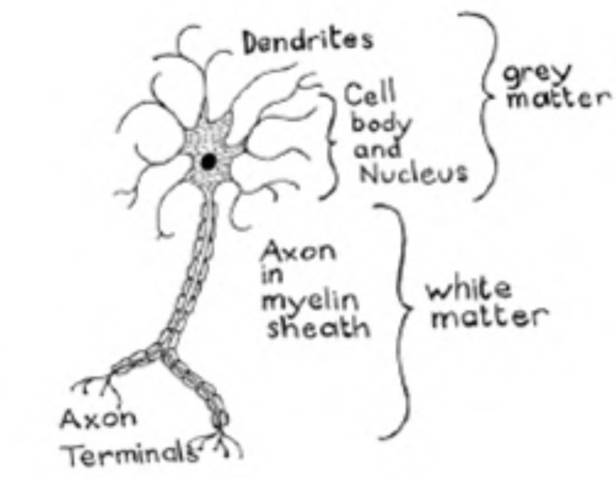
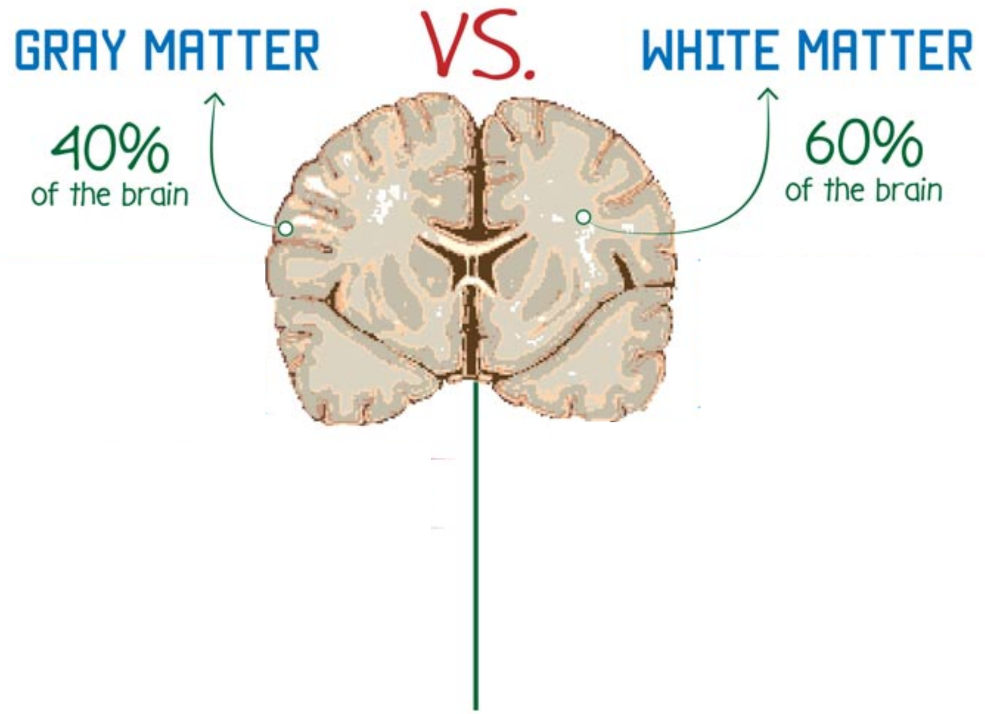
Neuromusicology

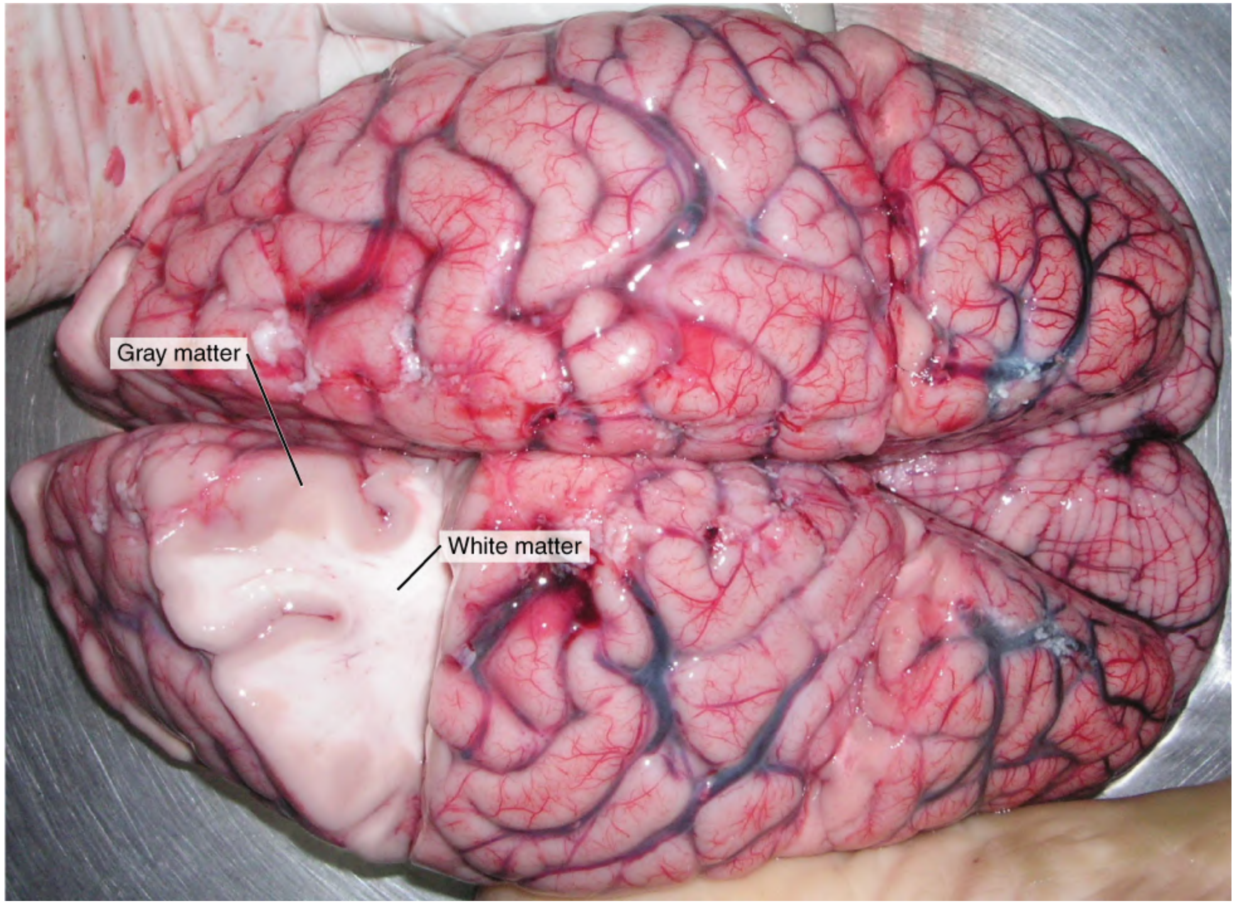
- a.k.a Cognitive Neuroscience of Music
- combination of cognitive neuroscience and empirical musicology

Brain


Dendrites
Cell body and Nucleus
grey matter
Axon in myelin sheath
white matter
Axon Terminals


