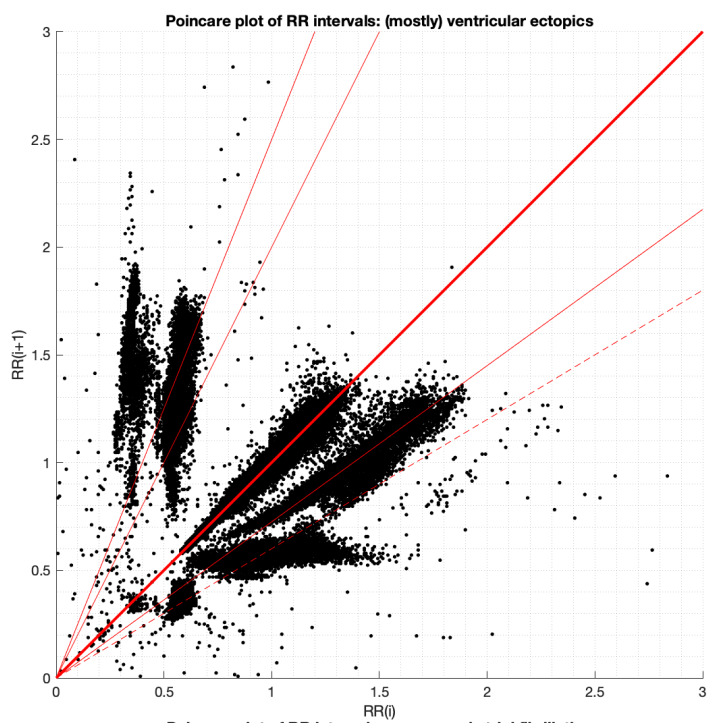
Arrhythmia Music

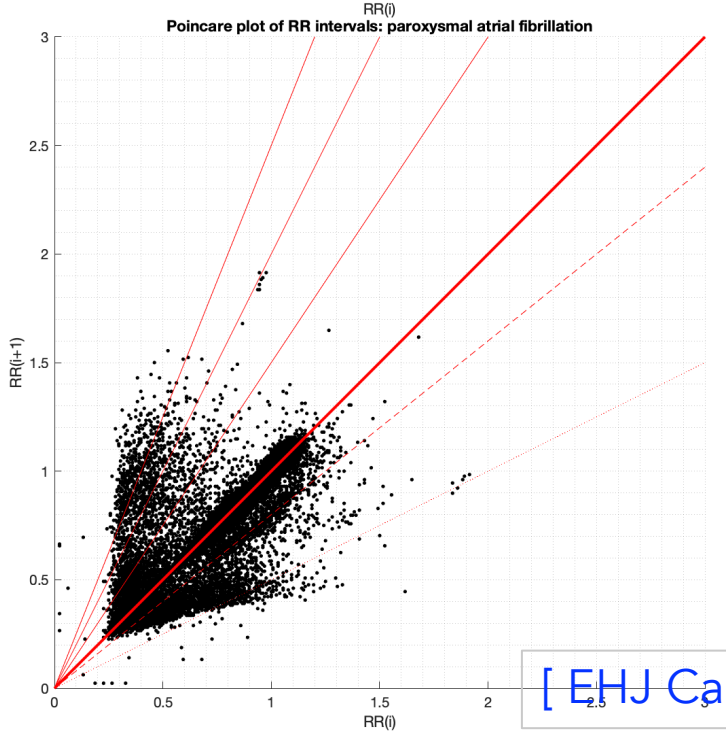
- **Holter Highlights** – https://youtu.be/Md-ocOH8Ut8
  I. Mixed Meters (after Libby Larsen's Penta Metrics)
  II. Siciliane (after Bach's Flute Sonata, BWV1031)
  III. Tango (after Piazzolla's Le Grand Tango)
- **Arrhythmia Suite**
  I. 161122 VT before during after ECG (after Holst's Mars) – https://youtu.be/z8aspgwes1o
  II. 161102 VT4 before after UNI (after Chopin's Ballade No. 2) – https://youtu.be/fBtpO6oJJp4
  III. Ventricular Ectopics with Short Ventricular Tachycardia Runs (after Beethoven's Symphony No.5: Andante – https://youtu.be/mKK7mvwzz5U

[Chew, E (2021) On Making Music with Heartbeats. In ER Miranda (ed.): Handbook of AI for Music, Springer: Cham, Switzerland, pp. 237-261]

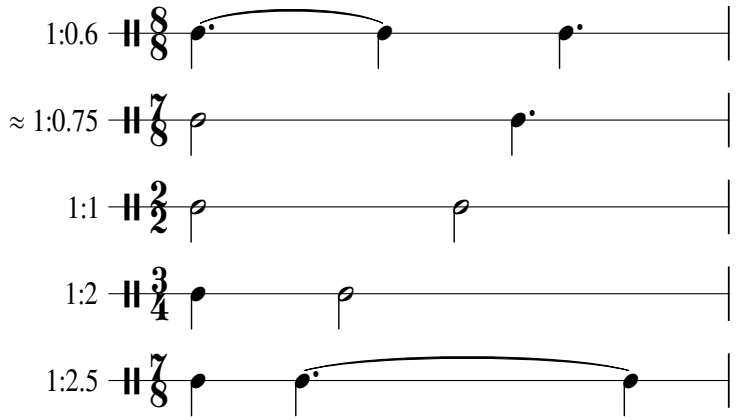




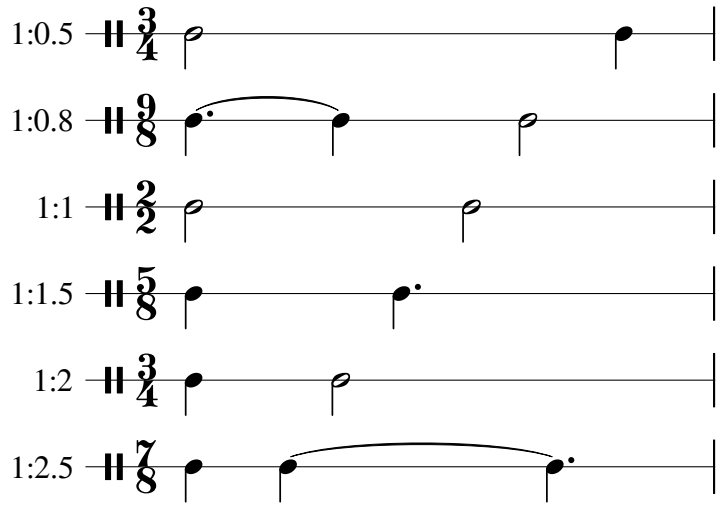




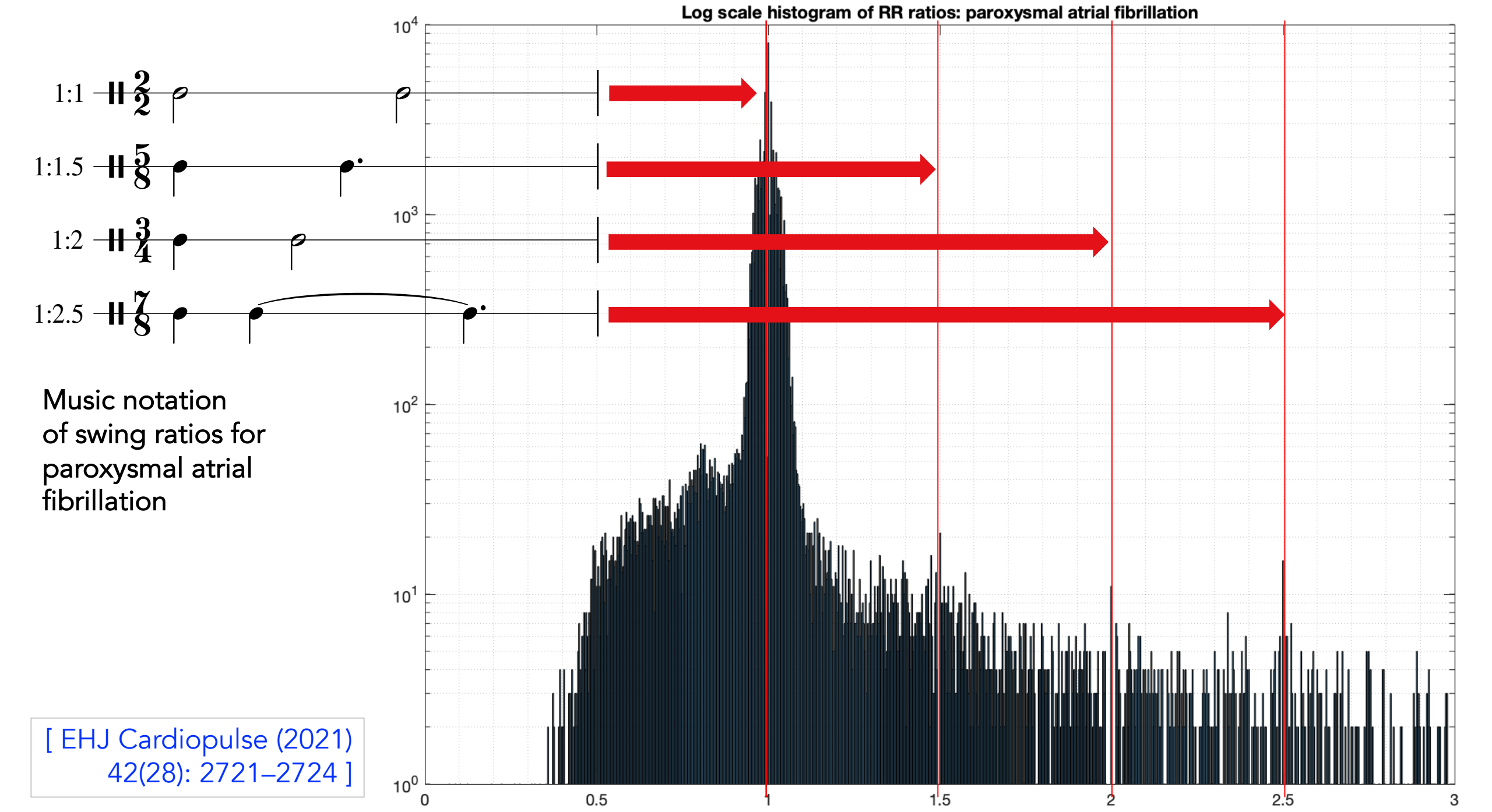
Ventricular ectopics



Paroxysmal atrial fibrillation

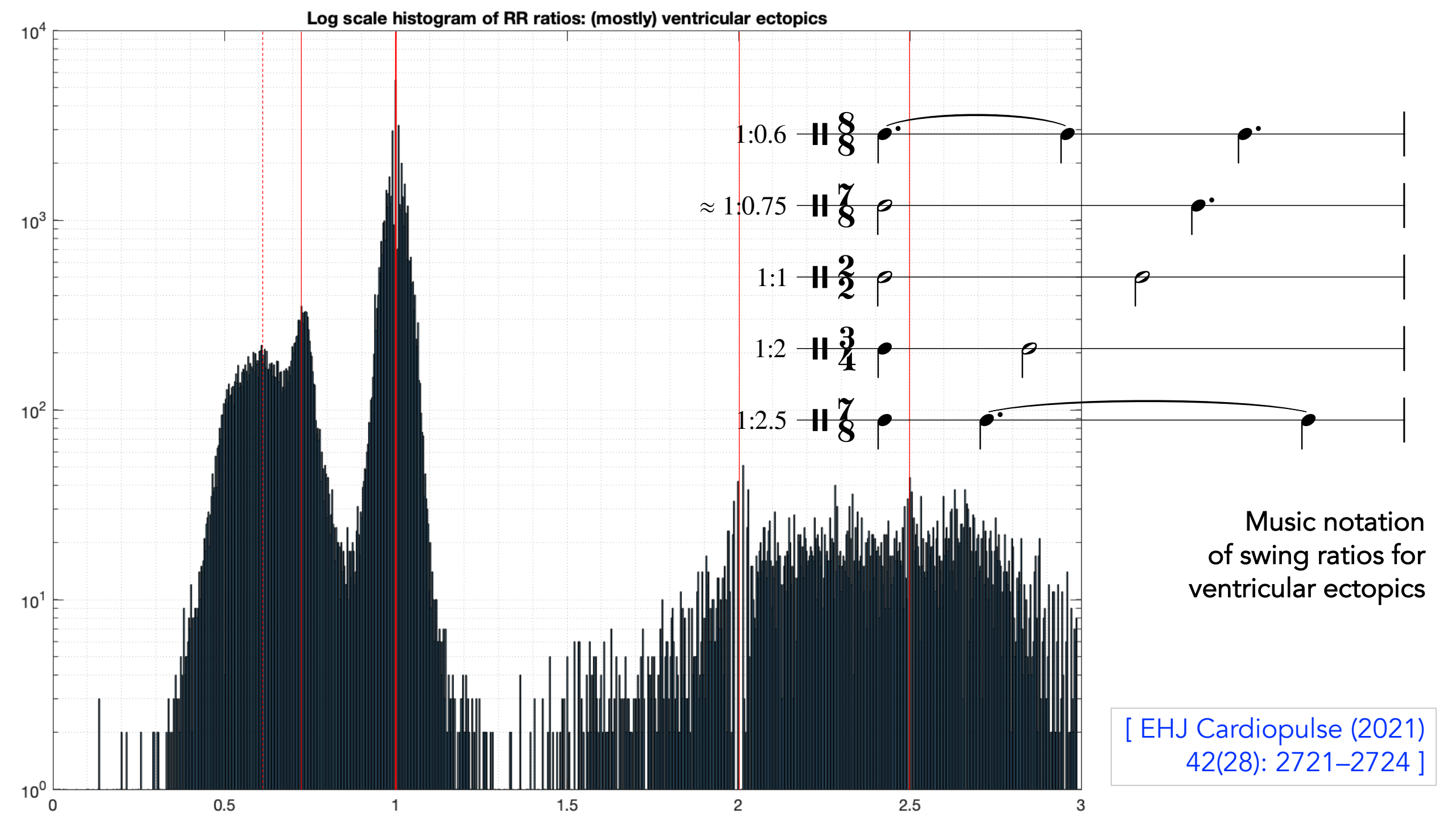


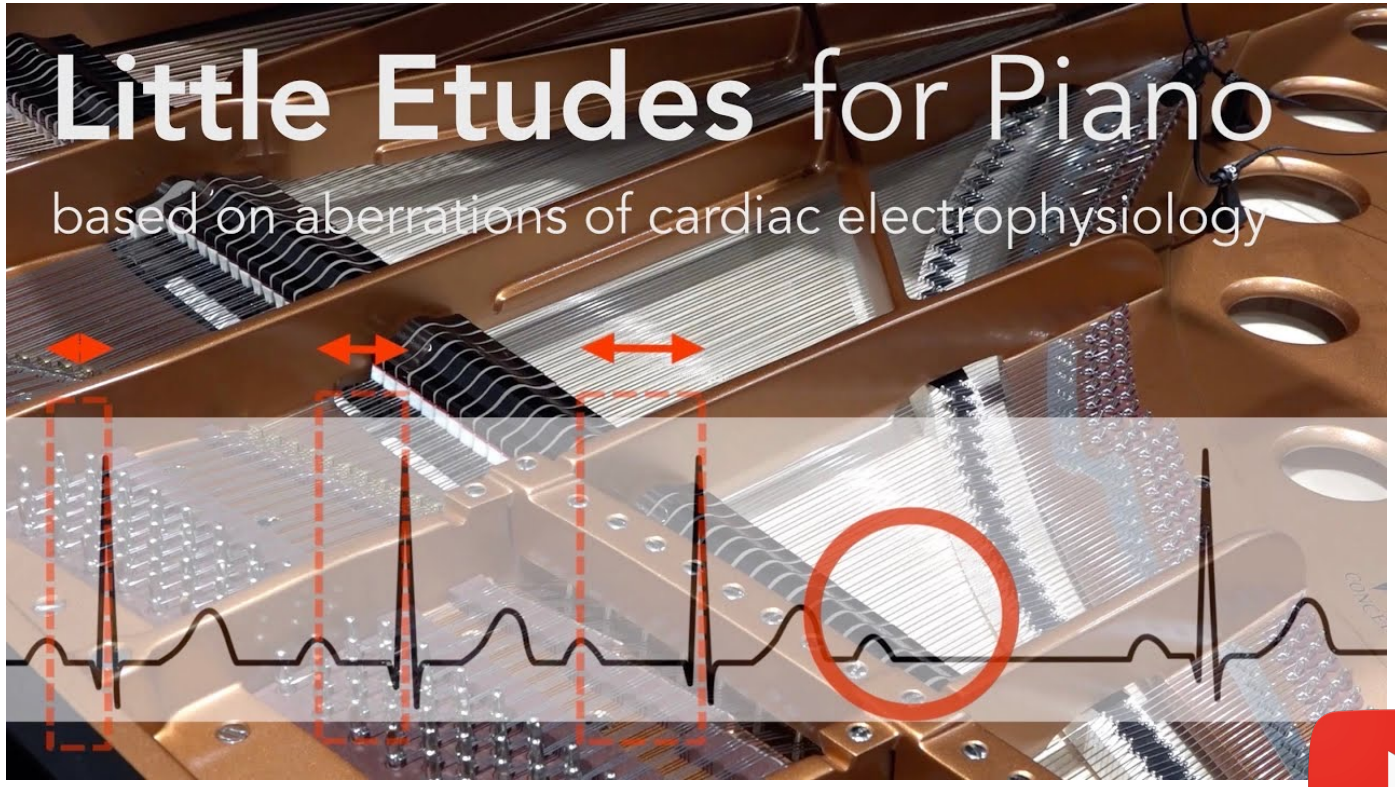
[EHJ CardioPulse (2021) 42(28): 2721–2724]