GRAY MATTER
VS.
WHITE MATTER
40% of the brain
60% of the brain

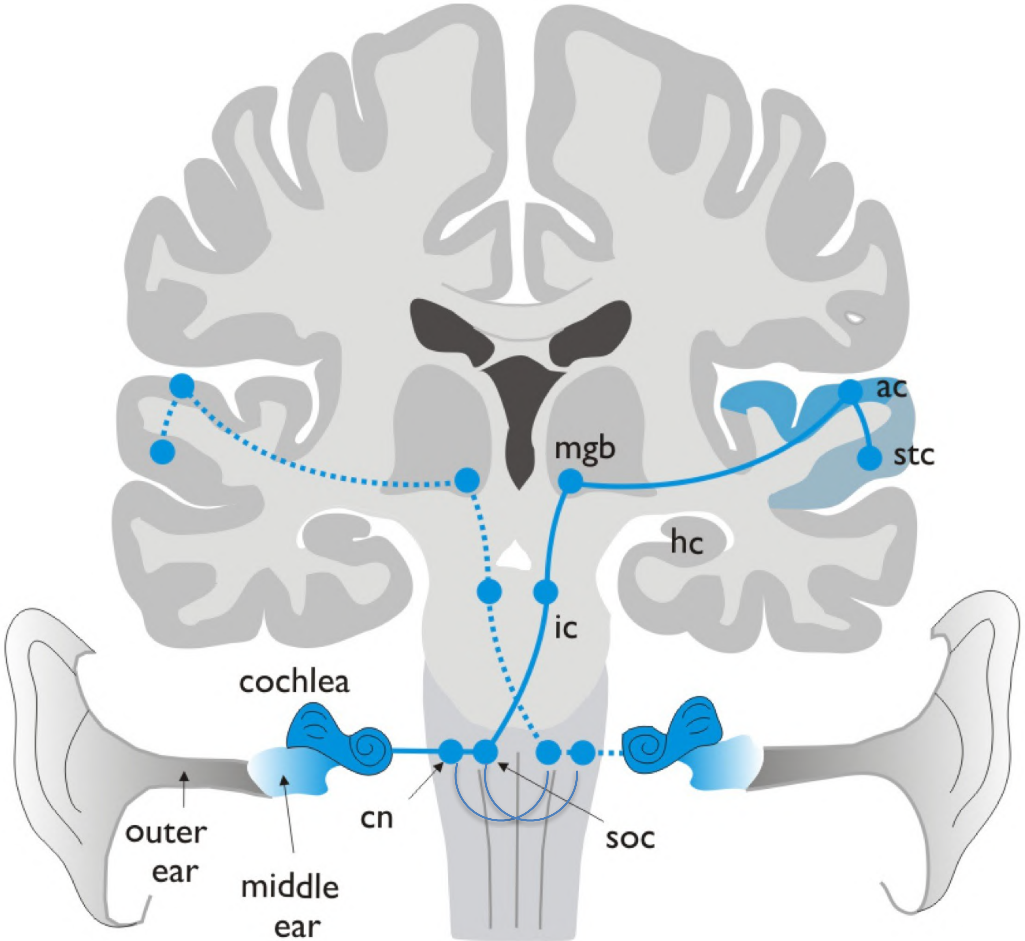
Brain

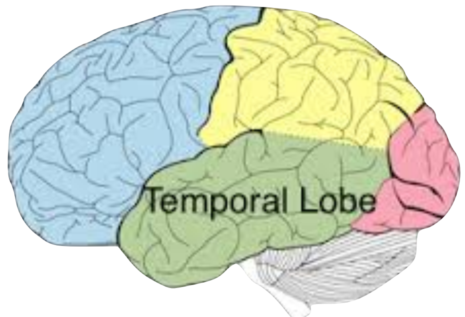


Brain

Structure vs **Function**

Auditory pathway



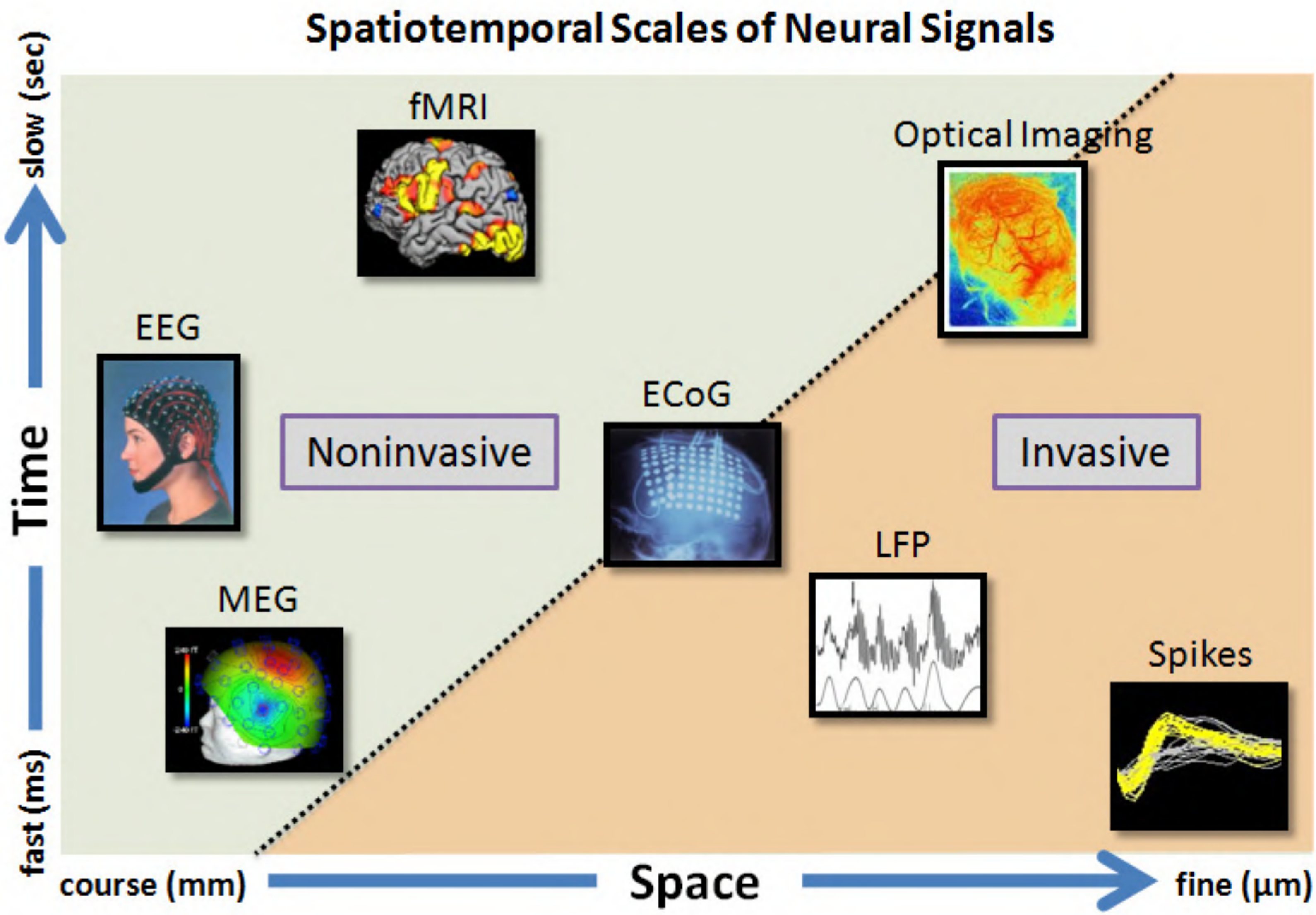


How would you investigate music and its effects?

What questions can we ask?

What would be the problems that would arise?

How to investigate the brain



How to investigate the brain

- Behavioural methods
- Lesion studies
- Animal models
- Recording from single cells and cell populations
- **Electroencephalography** (**EEG**)
- Magnetoencephalography (**MEG**)

How to investigate the brain

- Electrocorticography (**ECoG**) or intracranial electroencephalography (**iEEG**)
- Positron Emission Tomography (**PET**)
- **Magnetic Resonance Imaging** (**MRI**)
- Transcranial magnetic stimulation (**TMS**)
- Optical imaging

Keep in mind …

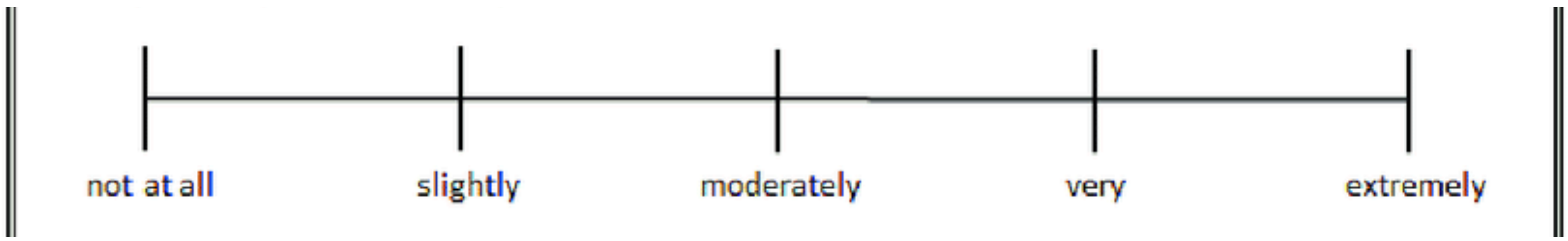
- All research methods are limited
- Limitations differ between the methods
- All methods have “**The Best Question**”, that is, the type of question that the methods answers with most accuracy and reliability
- When you have a **question**, you must choose the **method** accordingly
- When you have a **method**, you must choose the **question** accordingly

1. Behavioural methods “Listening tests”

- indirect approach
- questions related to sound features, qualitative and quantitative
- respiration, skin conductance, muscle relaxation etc can be measured (”lie detector”)

Example: loudness scaling

- **Question**: How similar is the perceived loudness of sound A to loudness of sound B?

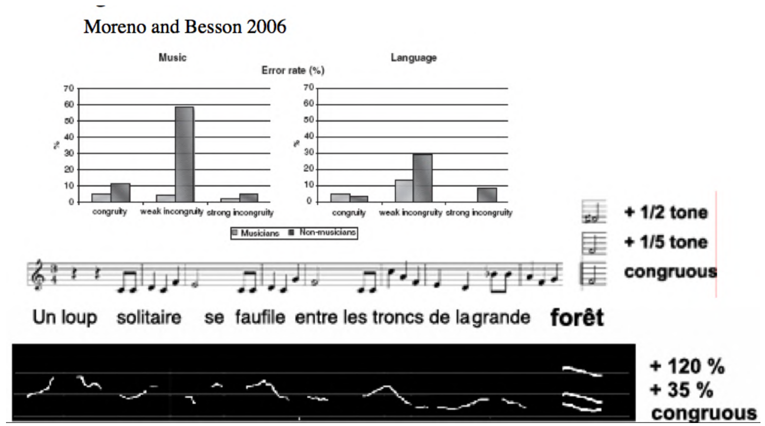


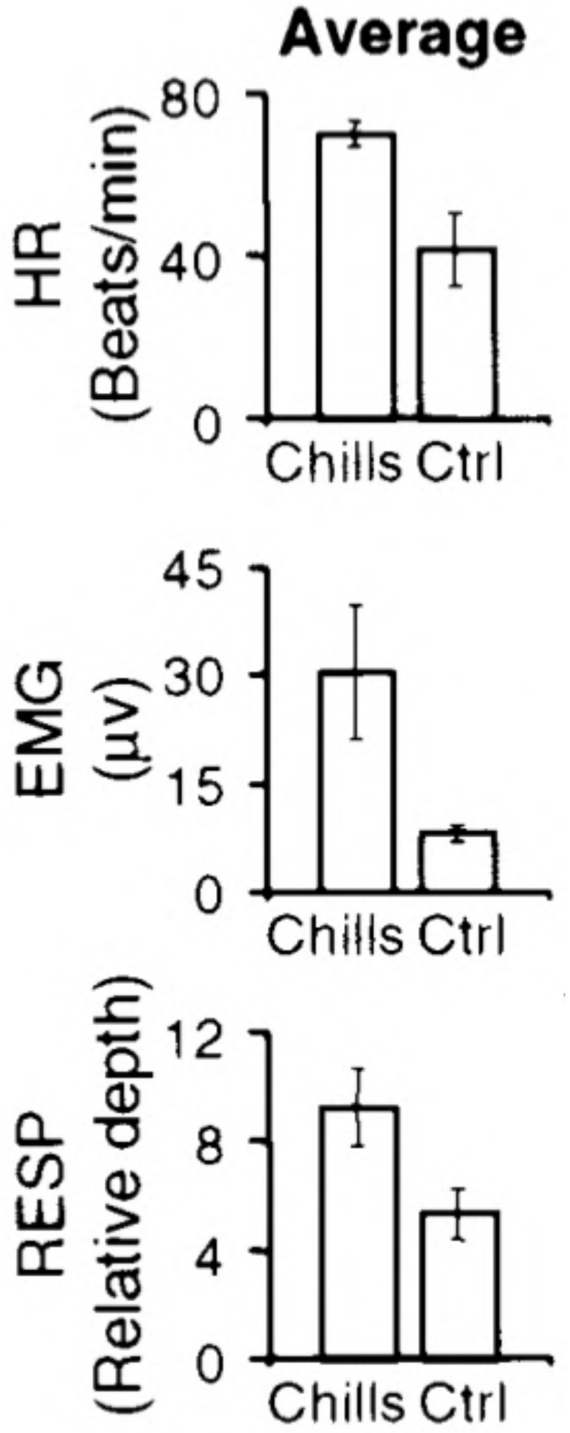
Example: incongruity identification

Question: How well do children notice changed pitches in music and speech? Does musicianship play a role here?

Children are asked to press the button when a melody or the prosody is ”wrong”.

Musicians are more accurate in both tasks.





Example: Bodily reactions to emotional music

- **Question:** what sort of music elicits ”chills”?
- **Question:** does failure to observe bodily responses to favourite music indicate underlying disorders?

Infant Language Lab

- Johns Hopkins University (1999)

- **Head-Turn** and **Auditory Preference** methods
  - Question: can she/he detect the change?
  - Question: which sound is preferred by the infant?




2. Lesion Studies

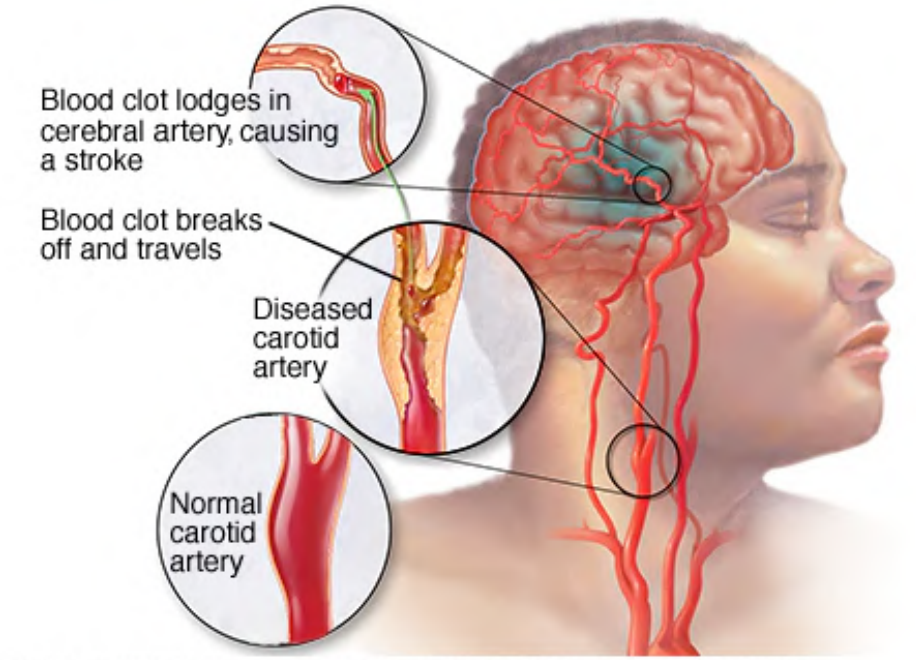
- attempt to locate a specific location in the brain's cognitive function
- brain injury - cognitive performance and comparison
- problems
  - fragmentation of processing
  - individual brains differ
  - cannot be repeated
  - brain plasticity

Phineas Gage

Harlow 1868

2. Lesion Studies

- **Acquired Amusia** (Tone deafness) - lesions in temporal lobe post ischemic stroke



2. Lesion Studies

- **Acquired Amusia** (Tone deafness) - lesions in temporal lobe post ischemic stroke
- **Congenital Amusia**
    - music as unpleasant, noise-like
    - arcuate fasciculus underdeveloped

3. Animal models

Scientific problem	Animal model	
Action potential generation →		**Squid** Squids were used to study the mechanisms underlying action potential generation because of their giant axons, which allow the insertion of voltage-clamp electrodes (*5*).
Synaptic transmission →		**Frog** Frogs were used to study the mechanisms of synaptic transmission because of the simple behavior and large size of the synapses involved (*43*).
Retinal physiology and lateral inhibition →		**Horseshoe crab** Horseshoe crabs were used to study mechanisms of retinal physiology, including lateral inhibition, because of the accessibility of individual nerve cells and convenient structure of the compound eye (*44*).
Learning and memory →		**Aplysia** Aplysia was used to study the neurobiology of learning and memory because of its capacity for simple forms of learning and the easily identifiable and accessible neurons that mediate these behaviors (*45*).
Spatial representation →		**Rat** Rats were used to study the neural components of spatial representation (*46, 47*) because of their exploration behavior and size, which enables neural recordings during free behavior. The neuroethological approach taken in these studies is described by O'Keefe and Nadel [section 4.7.1 of (*46*)].

“music can affect the physiology, production and behavior of multiple nonhuman species and provide evidence that some effects **of music exposure are similar between humans and animals**.”

“improving learning and memory, reducing stress and leading to positive changes in behavior”

Article type Journal Date

Showing 1–35 of 35 results Sort by Relevance

22 January 2013

The effects of music on animal physiology, behavior and welfare

Physiological and psychological effects of listening to music have been documented in humans... . The changes in physiology, cognition and brain chemistry and morphology induced by music have been studied in animal models, providing evidence that music may affect animals similarly to humans....