Music notation of swing ratios for paroxysmal atrial fibrillation

[EHJ Cardiopulse (2021) 42(28): 2721–2724]


Log scale histogram of RR ratios: (mostly) ventricular ectopics
10^4
10^3
10^2
10^1
10^0
0
0.5
1
1.5
2
2.5
3
1:0.6
≈ 1:0.75
1:1
1:2
1:2.5
Music notation
of swing ratios for
ventricular ectopics
[EHJ Cardiopulse (2021)
42(28): 2721–2724]



bit.ly/LittleEtudes-video

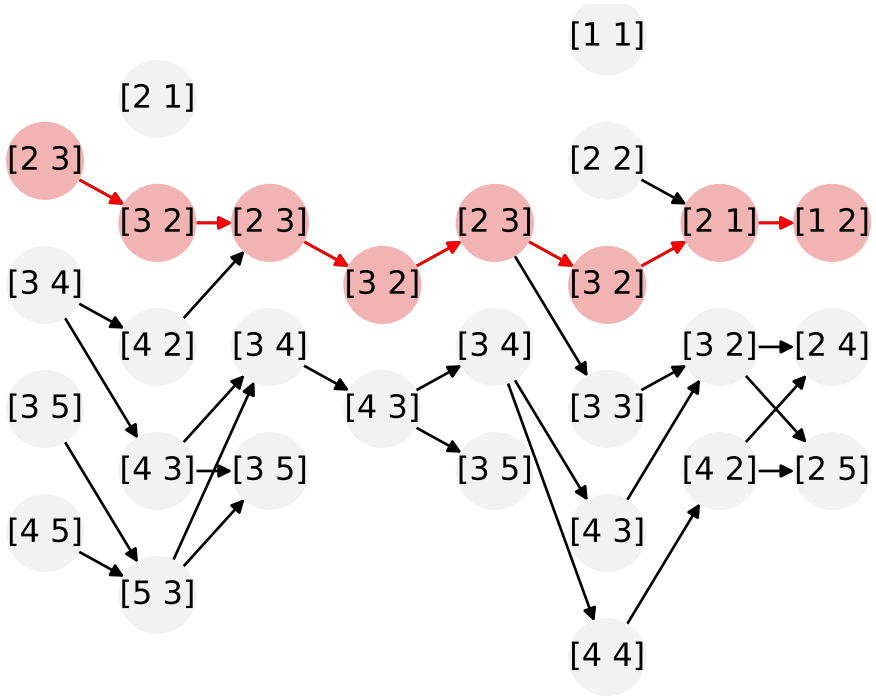
I. Atrial Fibrillation
II. Bigeminy Sea-snatch (Ventricular Bigeminy)
III. Atrial Flutter
IV. The Girl with the Labile T Waves
V. Per Torsade (Torsade de Pointes)
VI. A La Bru Rondo Turk (Ventricular Ectopics)
VII. Wenckebach Lullaby (Wenckebach Block)

[Chew, E (2021) On Making Music with Heartbeats. In ER Miranda (ed.): Handbook of AI for Music, Springer: Cham, Switzerland, pp. 237-261]

Agenda

- Background
- Heart Music
  - Putting One's Heart Into Music
- Music~Heart
  - Rhythm Transcription
  - Atrial Fibrillation Stratification via Vibrato Analysis
  - Mapping Heartbeat Coherence to Harmonic Tension
- Musical Hearts

Rhythm Transcription



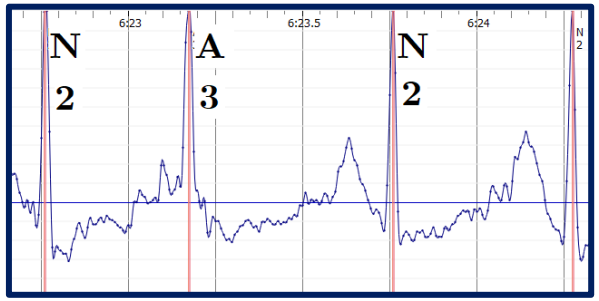
Let $T = (t_0, t_1, ..., t_n)$ be a series of onset times. Every a is associated with an error measure,

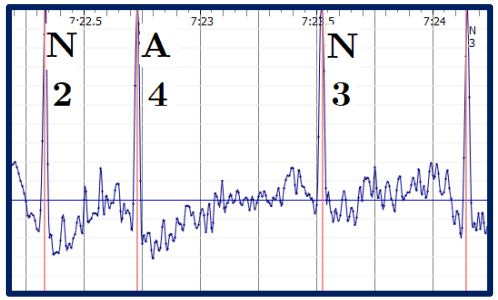
$$\varepsilon_T(a) = \max_n \min_{m \in \mathbb{Z}} |t_n - am| . \quad (1)$$

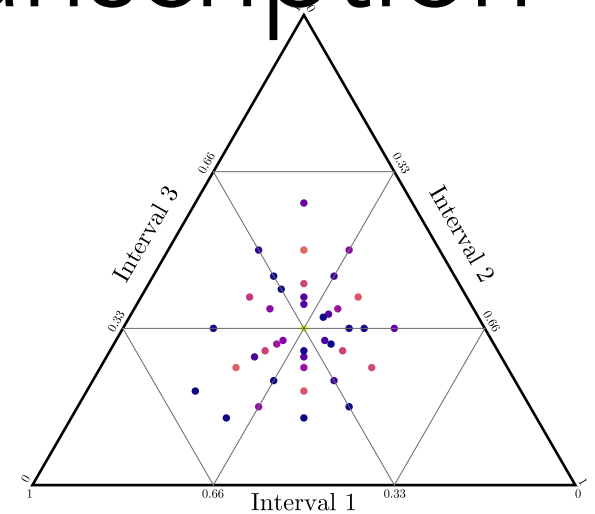
We say that $a > 0$ is an *approximate common divisor* (ACD) of T with threshold $\tau > 0$ if

1. $\epsilon_T(a) \leq \tau$
2. ϵ_T has a local minimum at a

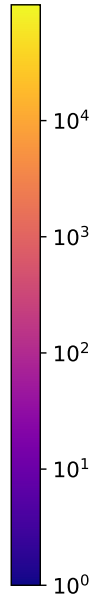
[Romero & Chew TENOR 2022;
Romero, Lascabettes, Chew CinC 2022]

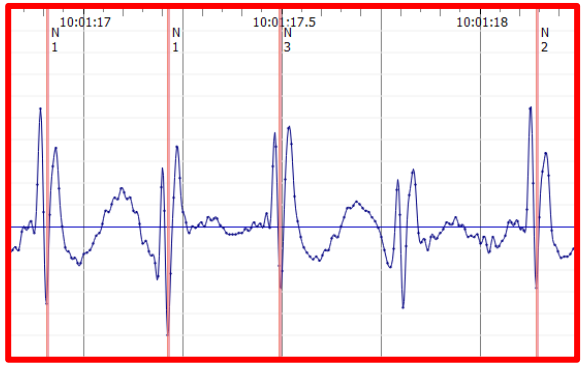


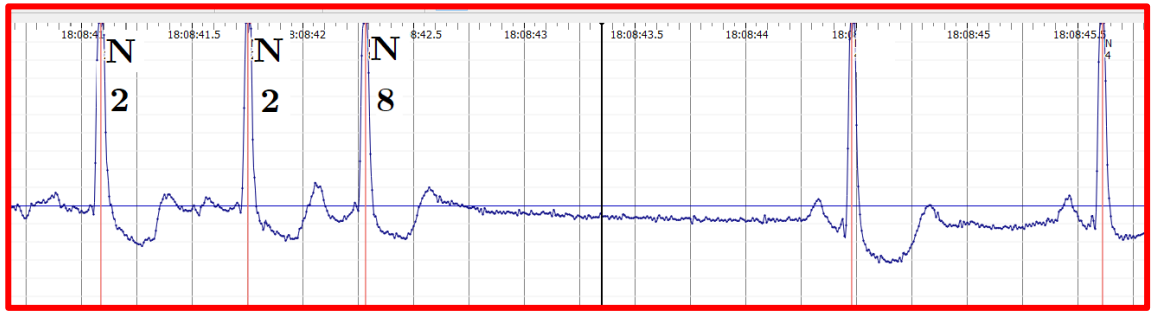




Transcriptions of N-N-N



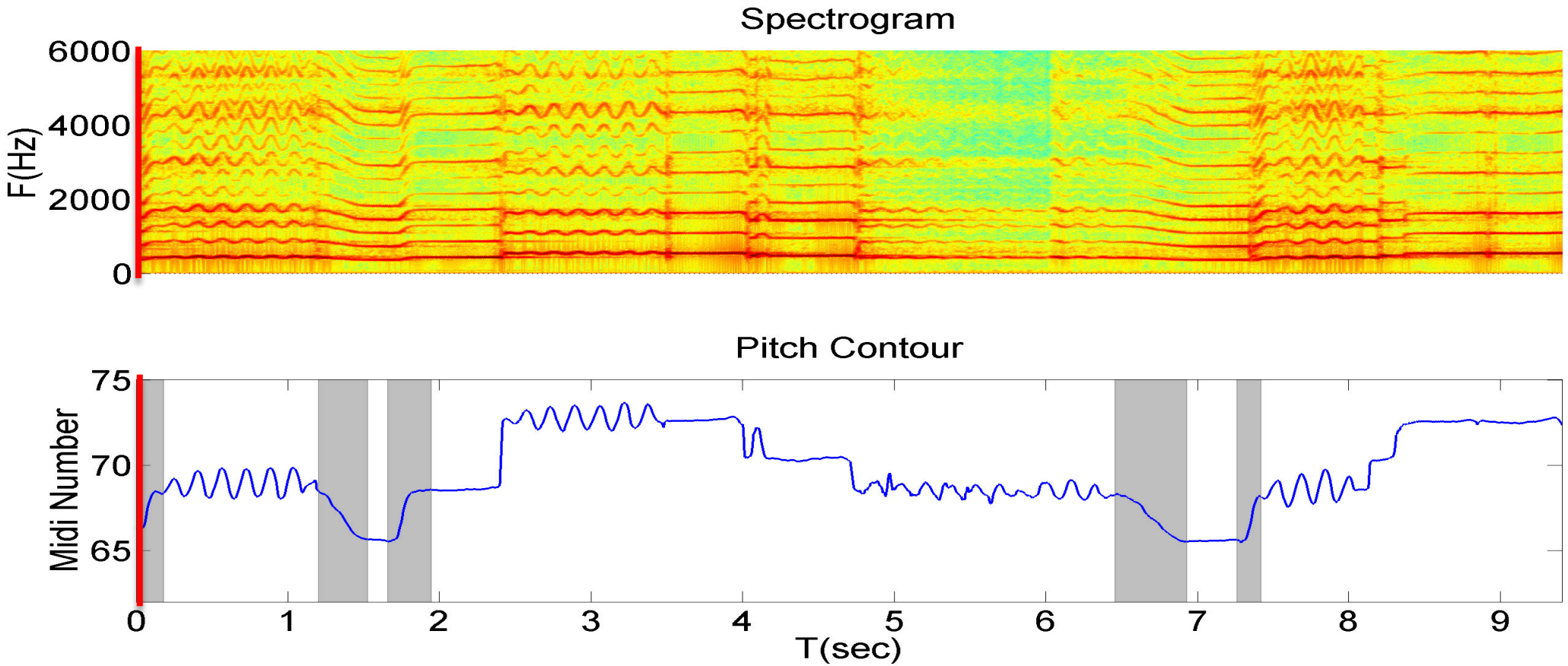




Gonzalo Romero

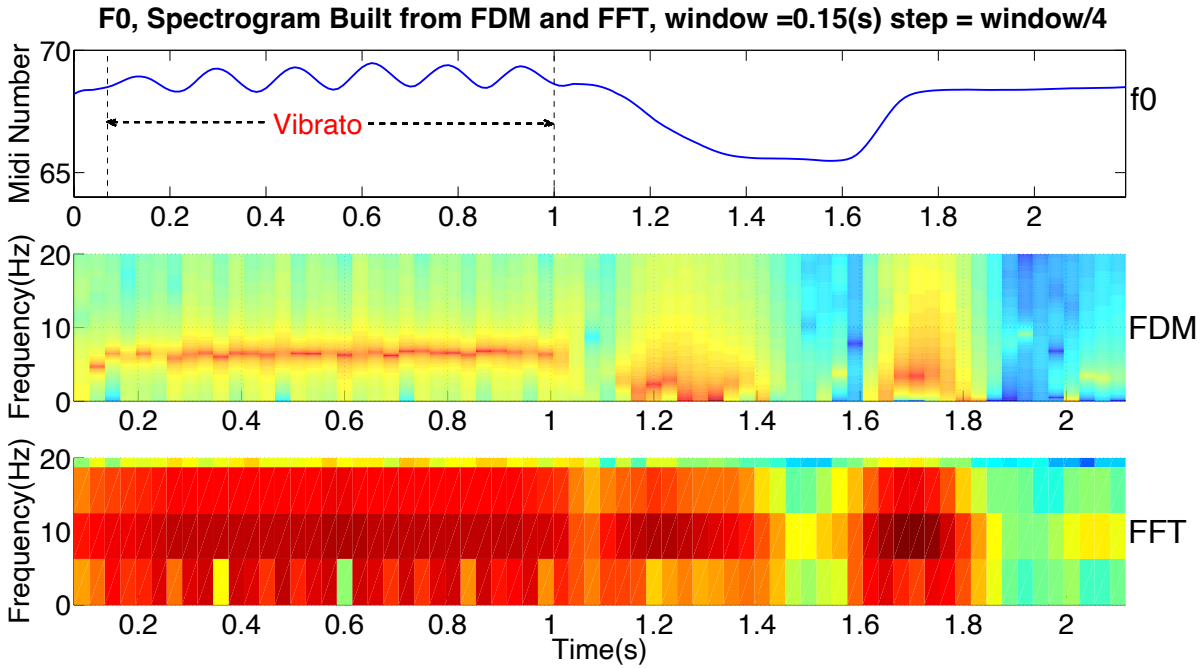
[Yang, Rajab, Chew CMMR 2013;
Yang, Rajab, Chew JMM 2017]

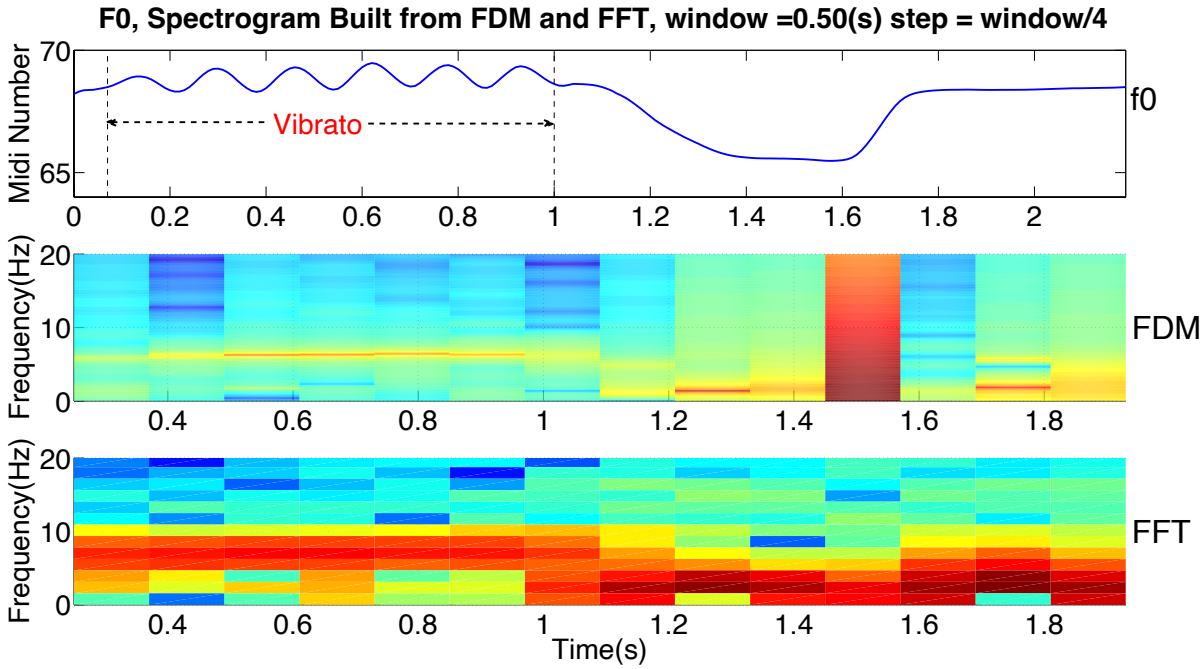
Erhu Vibratos and Portamentos



[Yang, Rajab, Chew CMMR 2013;
Yang, Rajab, Chew JMM 2017]