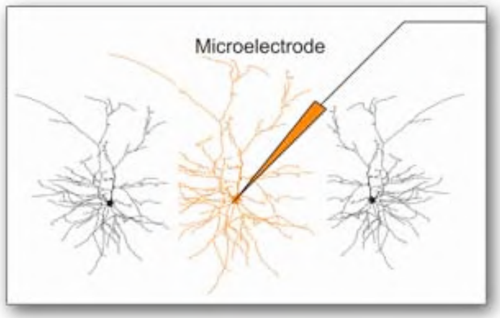
Leanne C. Alworth & Shawna C. Buerkle

Lab Animal **42** , 54–61

nature.com

4. Single cell recordings

- highest resolution of all brain imaging techniques
- up to fifty cells can be recorded at once
- Catherine Liegeois-Chauvel from Marseille is the pioneer of this work in the field of sound/music



4. Single cell recordings

- Problem:
  - highly invasive
  - limited to few neurons
  - low generalisability

fMRI, PET

EEG, MEG

- the are many important questions related to music that can not be answered with brain research
- always a trade-off

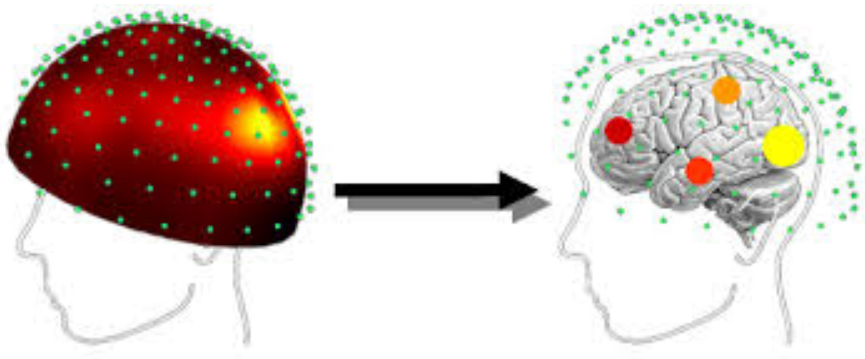
5. EEG and ERP

- electroencephalogram, event-related potentials

- the **oldest** and most established type of neuroscience methods

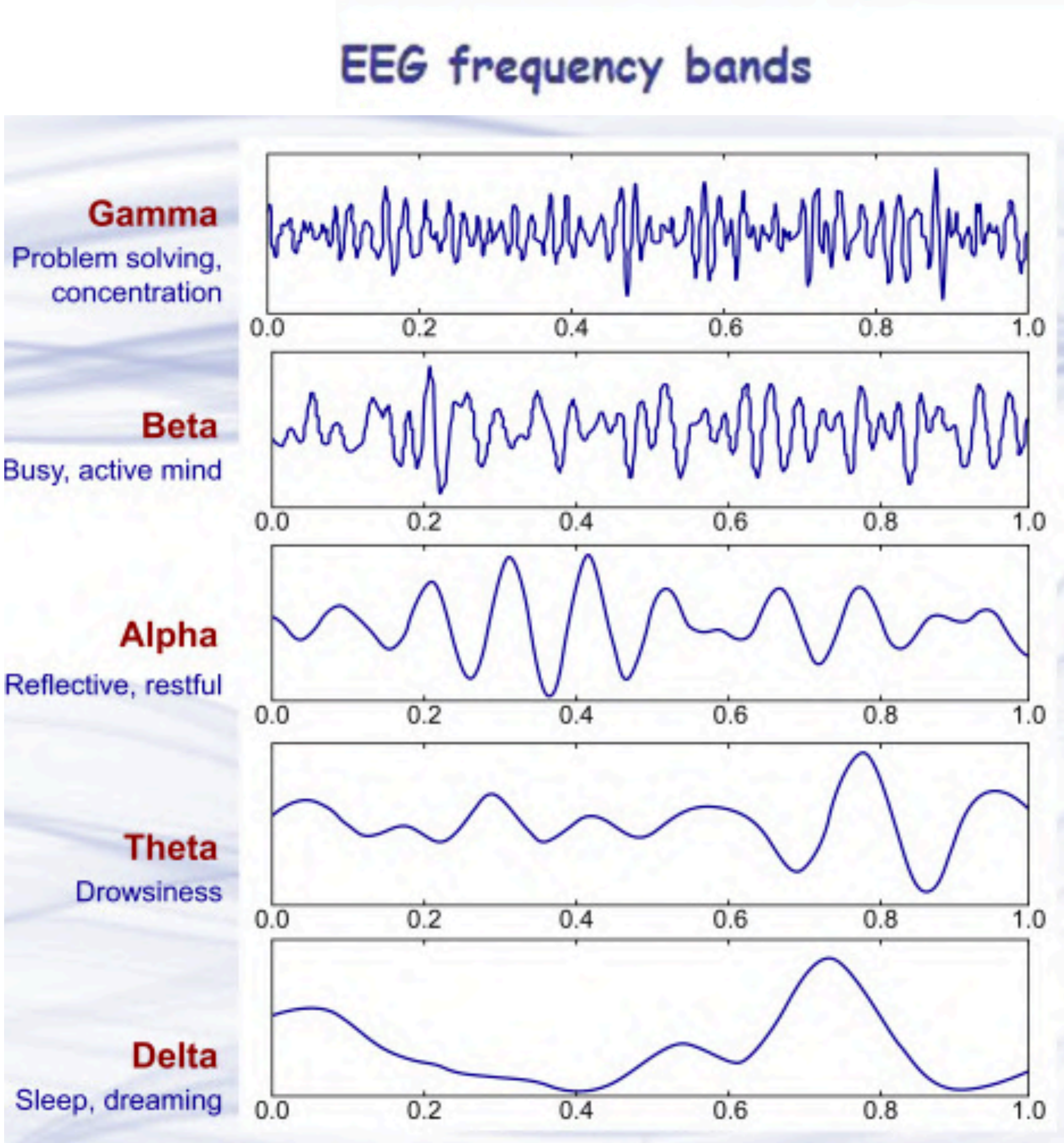
- electrodes placed onto the head's surface to record potentials

- temporally very accurate

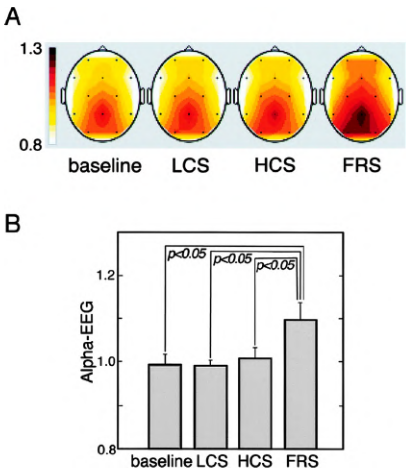


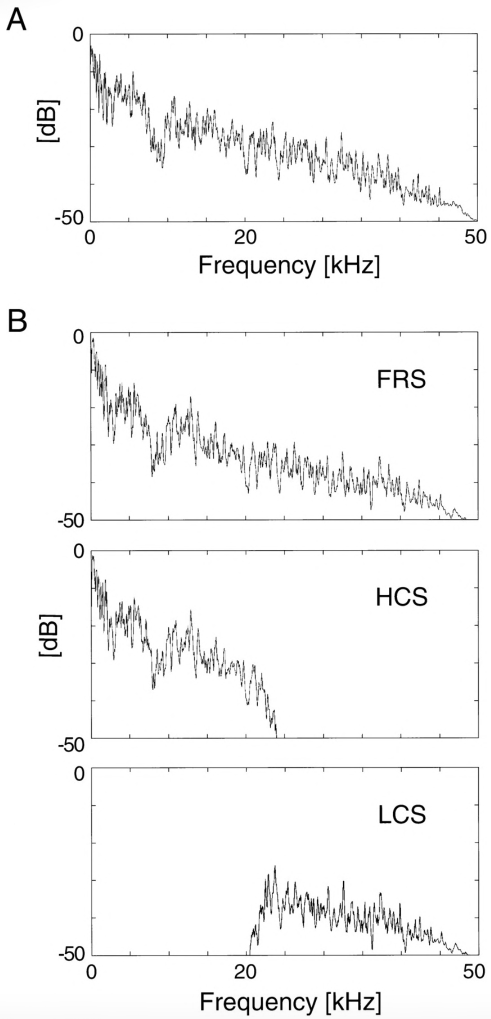
5. EEG and ERP

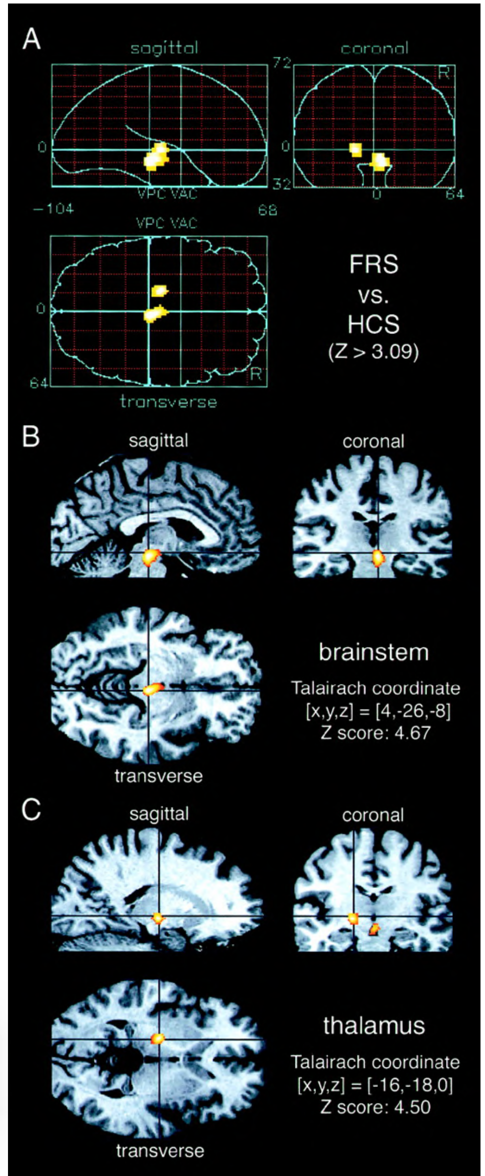
Activity	Frequency (HZ)
Delta	0.5–4
Theta	4–8
Alpha	8–13
Beta	13–30
Gamma	30–40