Filter Diagonalisation Method



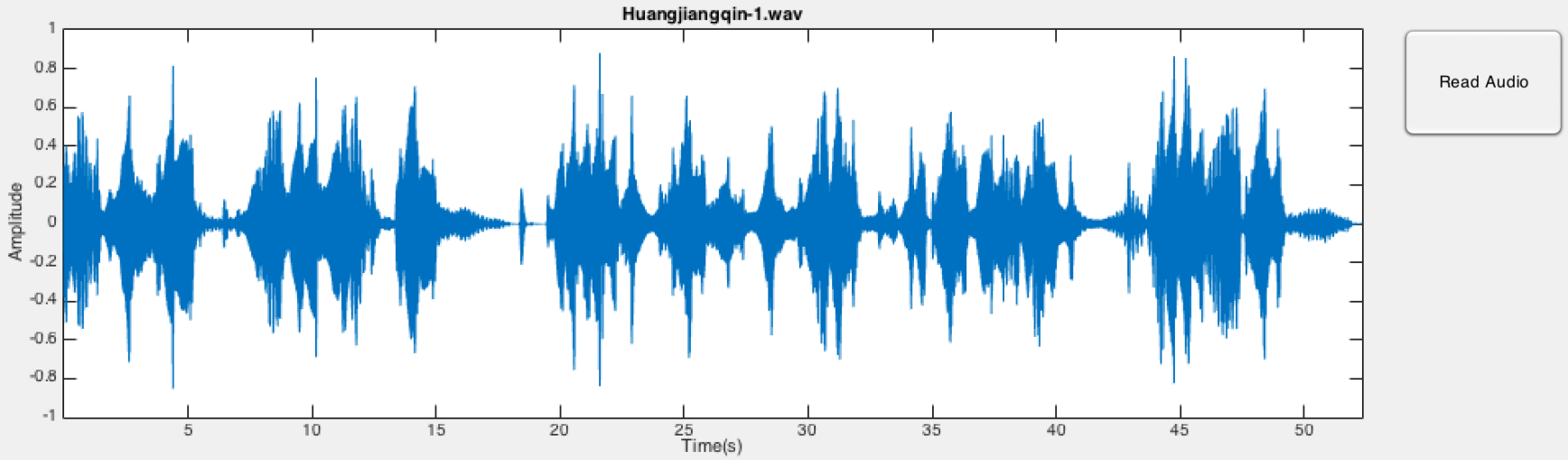


About 6-8 Hertz, or 360-480 cycles per minute

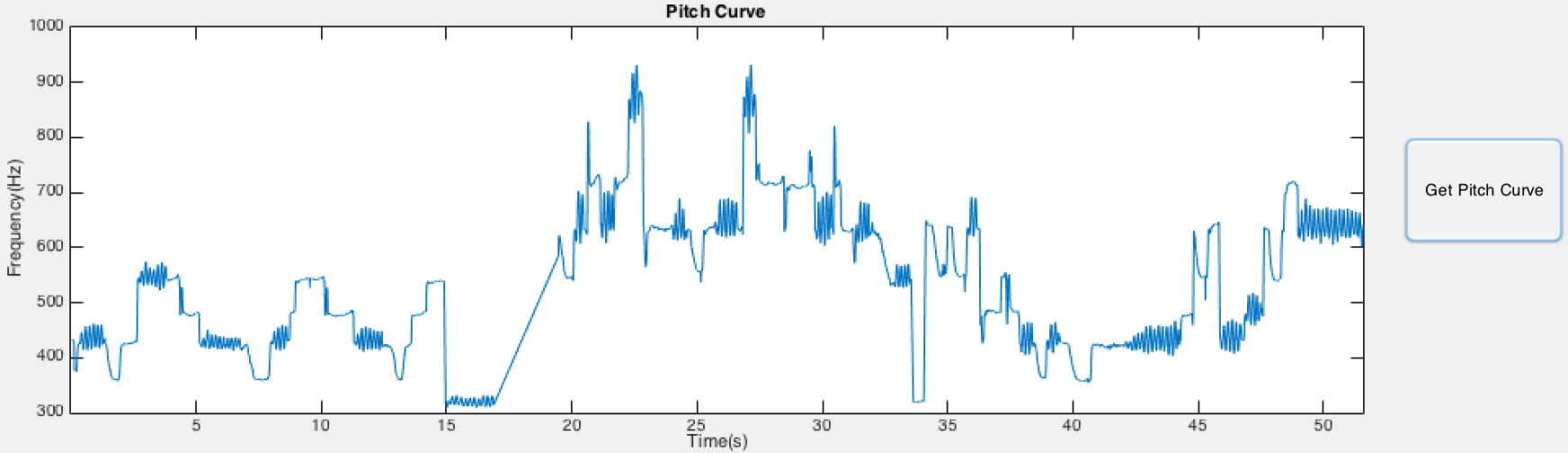
Expressive Feature Analysis

File Edit View Insert Tools Desktop Window Help

luweiyang.com/research/ava-project



Read Audio



Get Pitch Curve

Read Audio | Vibrato Analysis | Portamento Analysis

Luwei Yang
Now Senior Algorithm Engineer
at Alibaba Group

[Yang, Rajab, Chew ISMIR 2016;
Yang, Rajab, Chew ICMC 2016]

Expressive Feature Analysis

File Edit View Insert Tools Desktop Window Help

luweiyang.com/research/ava-project

Pitch Curve

Frequency(Hz)

Time(s)

Get Vibrato:

Window(s): 0.125

Step(%): 0.25

Get Vibrato(s)

Add Vibrato

Delete Vibrato

Vibratos

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

X axis:

Original Time

Selected Vibrato

Frequency(Hz)

Time(s)

Vibrato Statistics

Rate (Hz):

7.06023

Extent (Cent):

18.7542

Sinusoid Similarity:

0.95411

Method:

FDM

Play Vibrato | Pause Vibrato | Resume Vibrato | Stop Vibrato

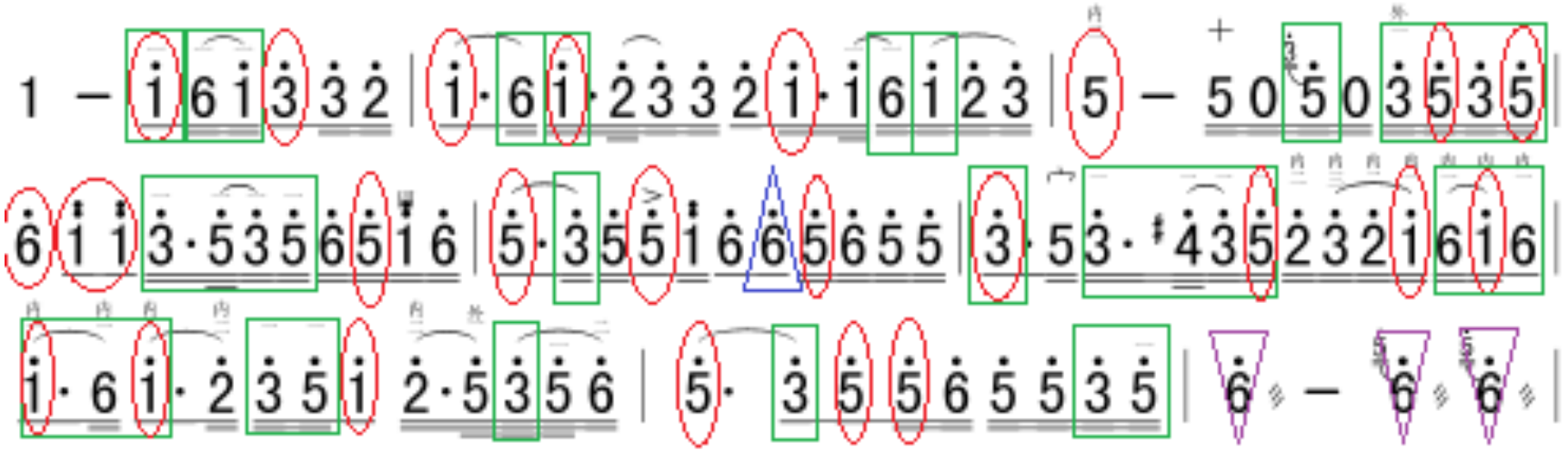
Read Audio | Vibrato Analysis | Portamento Analysis

Luwei Yang

Now Senior Algorithm Engineer at Alibaba Group

[Yang, Rajab, Chew ISMIR 2016; Yang, Rajab, Chew ICMC 2016]

Erhu music



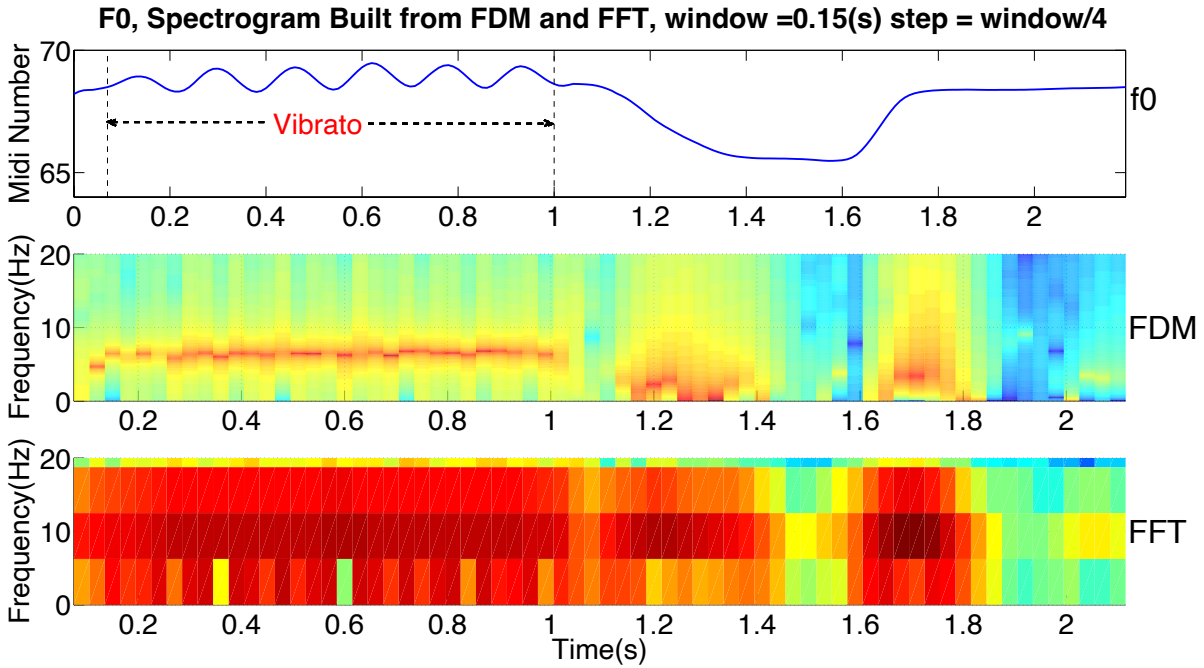
red ellipses = vibratos, green boxes = portamentos,

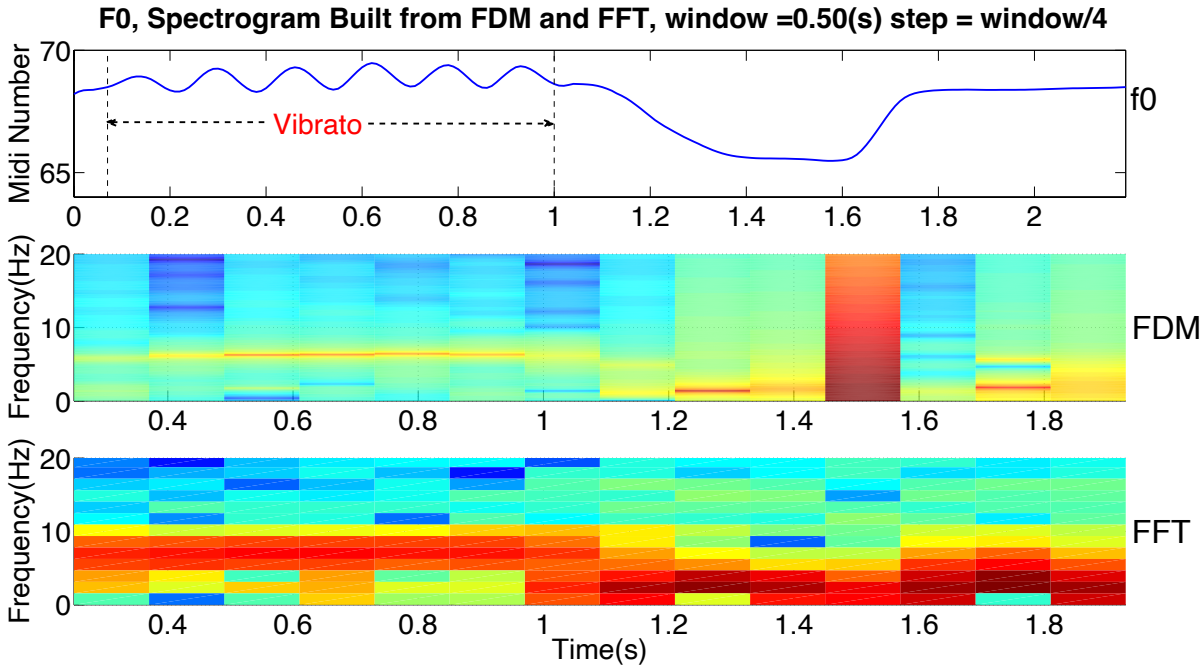
blue upright triangles = notes elaborated with trills,

purple upside down triangles = tremolo notes

[Yang, Rajab, Chew CMMR 2013;
Yang, Rajab, Chew JMM 2017]

Filter Diagonalisation Method





Vibratos: 6-8 Hertz

Fibrillatory waves: 3-12 Hertz

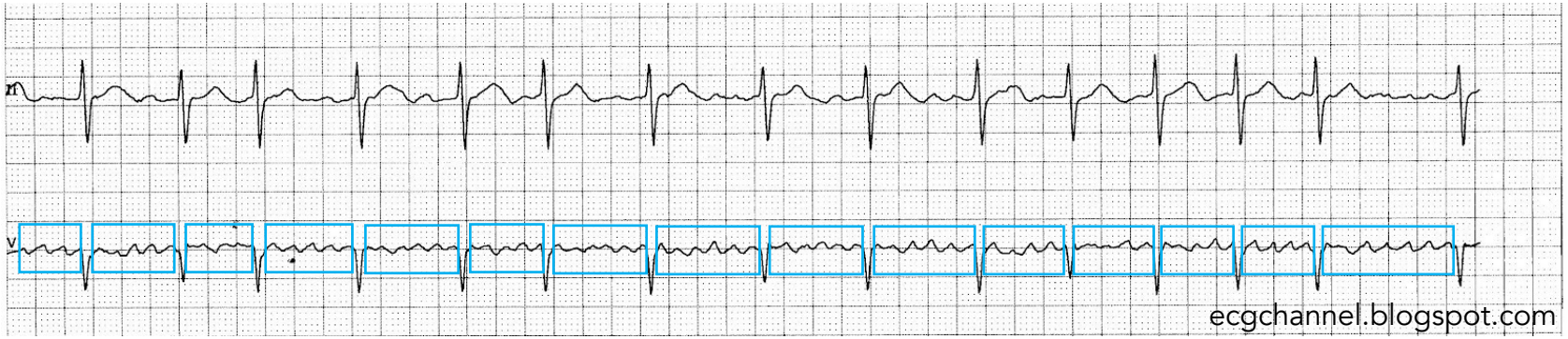
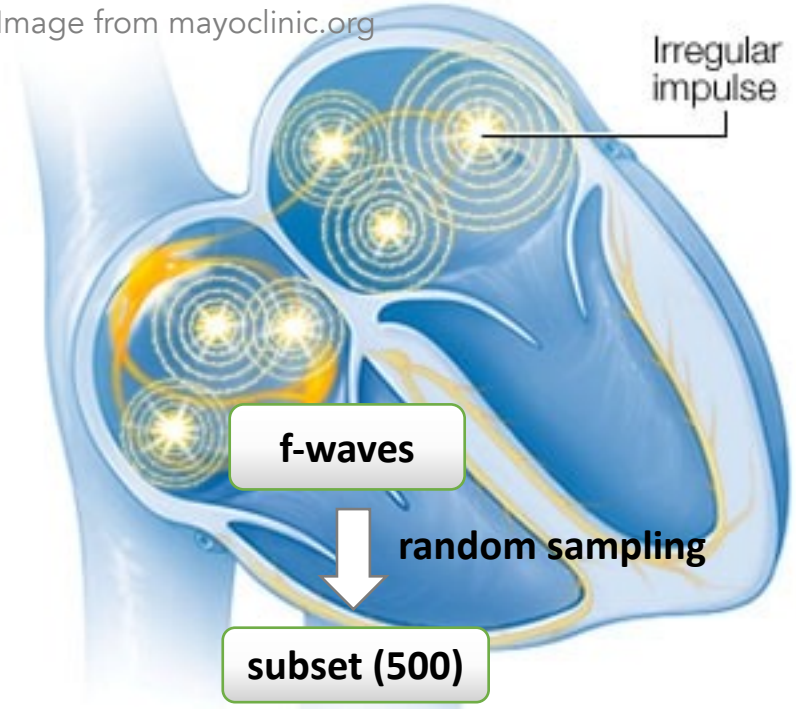


Image from mayoclinic.org

[Mishra, Rammohan, Rajab, Dhillon, Lambiase, Hunter, Chew CinC 2019]

Atrial Fibrillation Stratification



f-waves

random sampling

subset (500)

random sampling

held out evaluation dataset (10%)

cross validation subset (90%)

test set (10%)

random sampling

training set (90%)

Training classification models

- Apply to pre and pre-adenosine ECG data
- Classification models:
  - **Decision tree:** Interpretable, based on binary decision tree
  - **Random forest:** Complex, uses ensemble of decision trees with voting scheme.

Performance on the held-out dataset

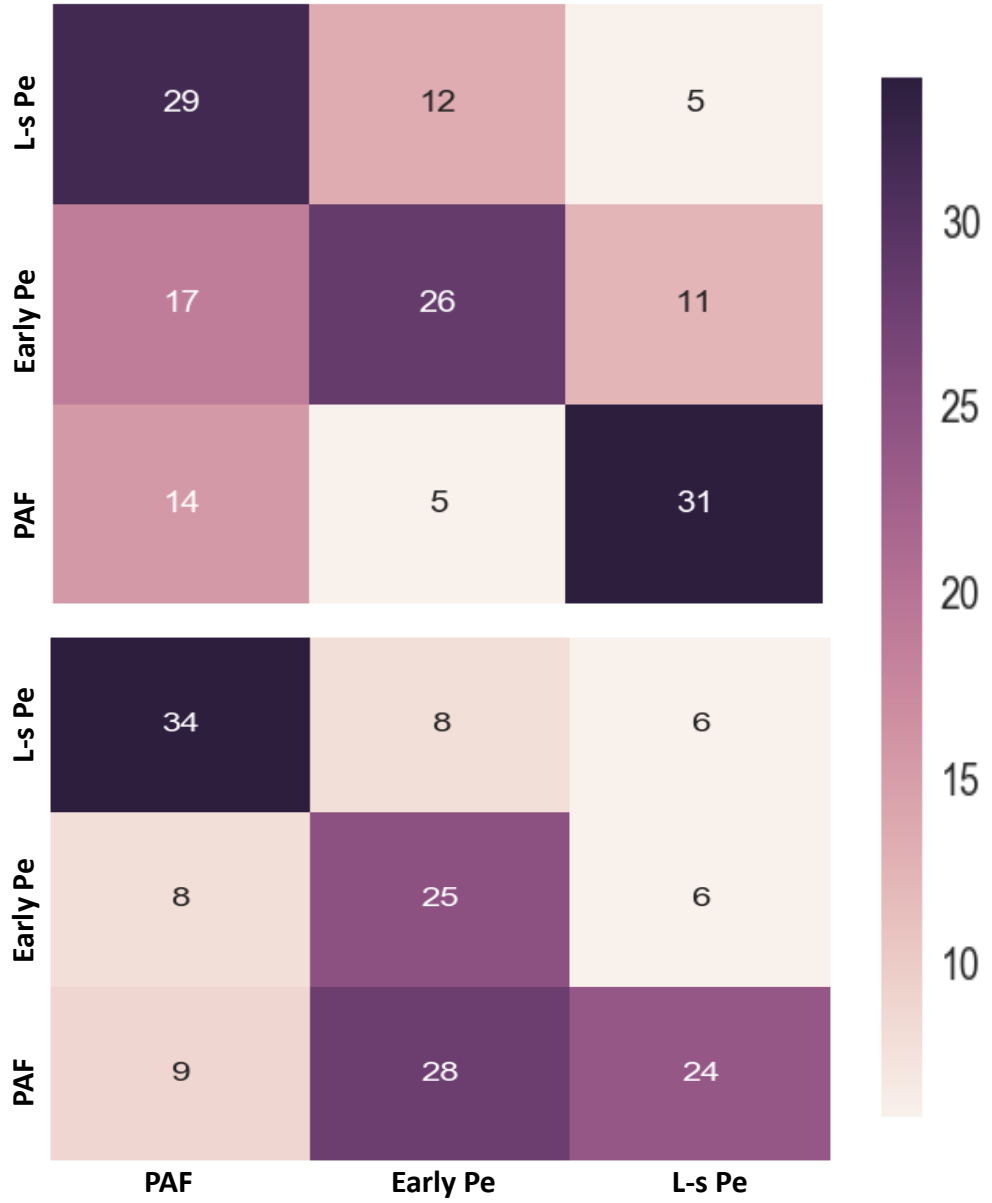
[Mishra, Rammohan, Rajab, Dhillon, Lambiase, Hunter, Chew CinC 2019]

Pre.txt – Best Model: Random Forest

Class	Accuracy (%)	Precision	Recall	F1-score
	57			
Paroxysmal		0.48	0.63	0.55
Early persistent		0.60	0.48	0.54
Long-standing persistent		0.66	0.62	0.64

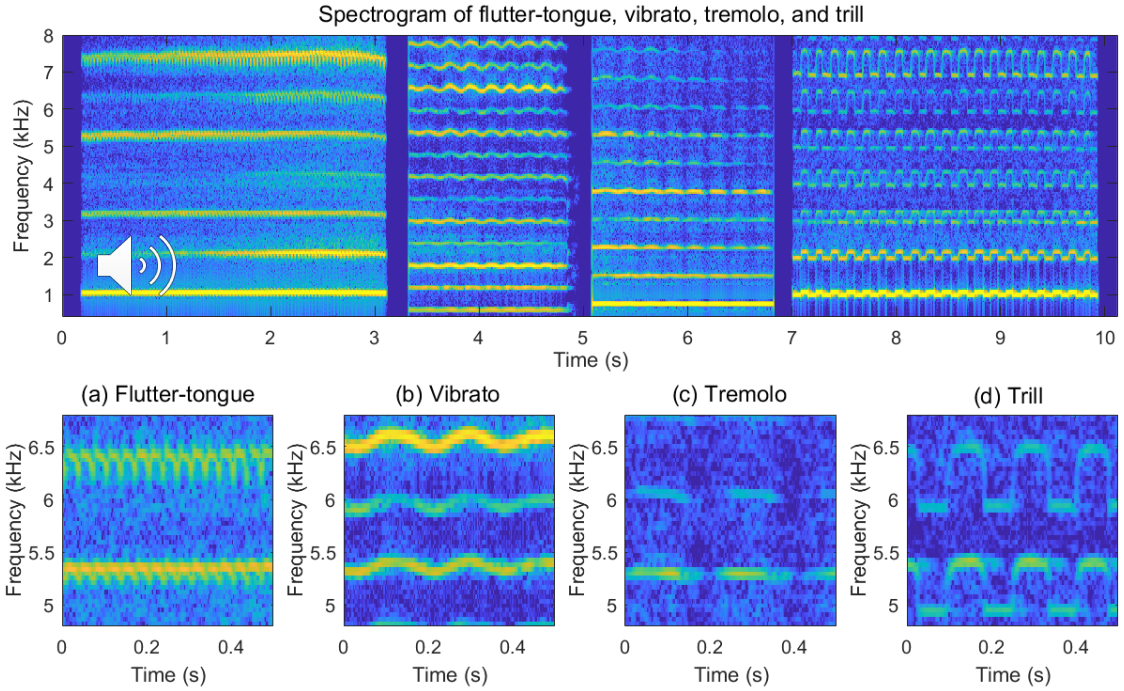
PreAdenosine.txt – Best Model: Decision Tree

Class	Accuracy (%)	Precision	Recall	F1-score
	56			
Paroxysmal		0.67	0.71	0.69
Early persistent		0.41	0.64	0.50
Long-standing persistent		0.67	0.39	0.49

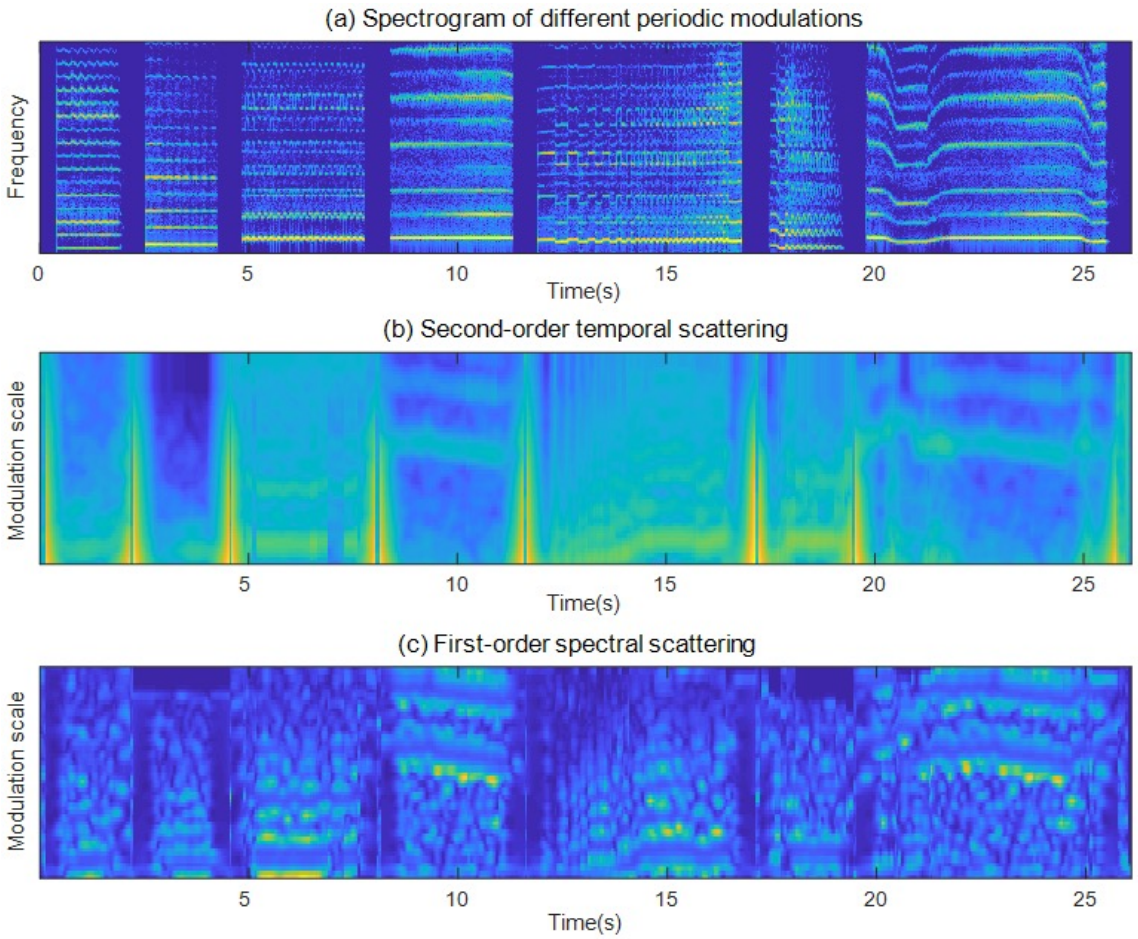


Playing Technique Recognition

Changhong Wang
Now a postdoc researcher at CNRS
Nantes Lab of Digital Sci (LS2N)



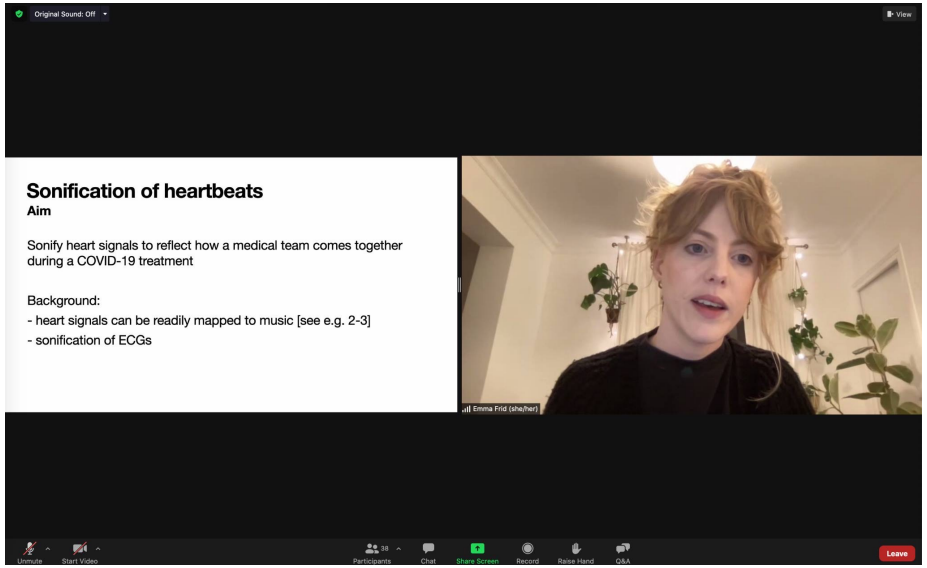
Periodic Modulations

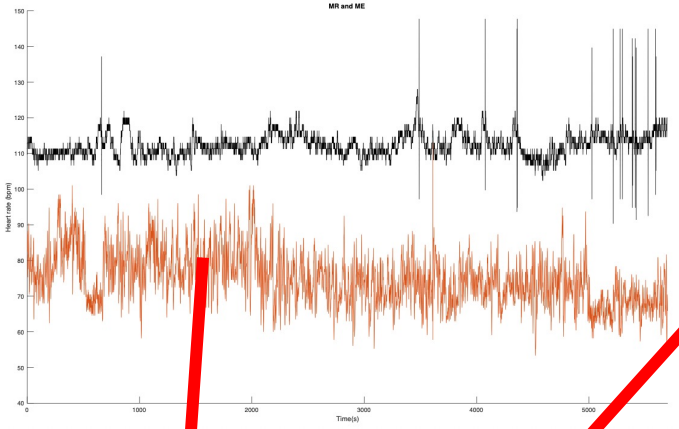


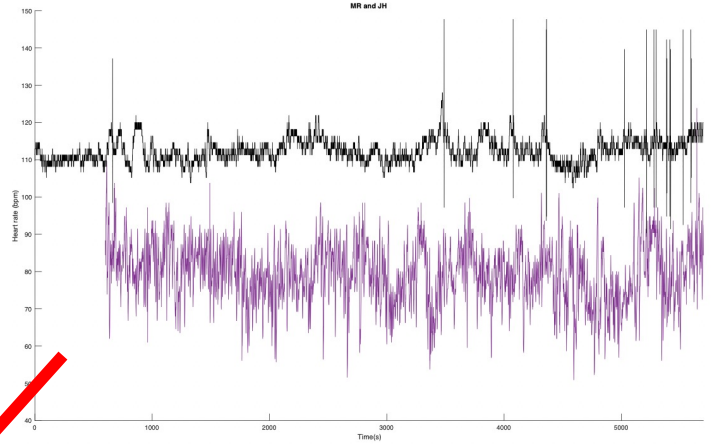
Adaptive time-frequency scattering representation

[Wang, Benetos, Lostanlen, Chew ISMIR 2019; Wang, Benetos, Lostanlen, Chew TASLP 2022]

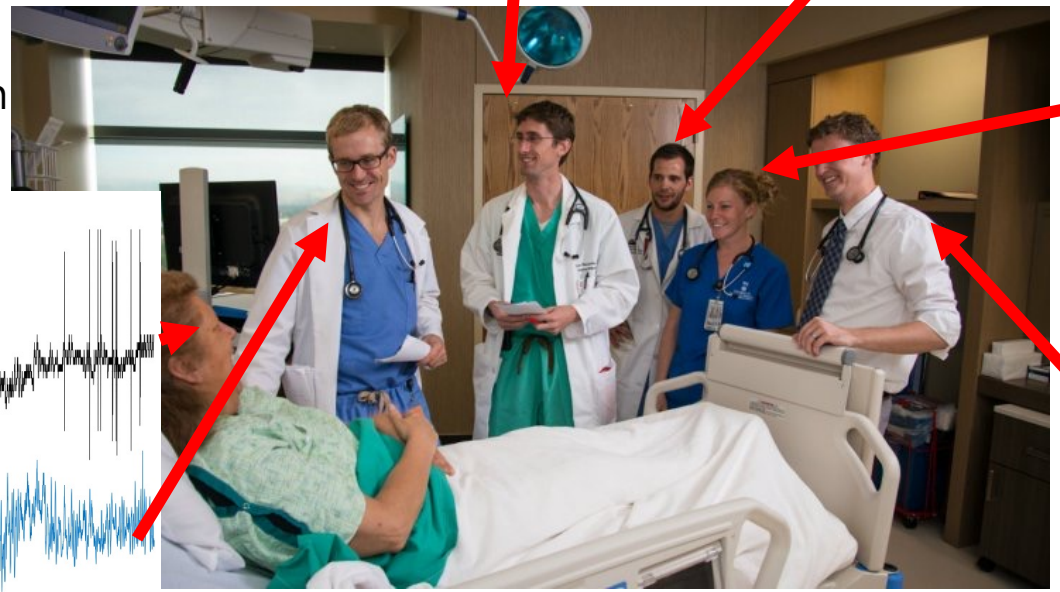
[Frid, Orini, Martinelli, Chew ICAD 2021]