Inaudible High-Frequency Sounds Affect Brain Activity: Hypersonic Effect
Oohashi et al. (2000). Journal of Neurophysiology, 83 (6) 3548-3558;

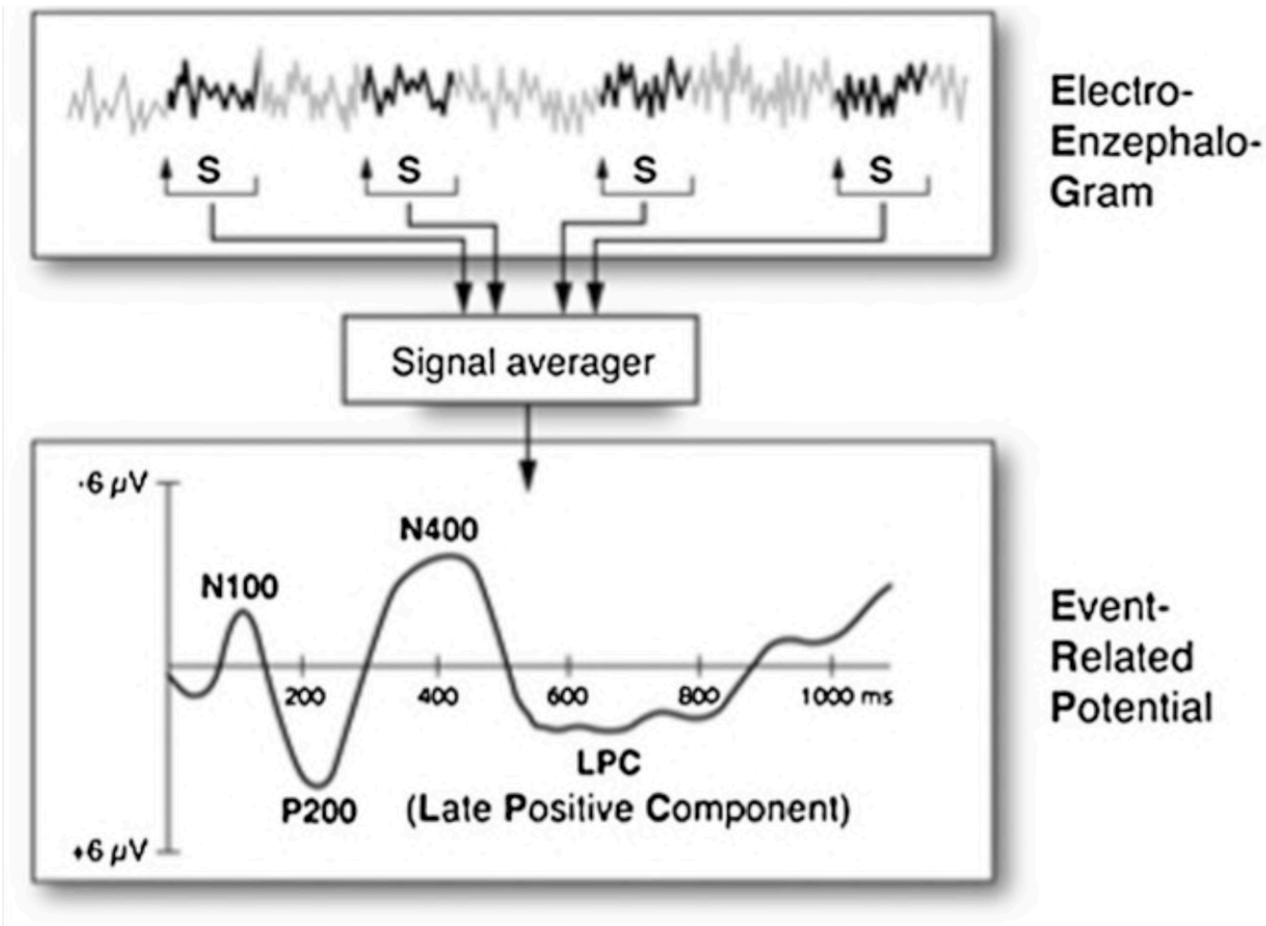






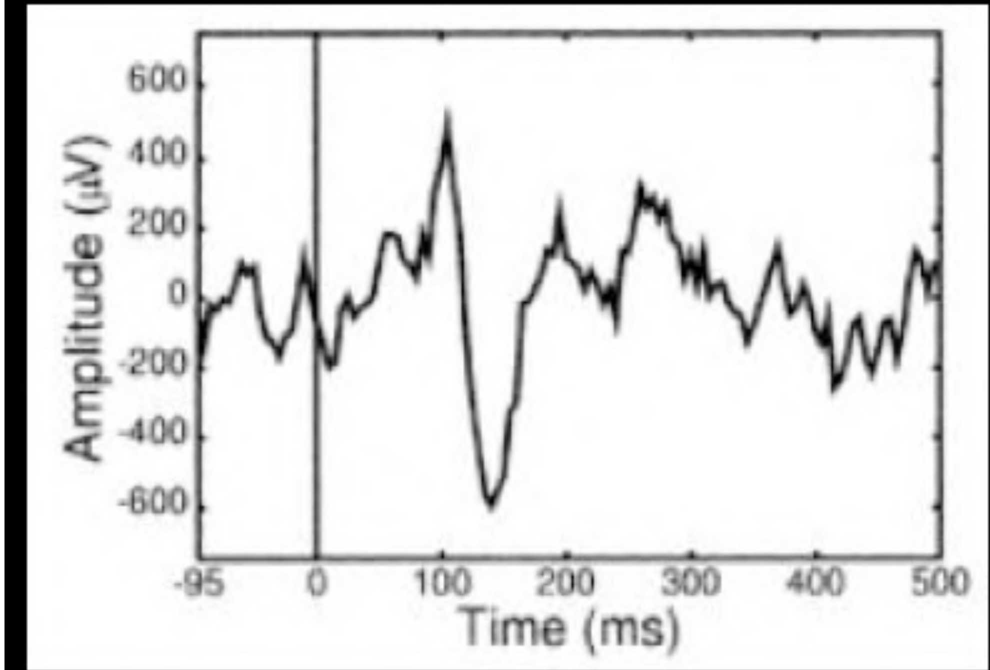
sound containing HFC to be more pleasant
than the same sound lacking an HFC