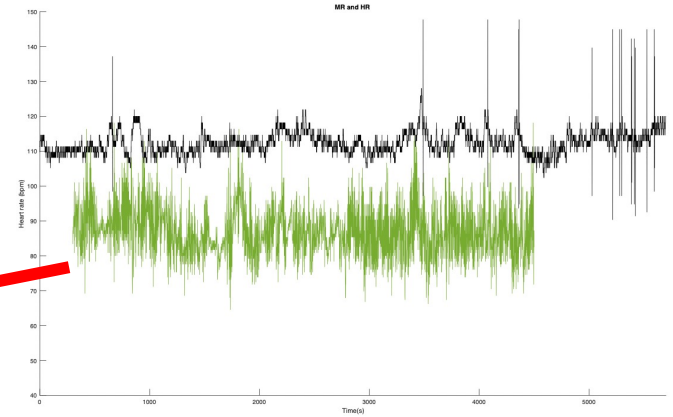


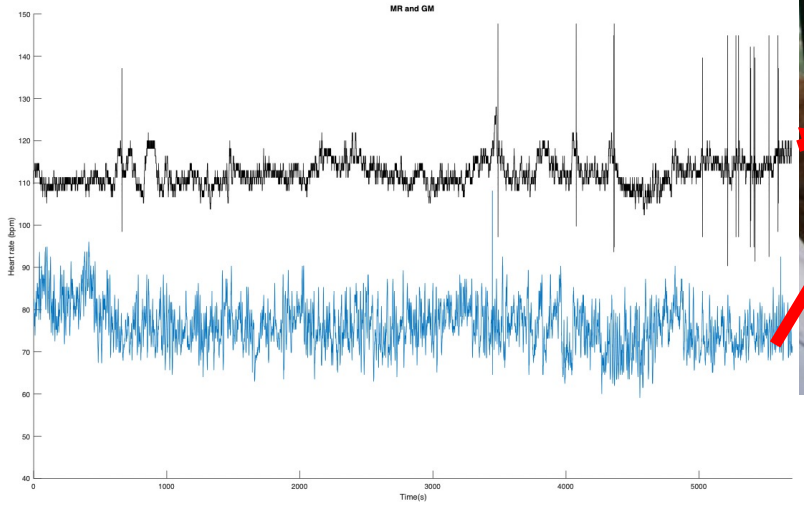


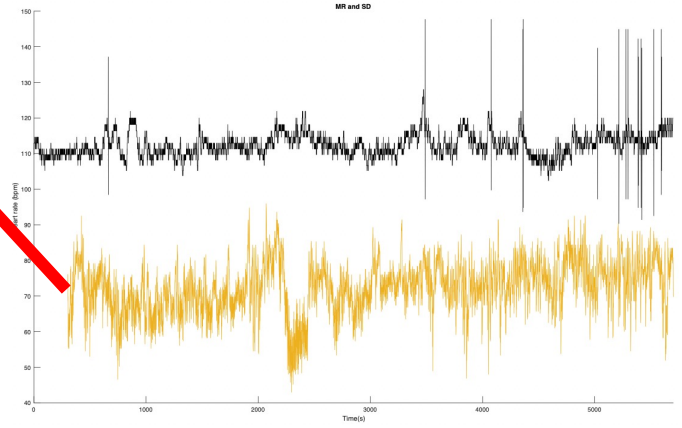


Time-frequency coherence mapped to harmonic tension

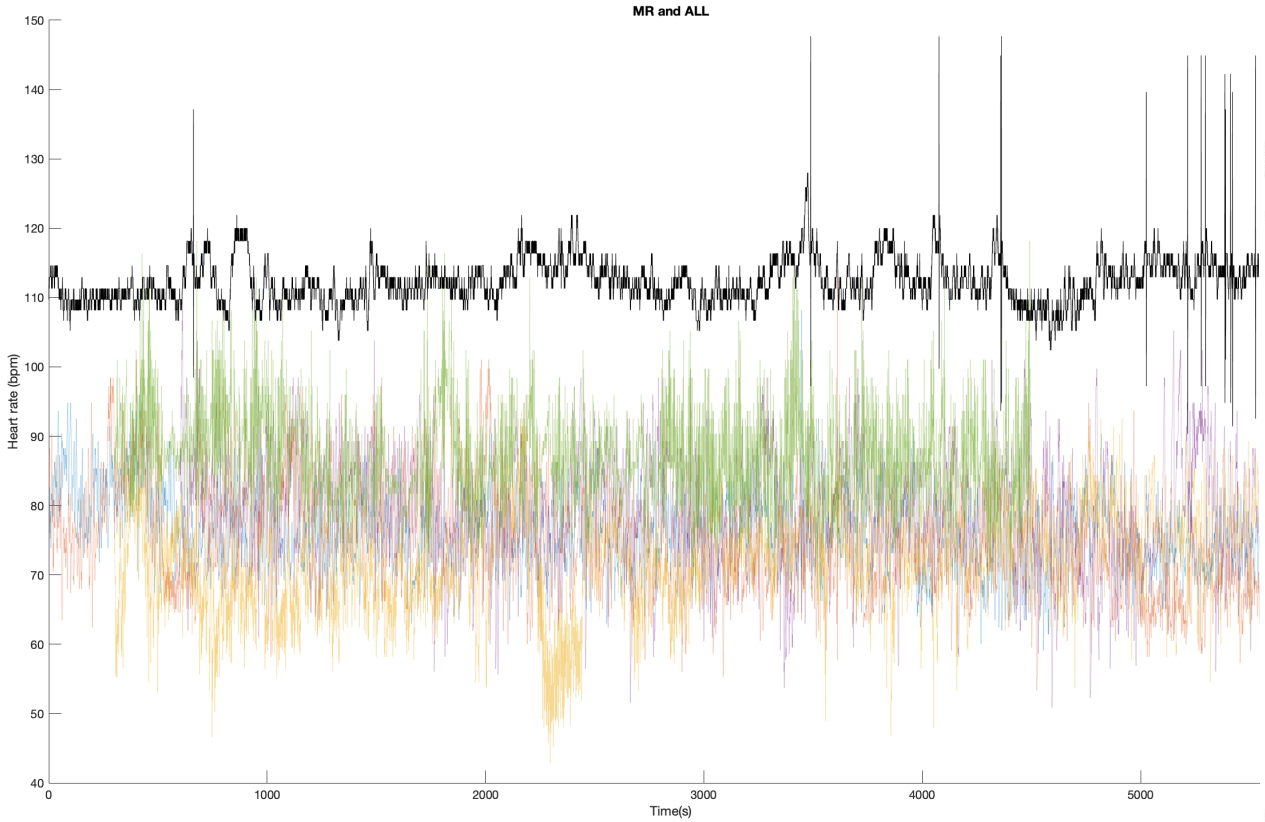


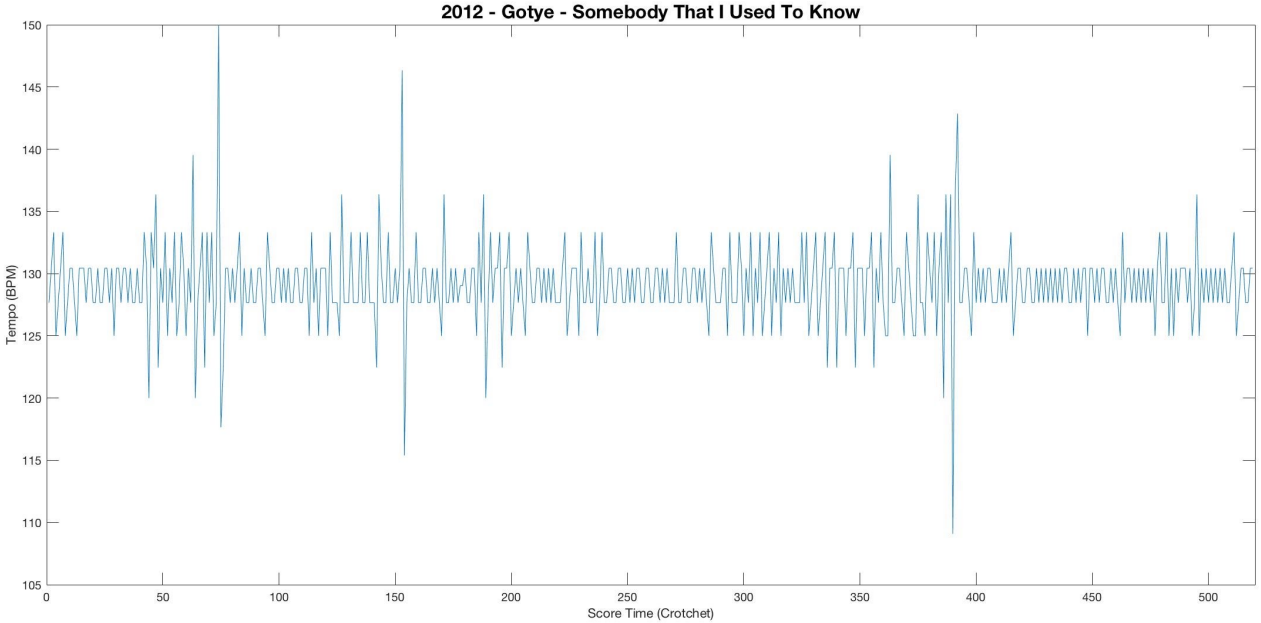


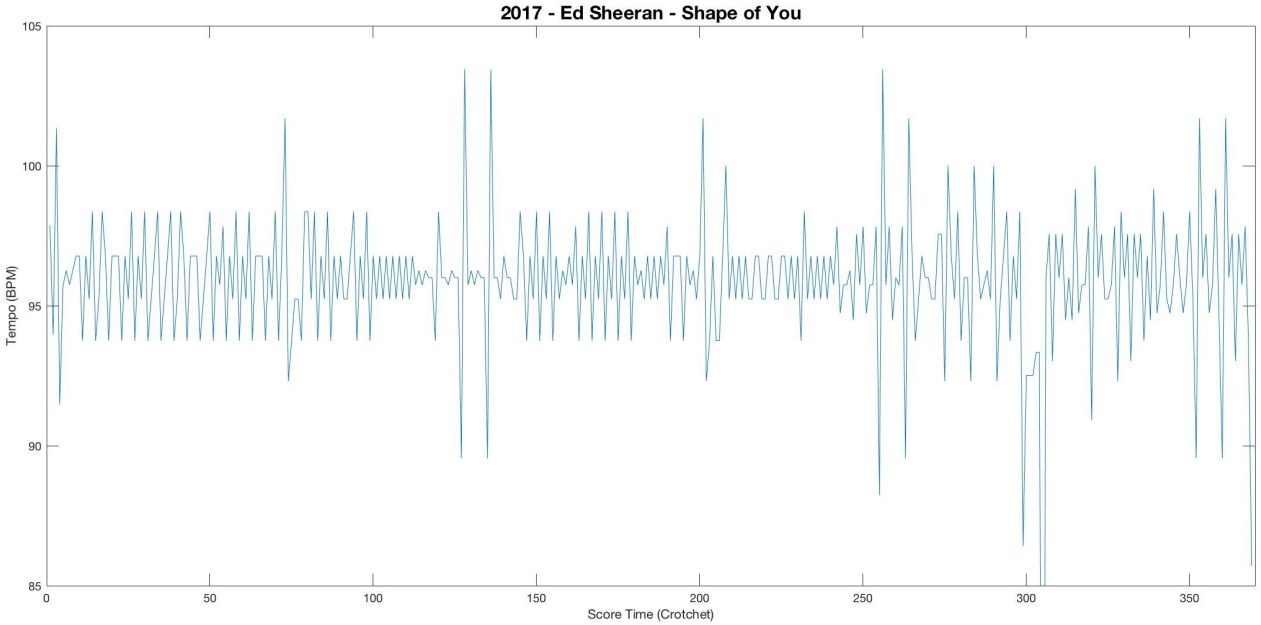




[Frid, Orini, Martinelli, Chew ICAD 2021]



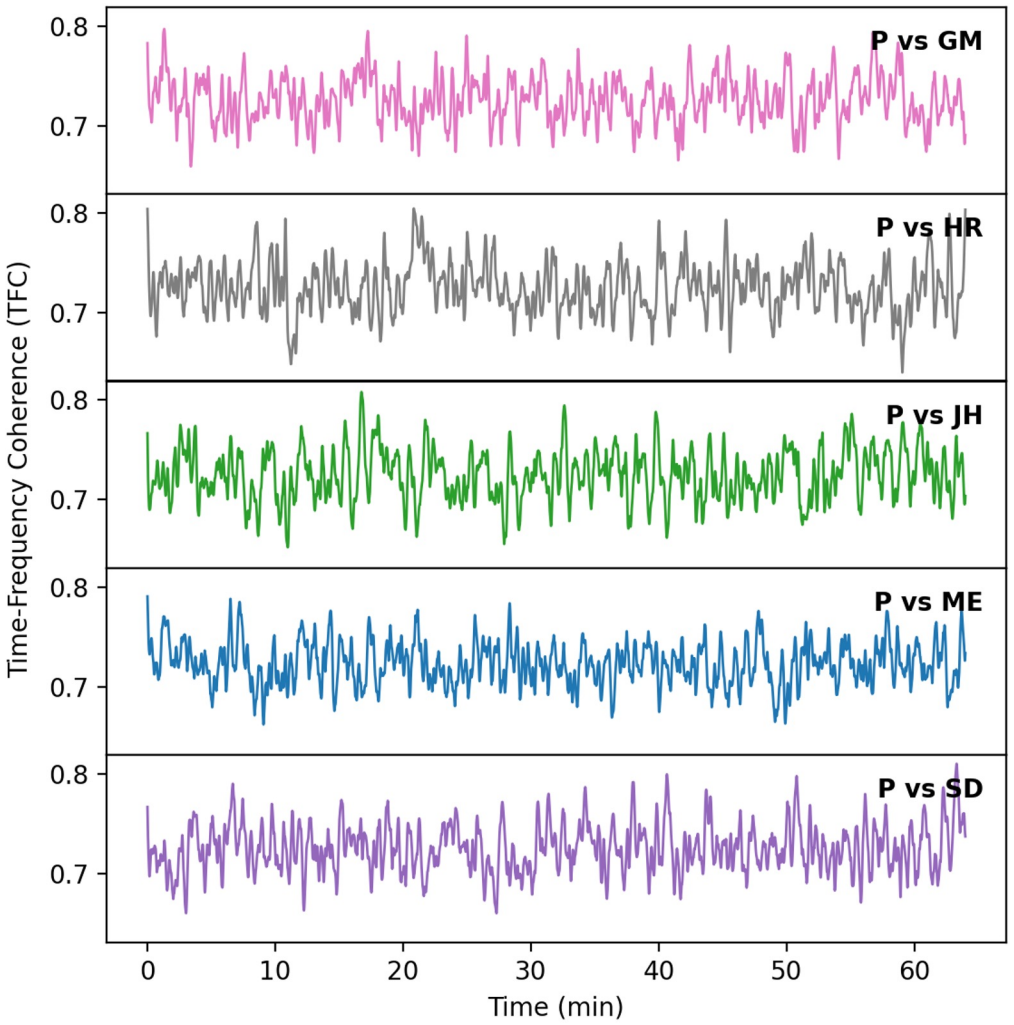


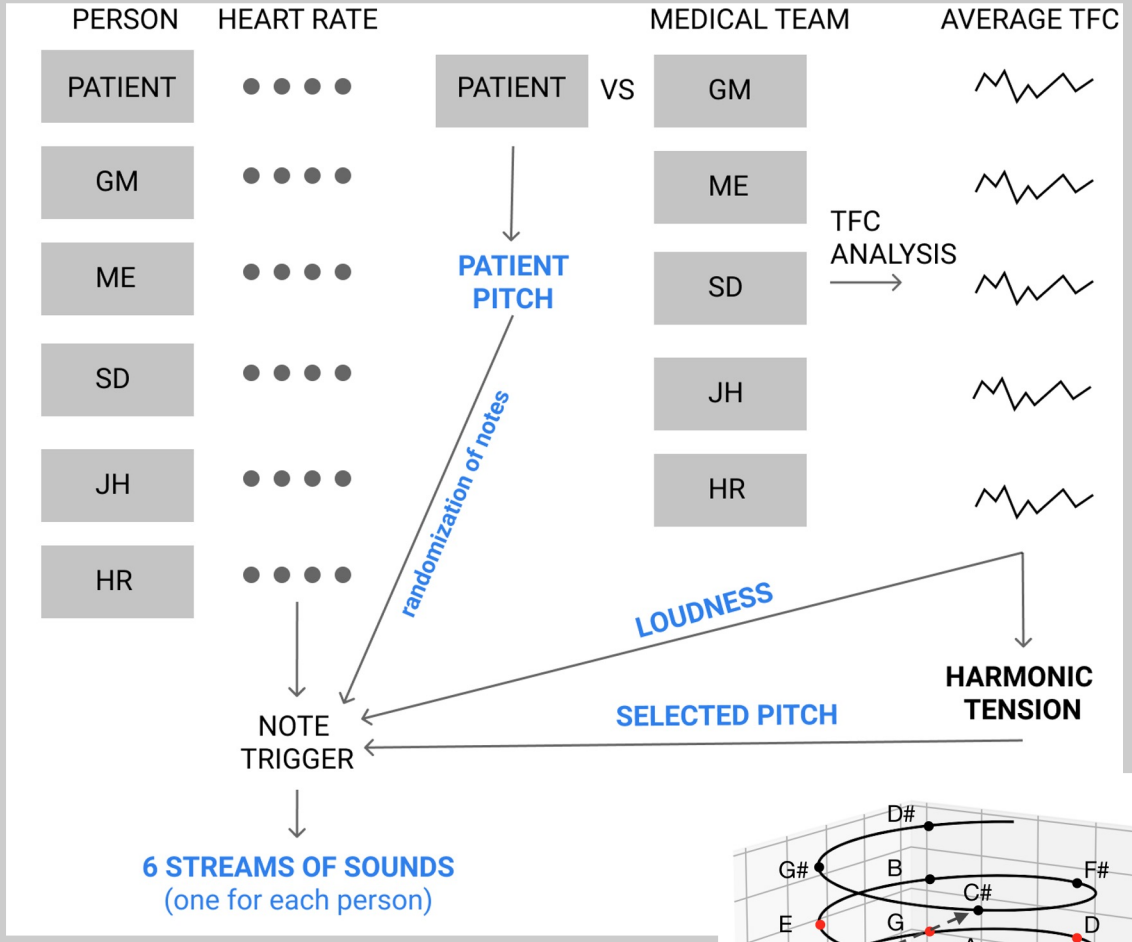


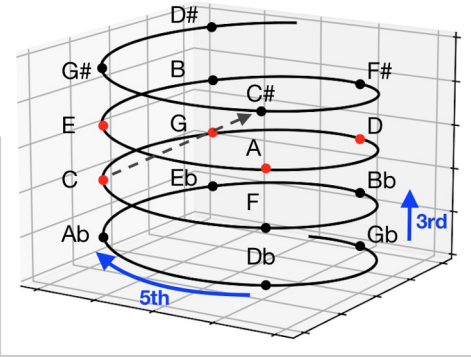
Click track tempo analysis by Jonathan Mark Pigrem