5. EEG and $\boxed{\textbf{ERP}}$

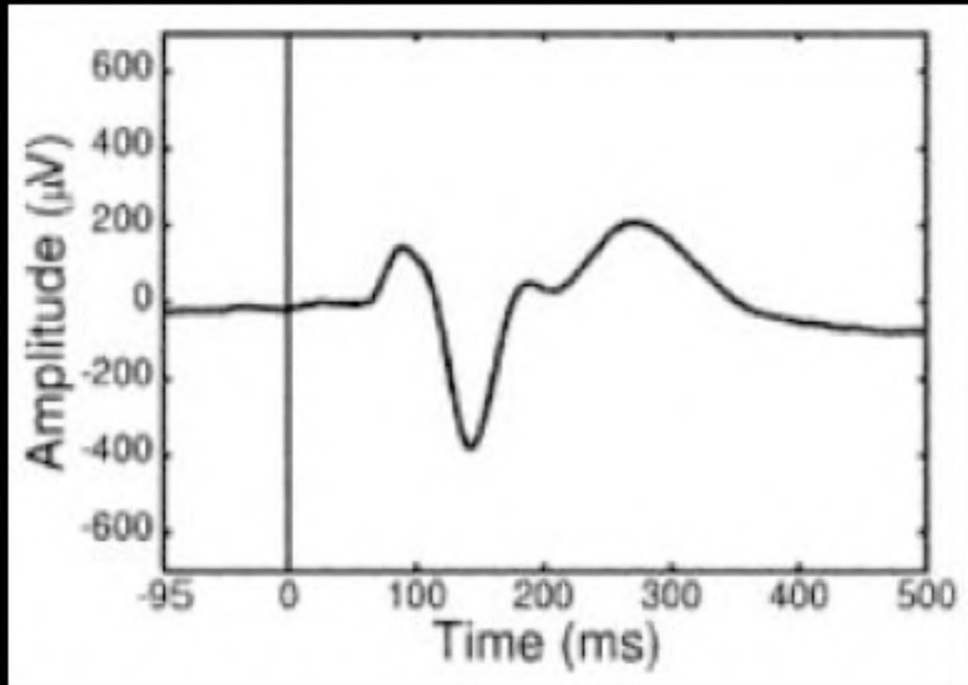


grand average ERPs

ERP derived from EEG

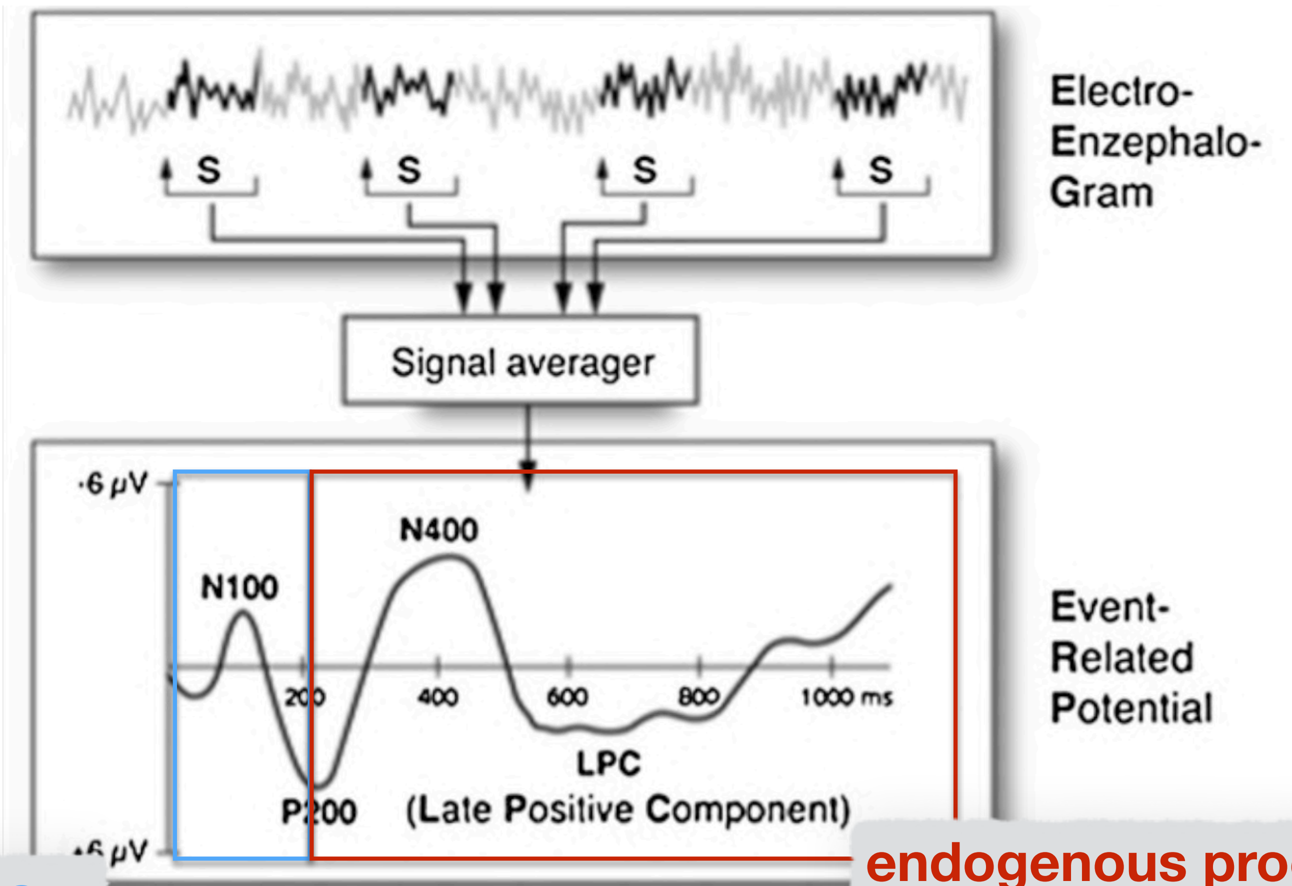


Single Trial: 100ms visual stimulus



Average of 200 trials to same stimulus

5. EEG and **ERP**

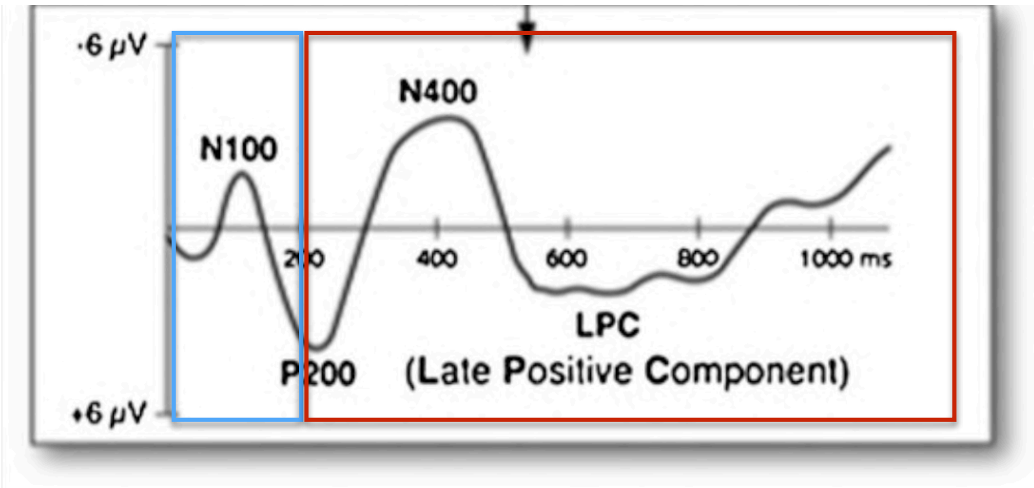


exogenous processes - determined by stimulus features such as frequency, intensity

grand average ERPs

endogenous processes - reflecting some task-related cognitive processing steps for which attention is required

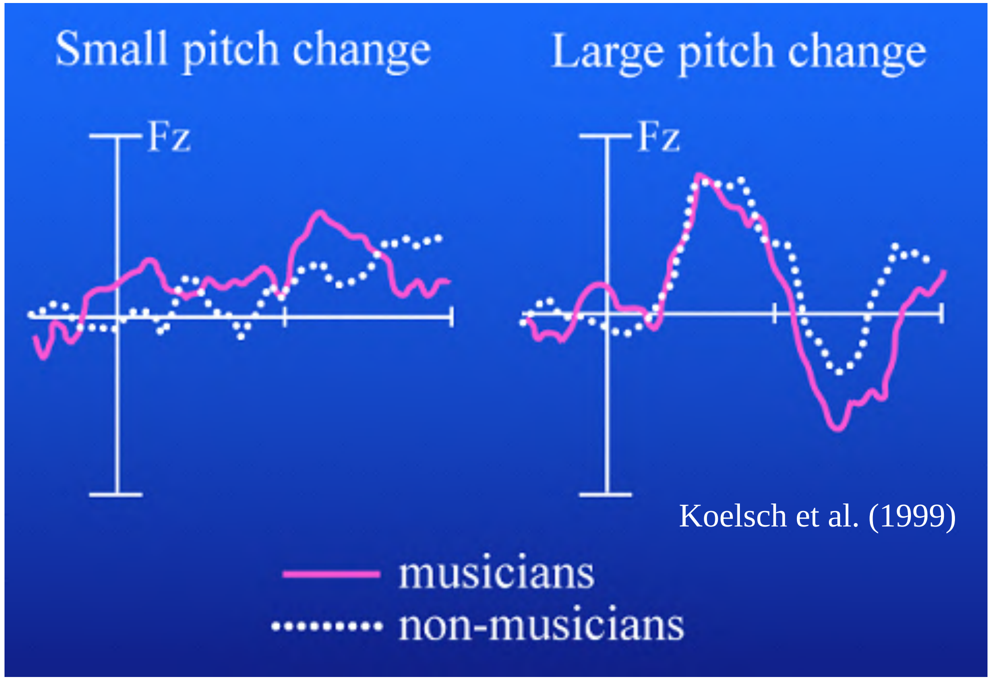
5. EEG and **ERP**

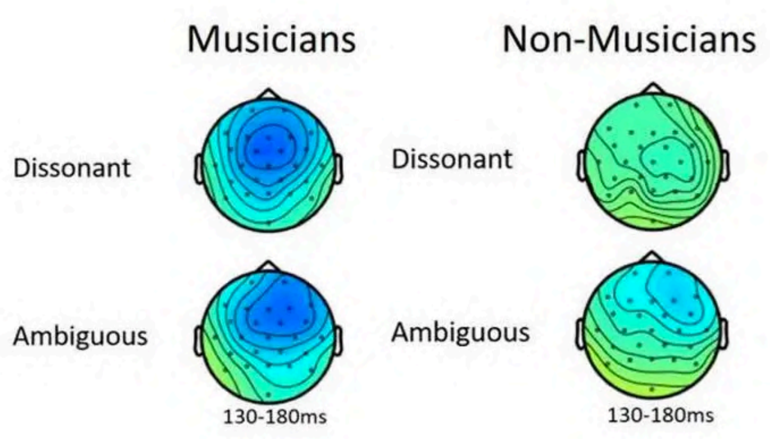


Event-Related Potential

Exogenous potentials	Endogenous potentials
- Depend on physical features of the sensory stimulus.	- Do not depend on physical features of sensory stimulus. They can be evoked, just with stimulus expectancy, even in the absence of stimulus.
- Do not depend on the subjects' level of consciousness.	- Can change depending on the level of attention, its relevancy during the task and resources required for stimulus processing.
- Are not influenced by cognition processes.	- Related to cognition processing.