ICAD slides by Emma Frid

Time Frequency Coherence (TFC)







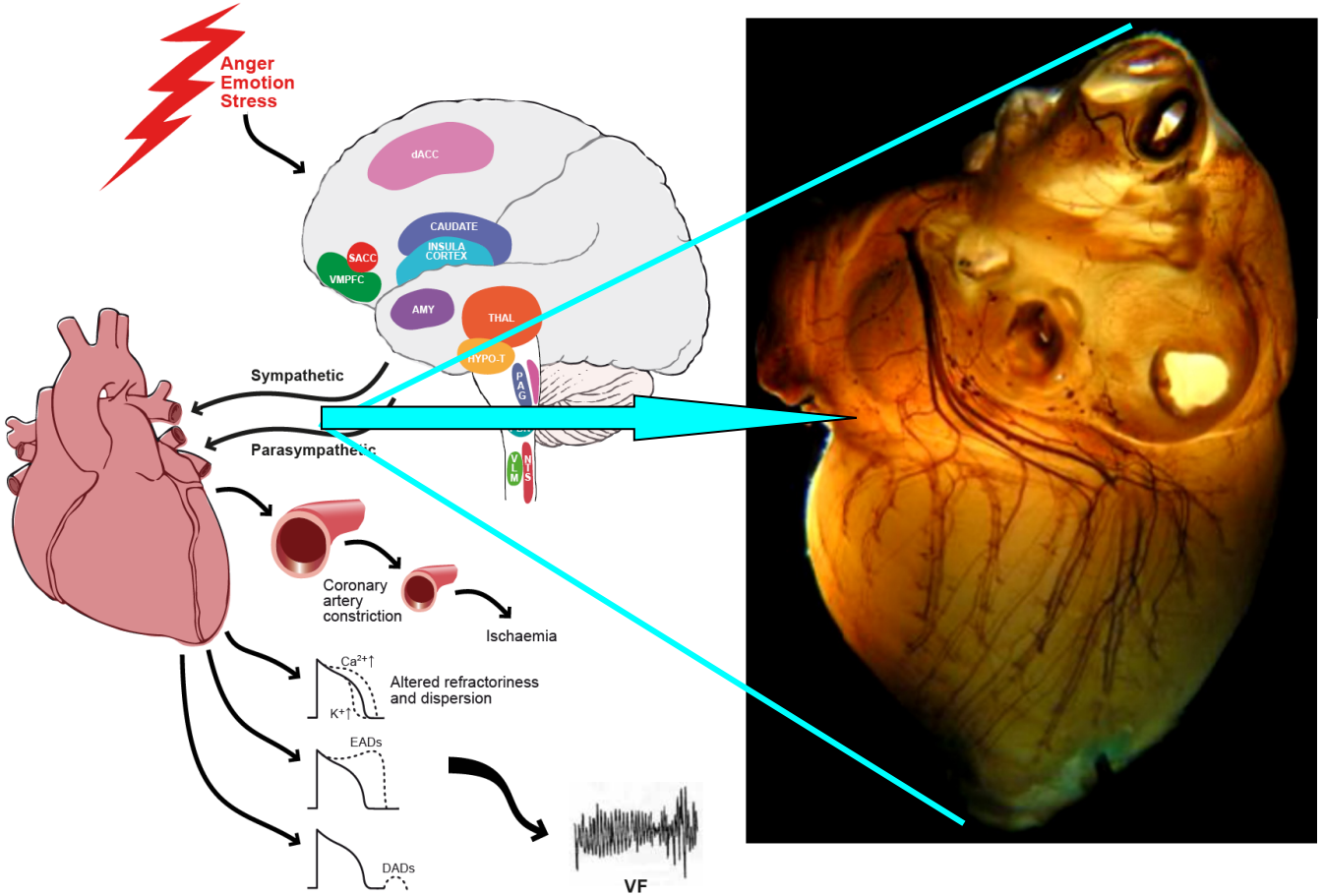
Degree of correlation between spectral components of two signals

Carter, GC (1987). Coherence and Time Delay Estimation. Proc IEEE, 75(2):236–255

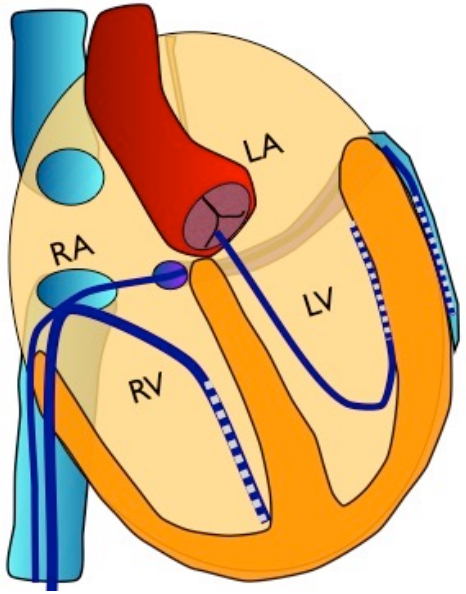
Agenda

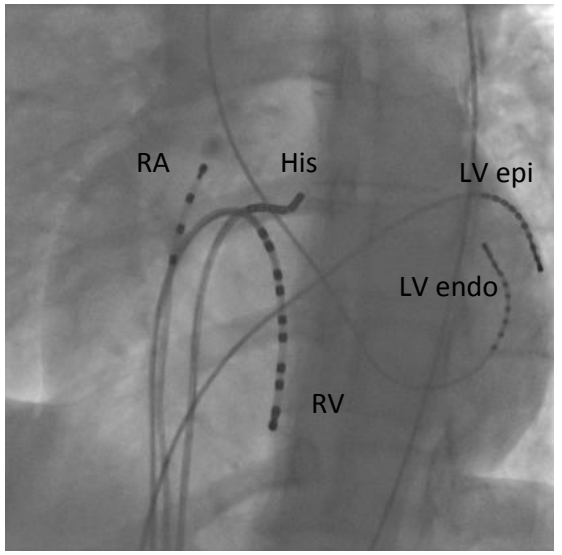
- Background
- Heart Music
  - Putting One's Heart Into Music
- Music~Heart
  - Rhythm Transcription
  - Atrial Fibrillation Stratification via Vibrato Analysis
  - Mapping Heartbeat Coherence to Harmonic Tension
- Musical Hearts
  - Pacemaker Patient Study
  - Tipping Points and Stress
  - Demonstration of Cardiac

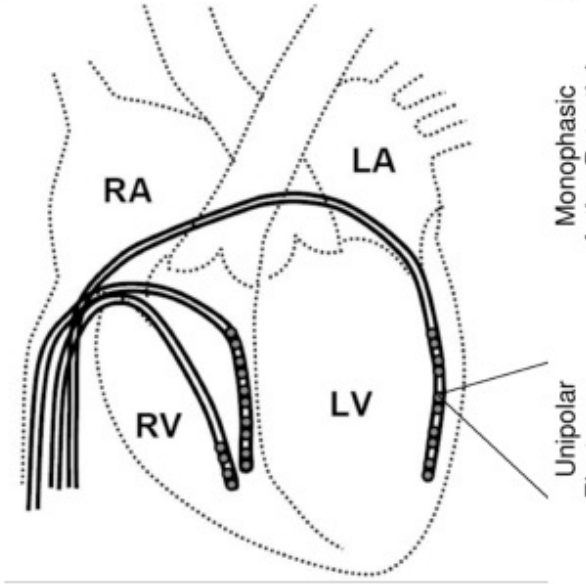
Heart-brain Interactions

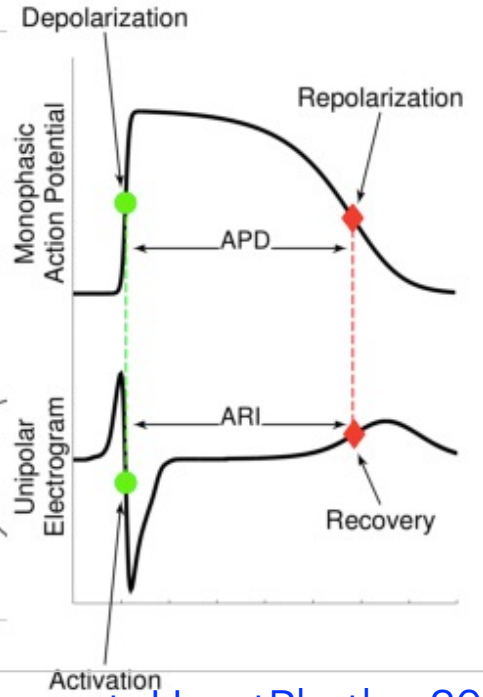


Invasive Recording of the Effects of Mental Stress







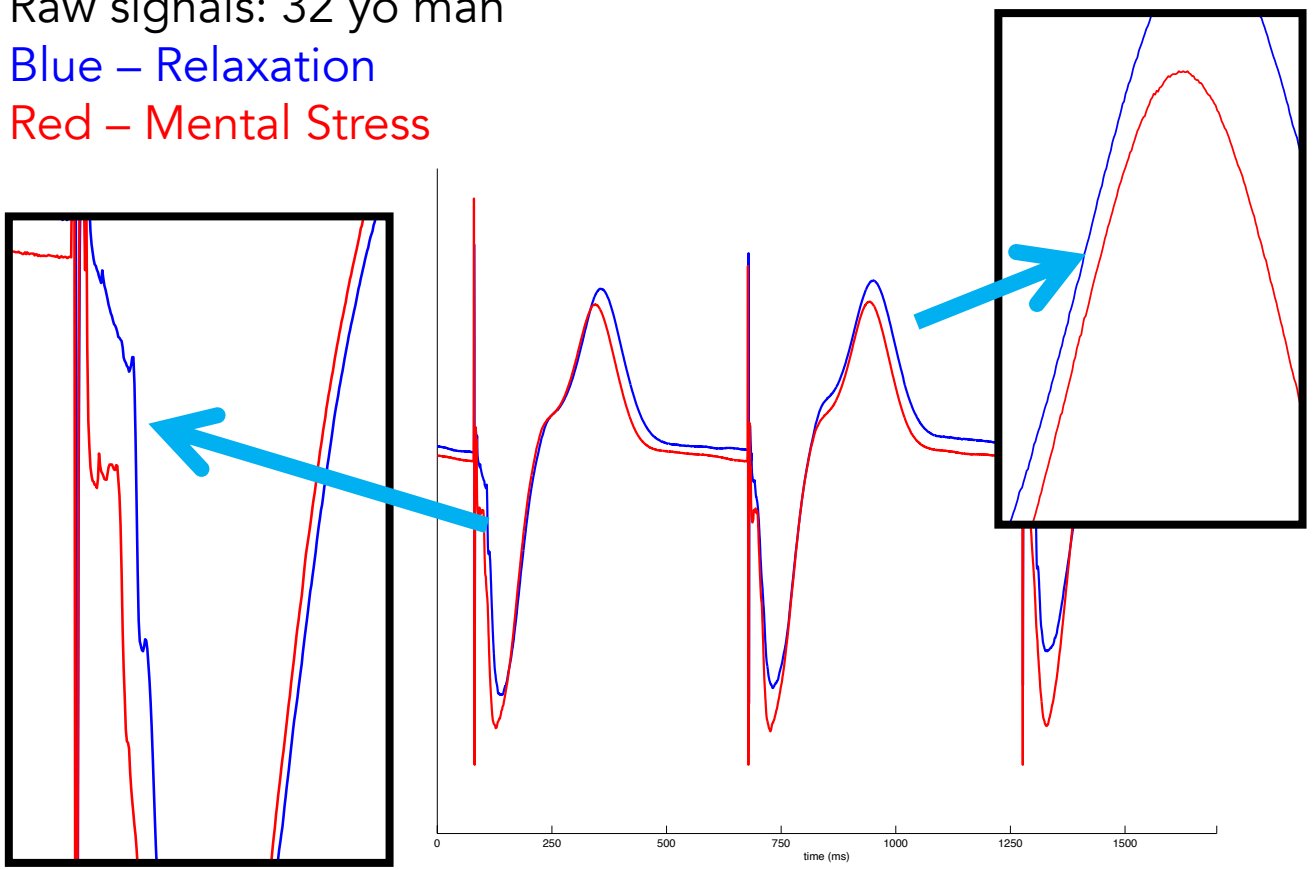


[Lambiase, Critchley, Taggart Heart2011;97:698-708]

[Finlay, Lambiase, Ben-Simon, Taggart. HeartRhythm2016]

Heart-brain Interactions

Raw signals: 32 yo man
Blue – Relaxation
Red – Mental Stress



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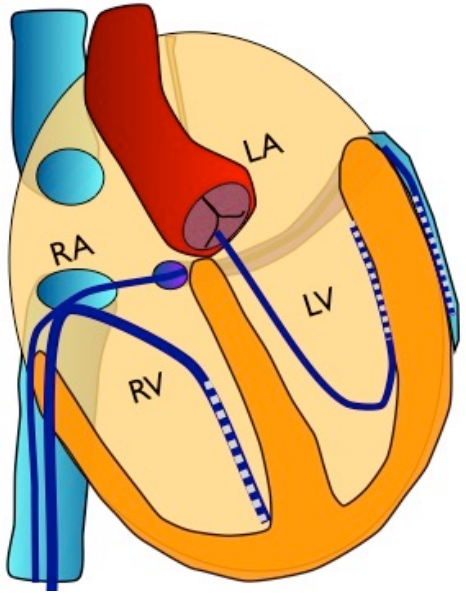
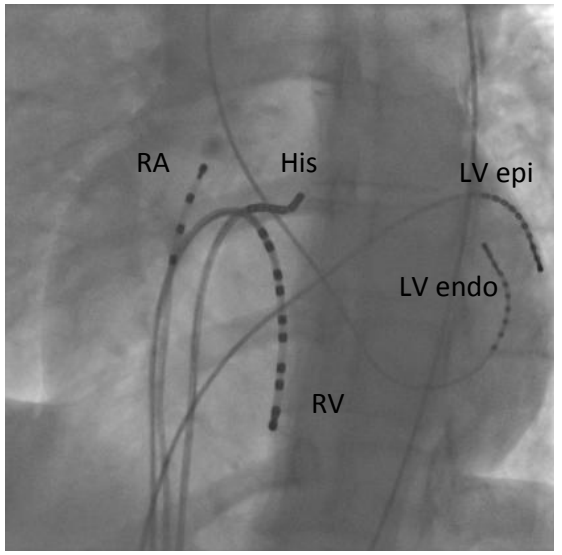
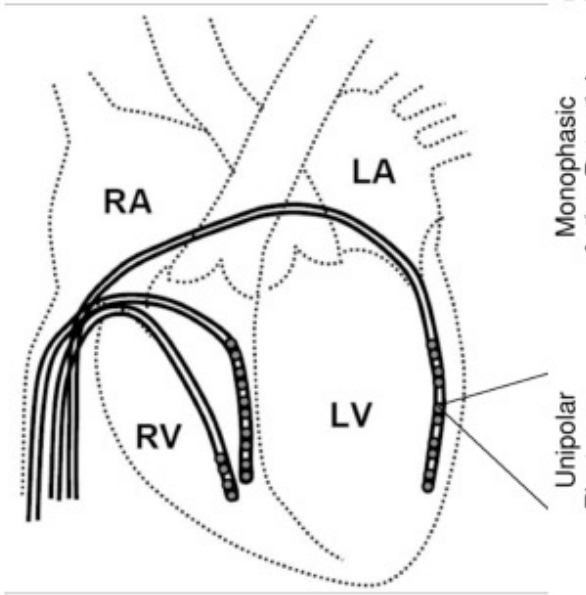
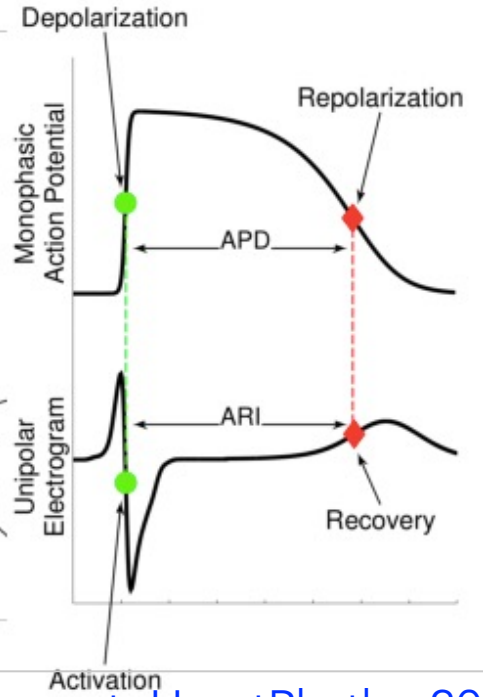