5. EEG and ERP


Small pitch change
Large pitch change
Fz
Fz
Koelsch et al. (1999)
musicians
non-musicians


Musicians
Non-Musicians
Dissonant
Dissonant
Ambiguous
Ambiguous
130-180ms
130-180ms

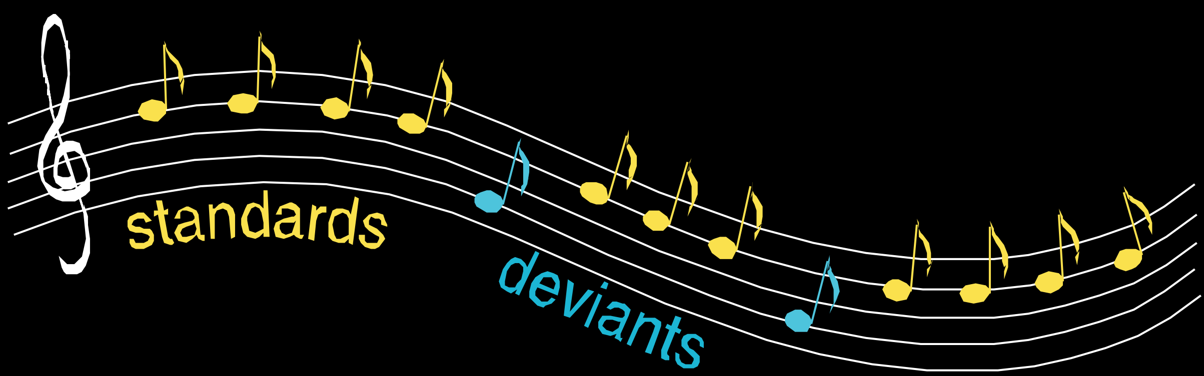
ERP in infants and neonates

Mismatch Negativity **(MMN)**

- ERP to a change in a sound stream or in general to an odd stimulus in a sequence of stimuli

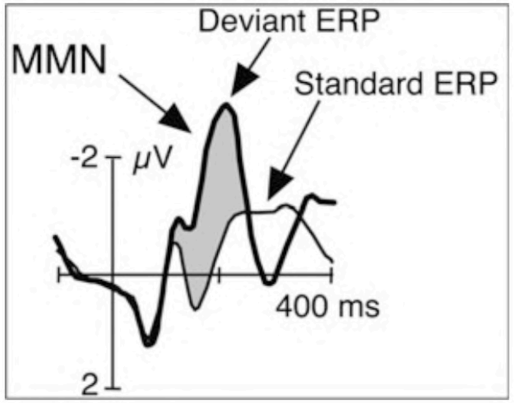
- Reflects the action of short-term memory
- Does not require attention
- In infants, recorded during sleep

Näätänen&Winkler:The concept of auditory stimulus representation in cognitive neuroscience. Psych Bull vol.125 (2000)

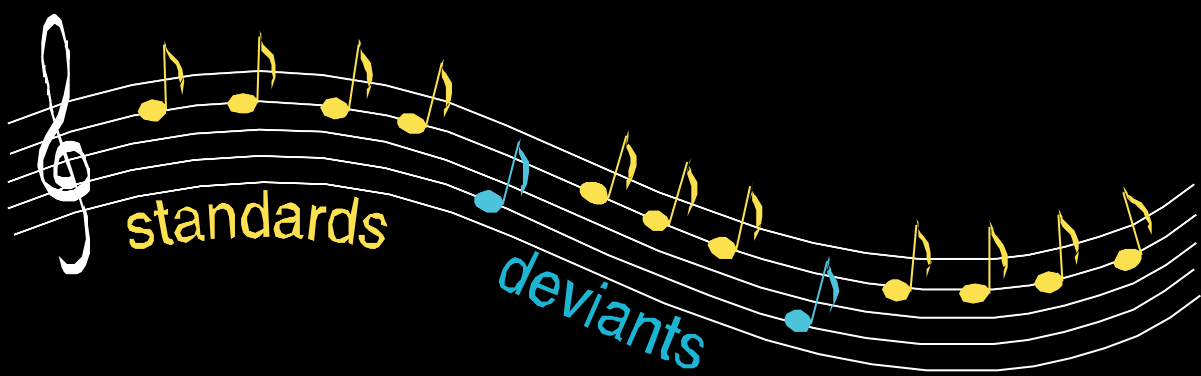


Mismatch Negativity **(MMN)**

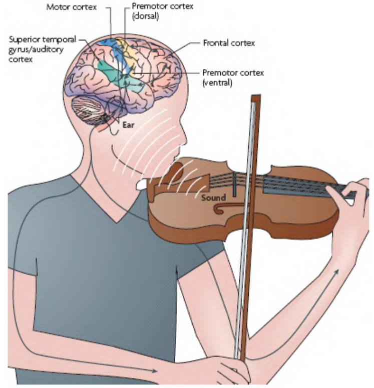
“Memory trace”



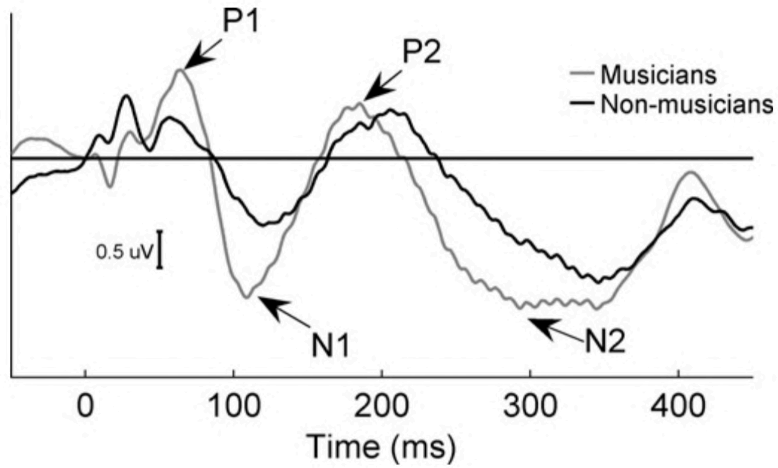
Näätänen&Winkler:The concept of auditory stimulus representation in cognitive neuroscience. Psych Bull vol.125 (2000)



Effects of musical training



- Musicians have an earlier and stronger response from the brainstem to speech and music sounds (Musacchia et al., 2007; Wong et al., 2007; Strait et al., 2009)



- Musicians have stronger responses to sound changes, esp. of own instrument (Pantev et al., 1998; Tervaniemi et al., 2001; Schneider, P. et al., 2002)

“**jazz musicians** outperformed other types of musicians in terms of general auditory abilities”