[Finlay, Lambiase, Ben-Simon, Taggart. HeartRhythm2016]

[Circulation 2014;7:518–523]

Effect of Mental Challenge Induced by Movie Clips on Action Potential Duration in Normal Human Subjects Independent of Heart Rate

Nicholas Child, BM; Ben Hanson, PhD; Martin Bishop, PhD; Christopher A. Rinaldi, MD; Julian Bostock, MSc; David Western, PhD; Michael Cooklin, MD; Mark O'Neil, MD; Matthew Wright, MRCP, PhD; Reza Razavi, MBBS, MD; Jaswinder Gill, MD; Peter Taggart, MD, DSc

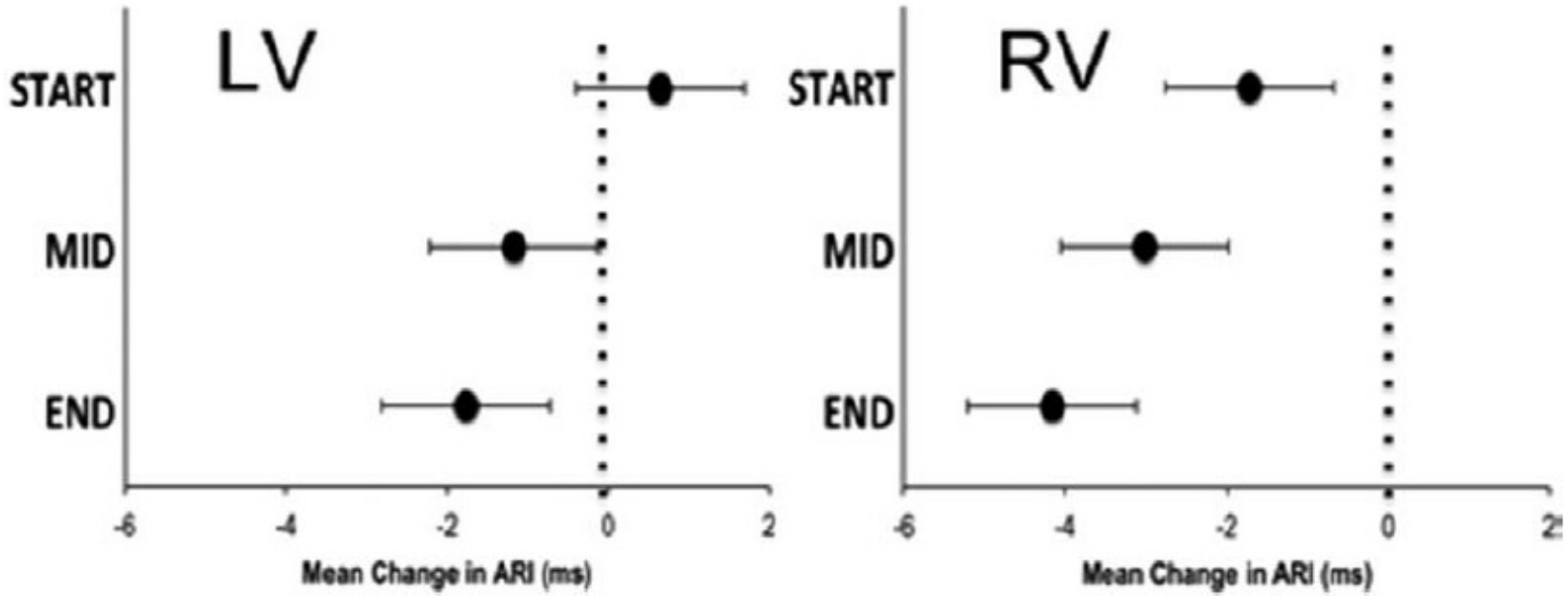
BBC TIME

EXPRESS Home of the Daily and Sunday Express

THE SCOTSMAN

theguardian

South China Morning Post 南華早報



Cardiac Response to Live Music Performance

Strong emotions linked to deadly arrhythmias [Lampert *Curr Cardiol* (2016); Taggart, Boyett, Logantha, Lambiase *Front Physiol* (2011), Wilbert-Lampern et al. *N Engl J Med* (2008)]

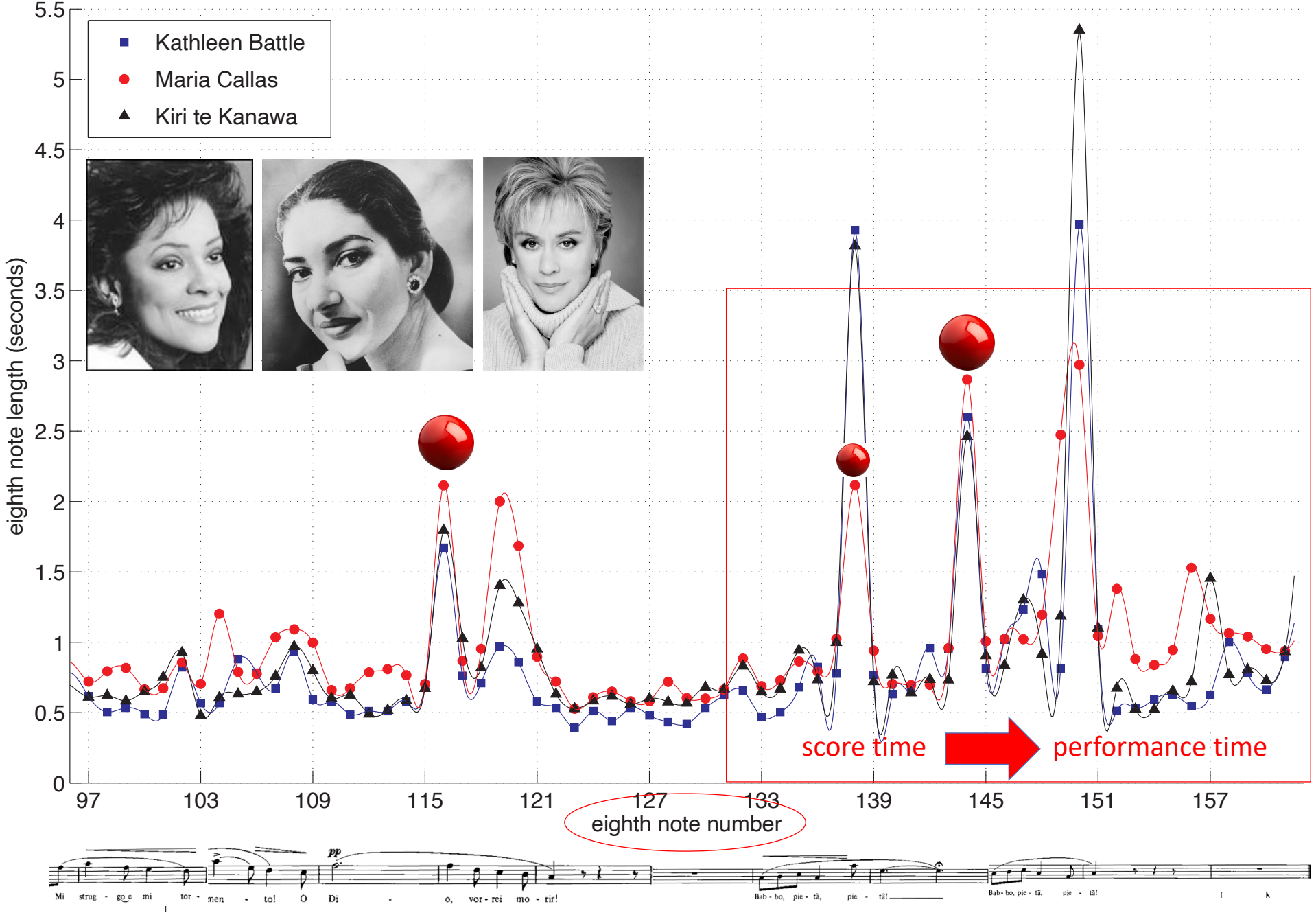
Biventricular pacemaker programmed from CRT to dual chamber pacing at 80 beats/min or 10 above intrinsic heart rate. Patients given 10 minutes to adjust.

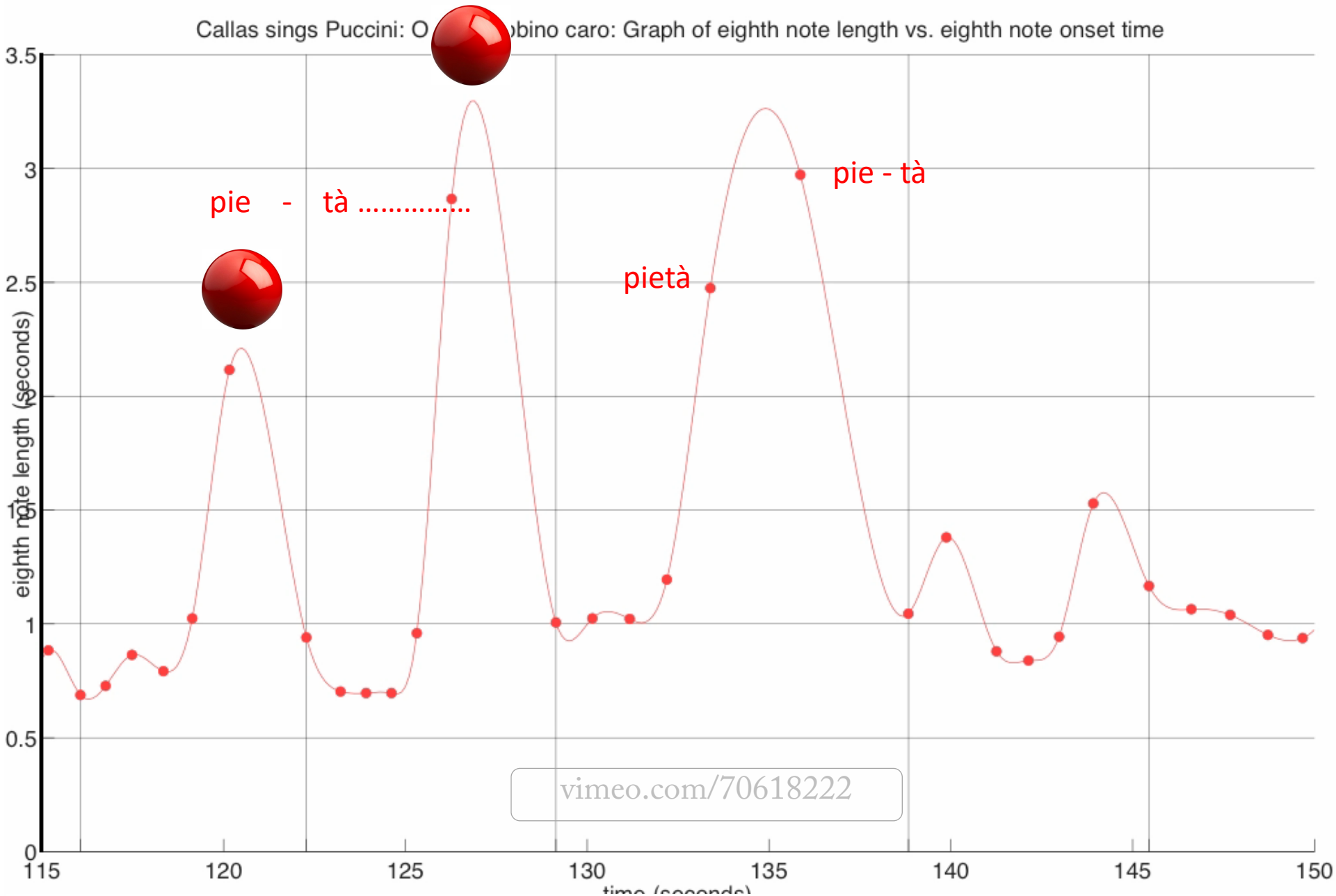
EGM data is downloaded from the pacemakers whilst patients listen to the live music performance.

Prof. Pier Lambiase

Prof. Peter Taggart

Puccini: O mio babbino caro: Graph of eighth note length vs. eighth note number



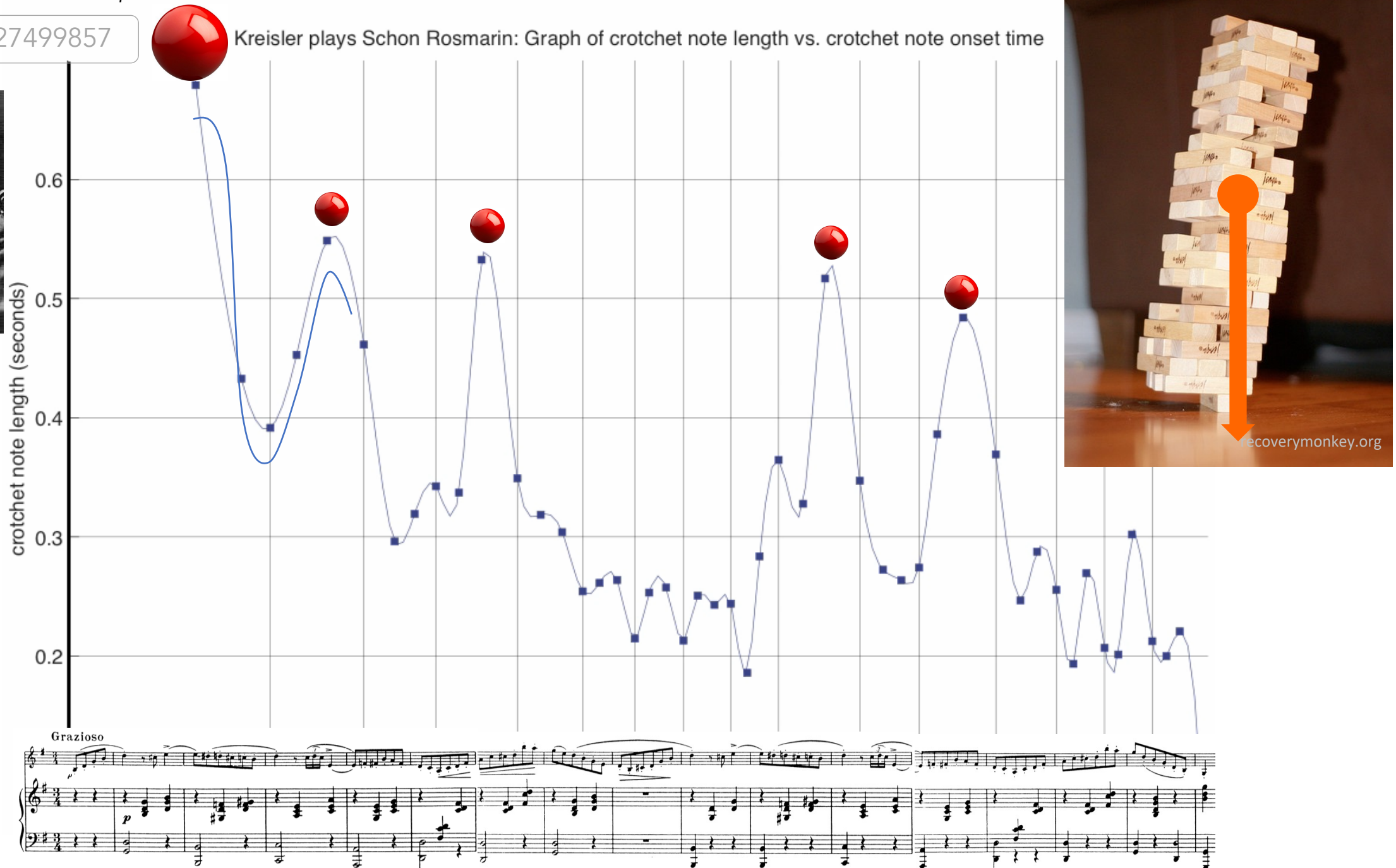


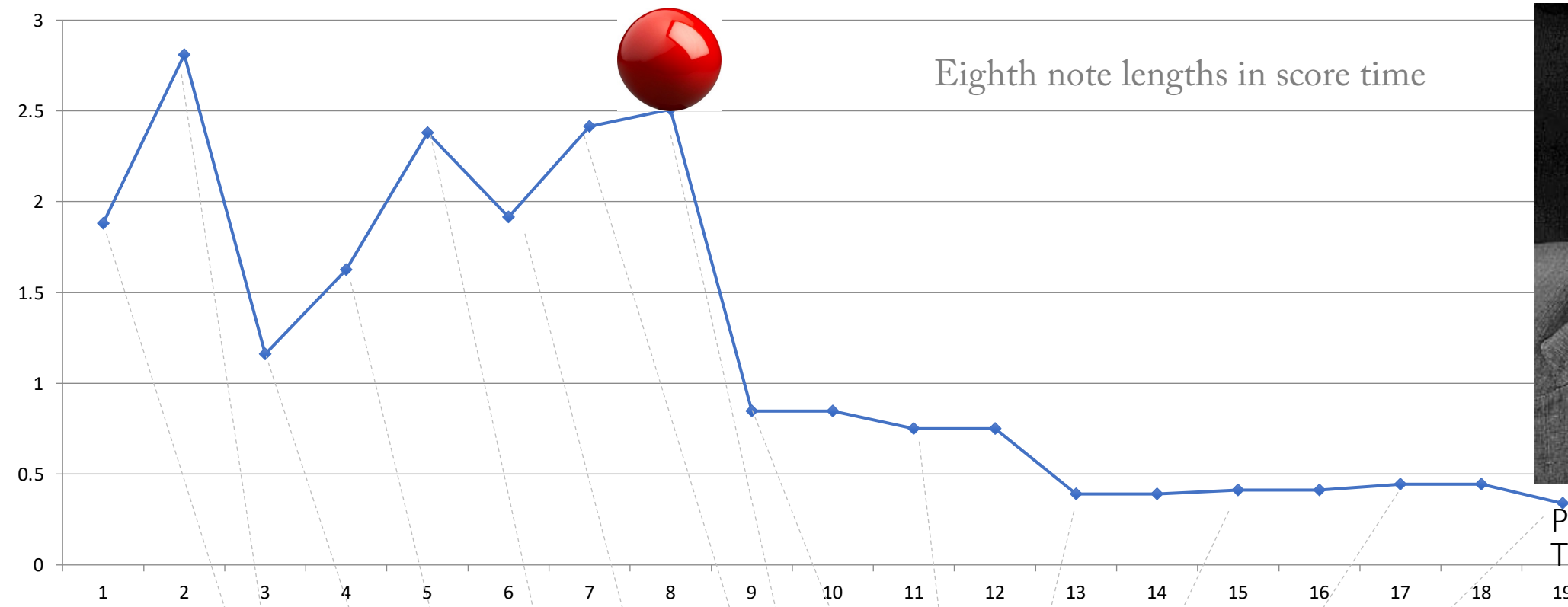
Chew, E. (2016). Playing with the edge: Tipping points and the role of tonality. In Stephen McAdams, David Temperley, Alexander Rozin (eds.): Milestones in Music Cognition Special Issue, *Music Perception*, 33(3):344-366

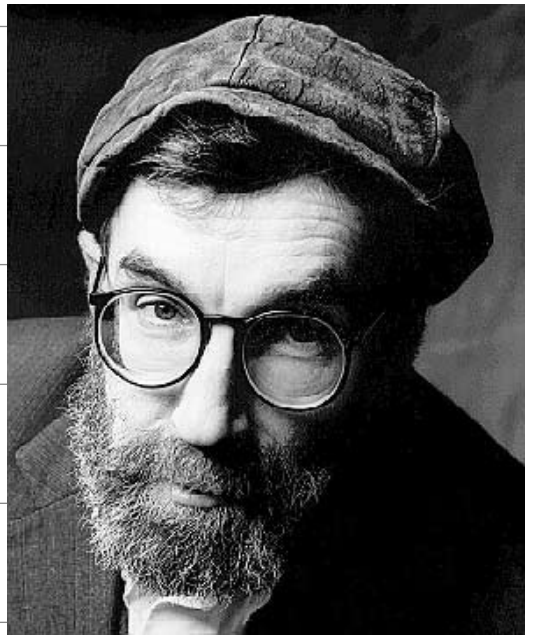
Chew, E. (2016). *Music Perception*, 33(3):344-366

vimeo.com/127499857

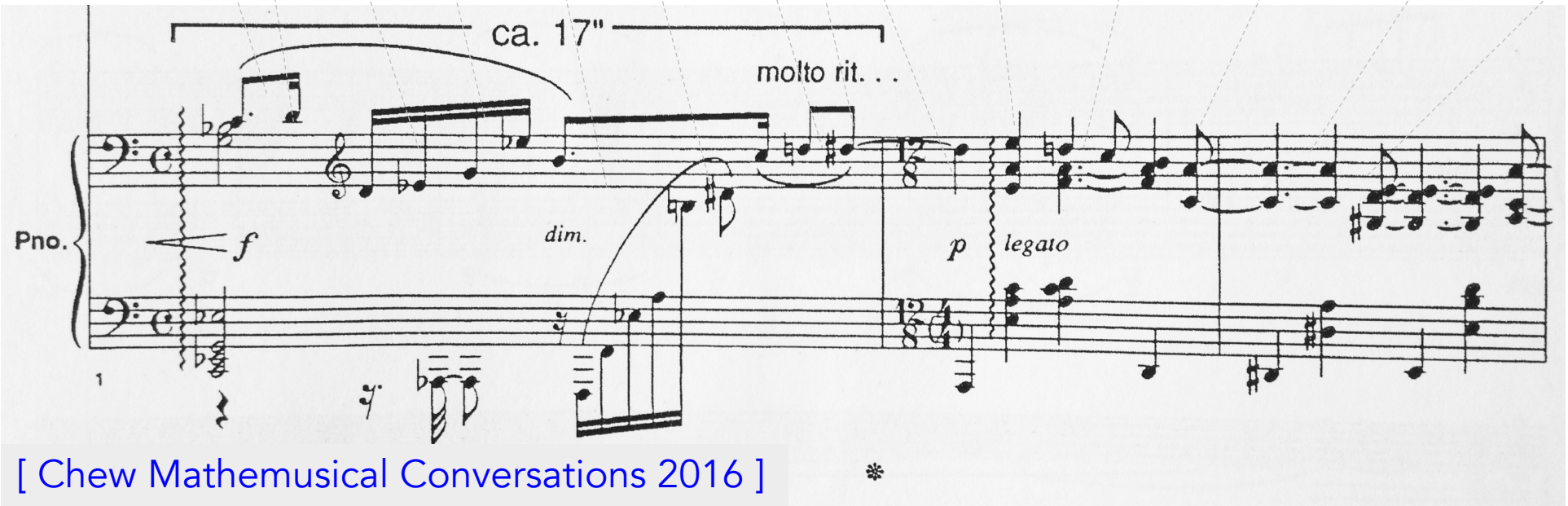
Fritz Kreisler



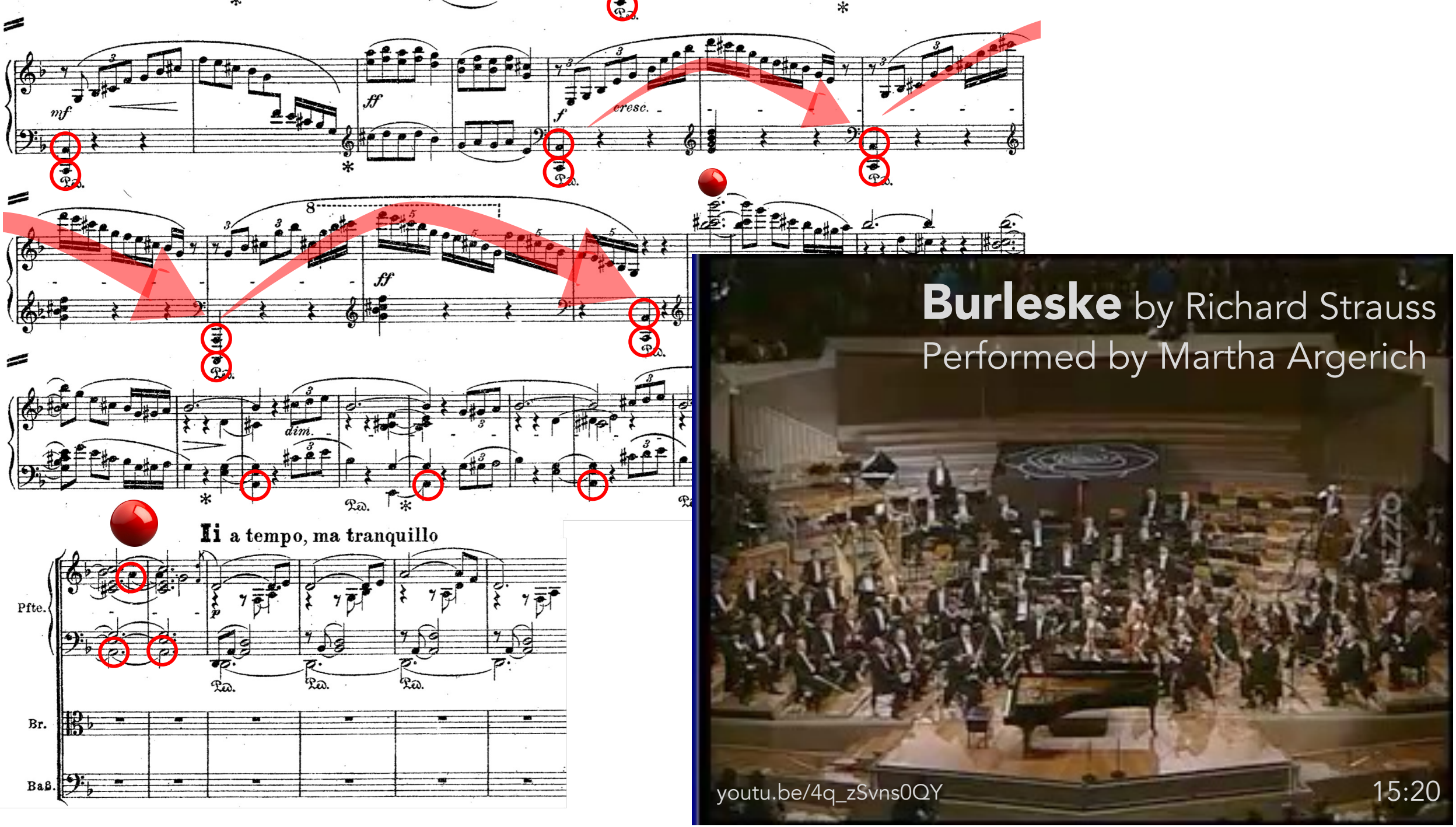




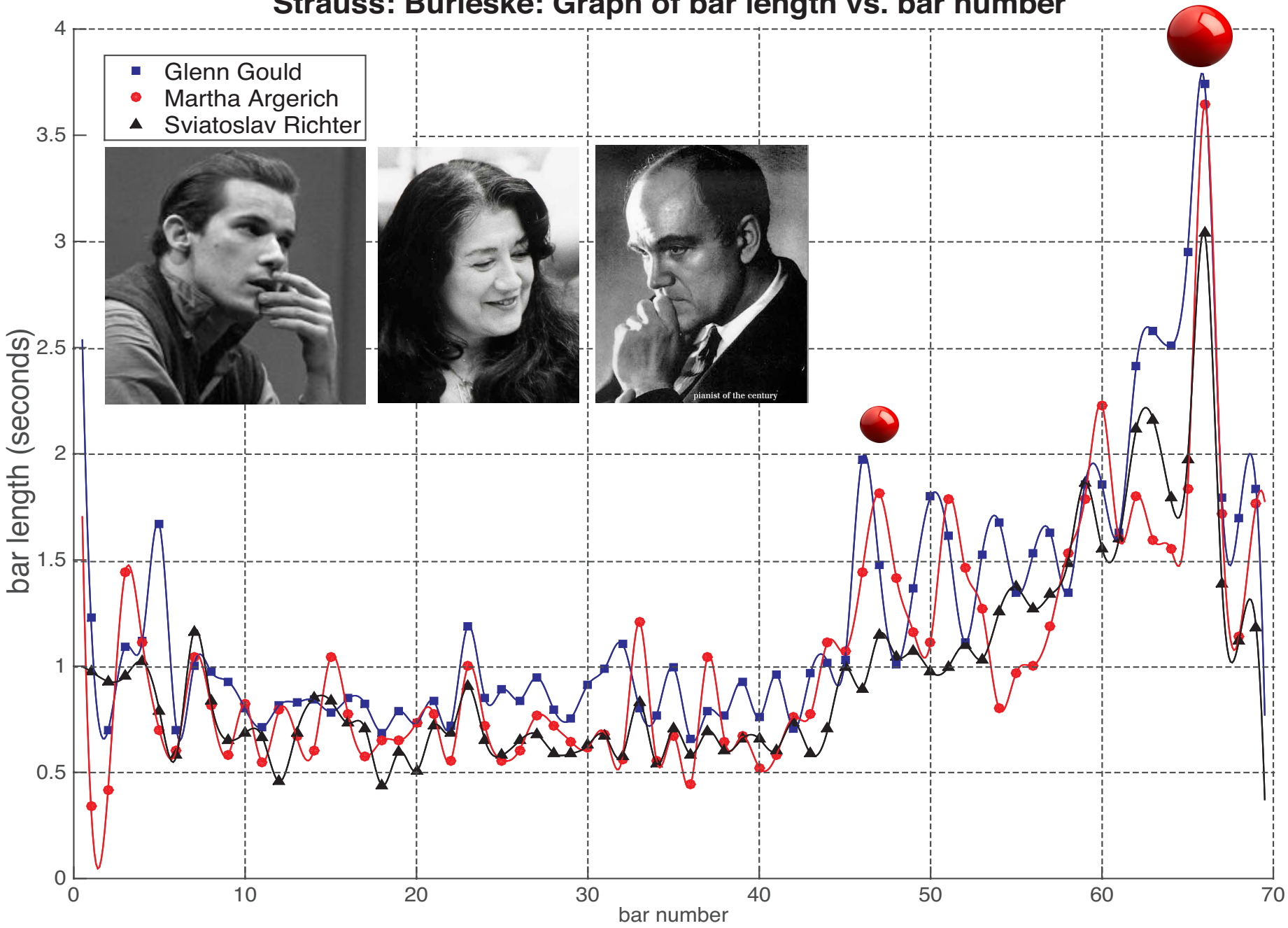
Paul Schoenfield
Trio (1990)



[Chew Mathemusical Conversations 2016]


mf
ff
f
cresc.
ff
dim.
II a tempo, ma tranquillo
Pfte.
Br.
Bas.
Burleske by Richard Strauss
Performed by Martha Argerich
youtu.be/4q_zSvns0QY
15:20

Strauss: Burleske: Graph of bar length vs. bar number



Agenda

- Background
- Heart Music
  - Putting One's Heart Into Music
- Music~Heart
  - Rhythm Transcription
  - Atrial Fibrillation Stratification via Vibrato Analysis
  - Mapping Heartbeat Coherence to Harmonic Tension
- Musical Hearts
  - Pacemaker Patient Study
  - Tipping Points and Stress
  - Demonstration of Cardiac

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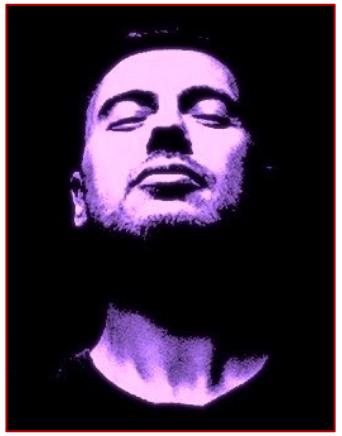
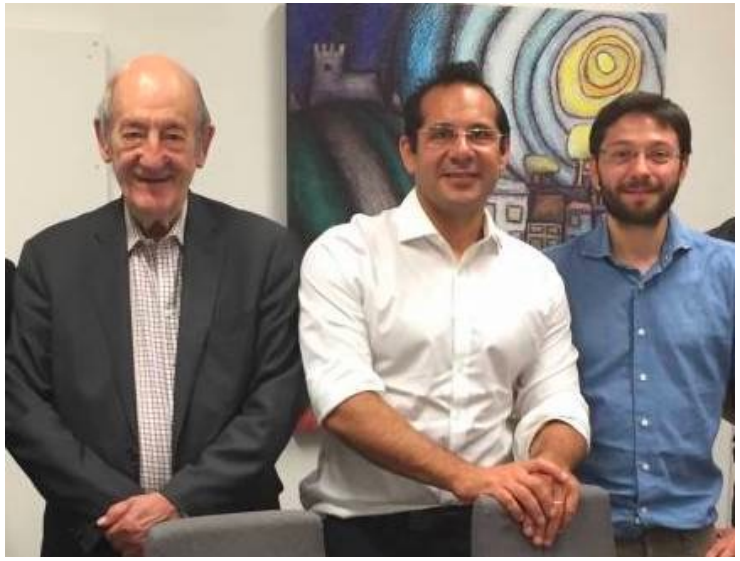
CNRS – UMR9912/STMS (IRCAM)

- Daniel Bedoya, doctoral student
- Lawrence Fyfe, CosmoNote engineer
- Corentin Guichaoua, postdoc
- Emma Frid, Swedish Res Council postdoc fellow
- Paul Lascabettes, doctoral student
- Charles Picasso, Heart.FM engineer
- Gonzalo Romero, masters intern (2020)
- Emily Graber, MSCA postdoc fellow





Collaborators:

UCL / Barts Heart Centre

Pier Lambiase, Prof of Cardiolog
Peter Taggart, Prof Emeritus
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Giampaolo Martinelli, C-T anaes


KING'S College LONDON

Department of Engineering, Faculty of Natural, Mathematical & Engineering Sciences (Dean: Bashir Al-Hashimi)
School of Biomedical Engineering and Imaging Sciences (Head: Seb Ourselin), Faculty of Life Sciences & Medicine

ERC project Cosmos Phase 2

Postdoc in Perception Analytics and Music Physiology

jobs.kcl.ac.uk/gb/en/job/052436/Research-Associate-in-Perception-Analytics-and-Music-Physiology

Postdoc in Design Analytics and Music Physiology

jobs.kcl.ac.uk/gb/en/job/052431/Research-Associate-in-Design-Analytics-and-Music-Physiology

Research Software Engineer

Closing date: 19 Sep 2022

jobs.kcl.ac.uk/gb/en/job/052430/Research-Software-Engineer

+ UK PhD Studentship (forthcoming)

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Thank you

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ERC PoC HeartFM I bit.ly/HeartFM-about

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2 in 22 stream DAFx September 9

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