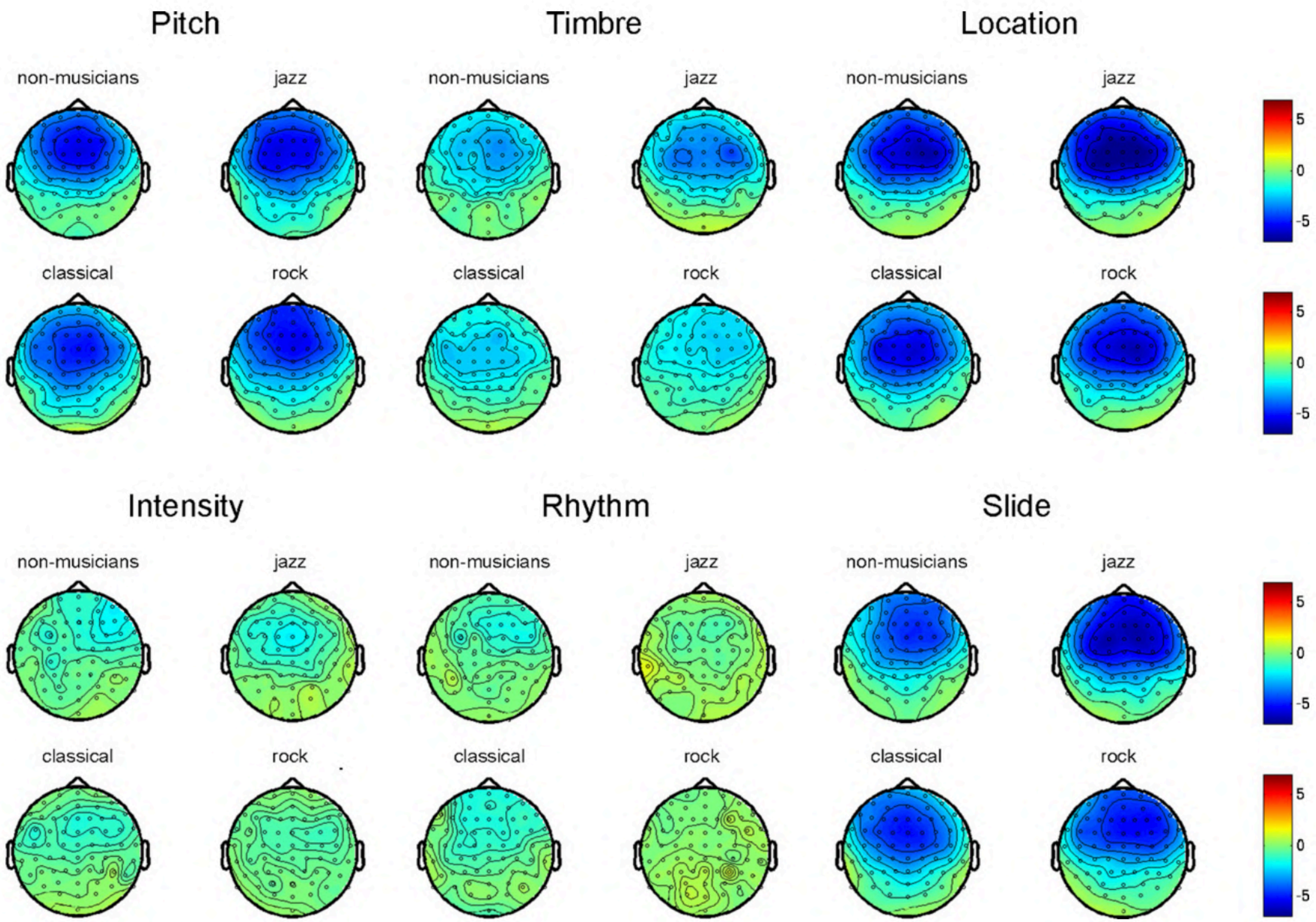


Fig. 4. EEG voltage isopotential maps of the difference between the responses to deviants and standards averaged in an interval of ±20 ms around maximal peak amplitudes.

jazz musicians had larger MMN-amplitude than all other experimental groups across the six different sound features, indicating a greater overall sensitivity to auditory outliers

Vuust, P., Brattico, E., Seppänen, M., Näätänen, R., & Tervaniemi, M. (2012). The sound of music: Differentiating musicians using a fast, musical multi-feature mismatch negativity paradigm. Neuropsychologia, 50(7), 1432–1443. doi:10.1016/j.neuropsychologia.2012.02.028

5. EEG and ERP

EMOTIV

ELSEVIER

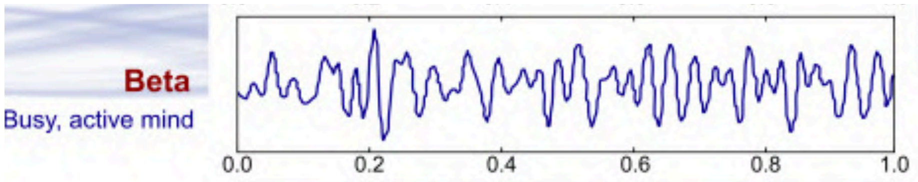
Information Sciences

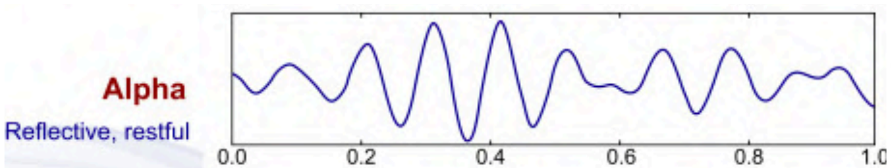
Volumes 343–344, 20 May 2016, Pages 94-108

Towards the bio-personalization of music recommendation systems: A single-sensor EEG biomarker of subjective music preference

Dimitrios A. Adamos [a, c], Stavros I. Dimitriadis [b, c], Nikolaos A. Laskaris [b, c]

5. EEG and ERP

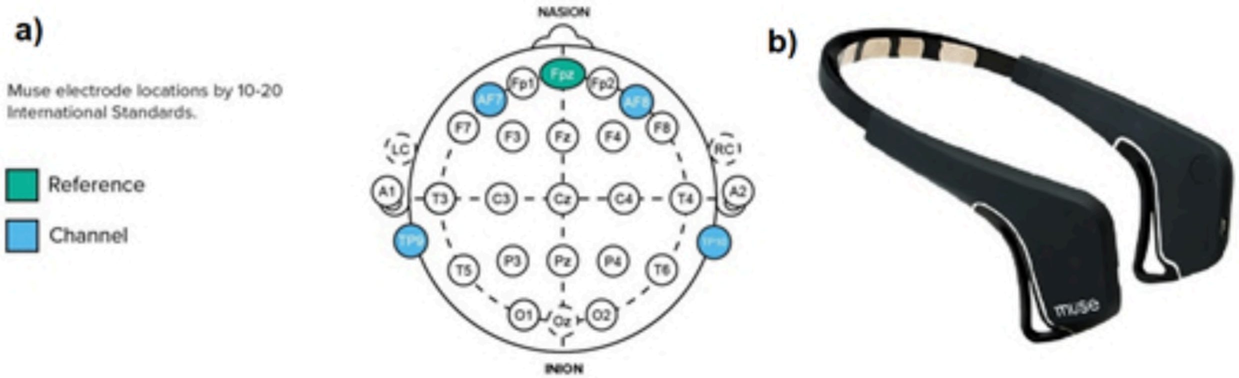


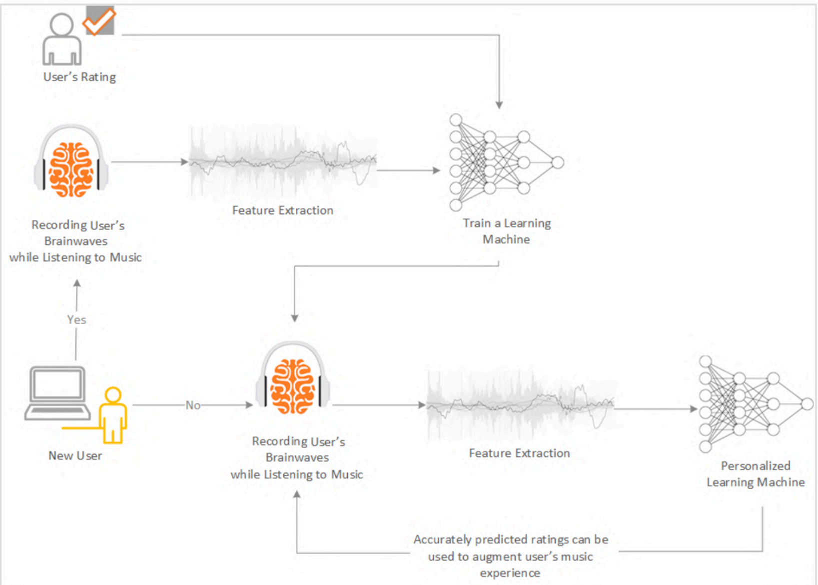


Immersion and emotional engagement (high alpha) during liked music.

Reduced cognitive control or evaluative thinking (lower beta).

5. EEG and ERP





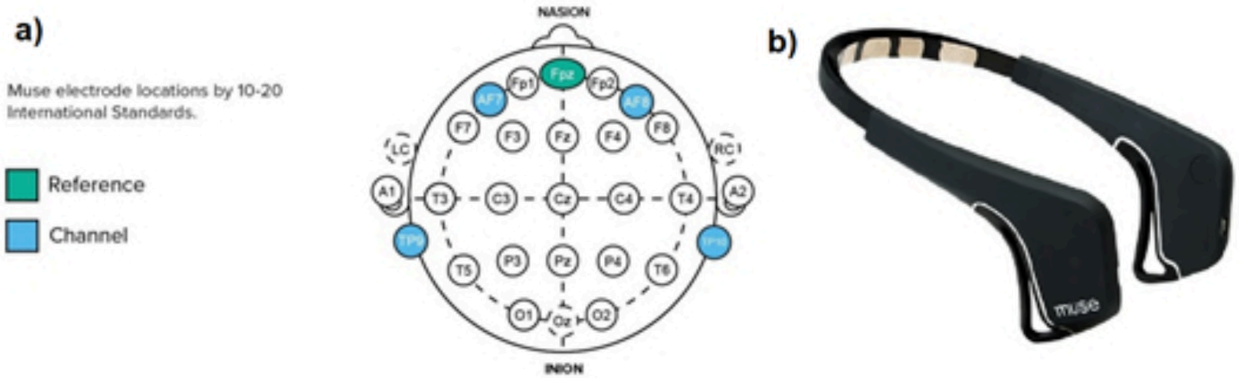
Musical NeuroPicks :

a consumer-grade BCI for on-demand music streaming services

https://arxiv.org/pdf/1709.01116.pdf

https://arxiv.org/pdf/1609.06374.pdf

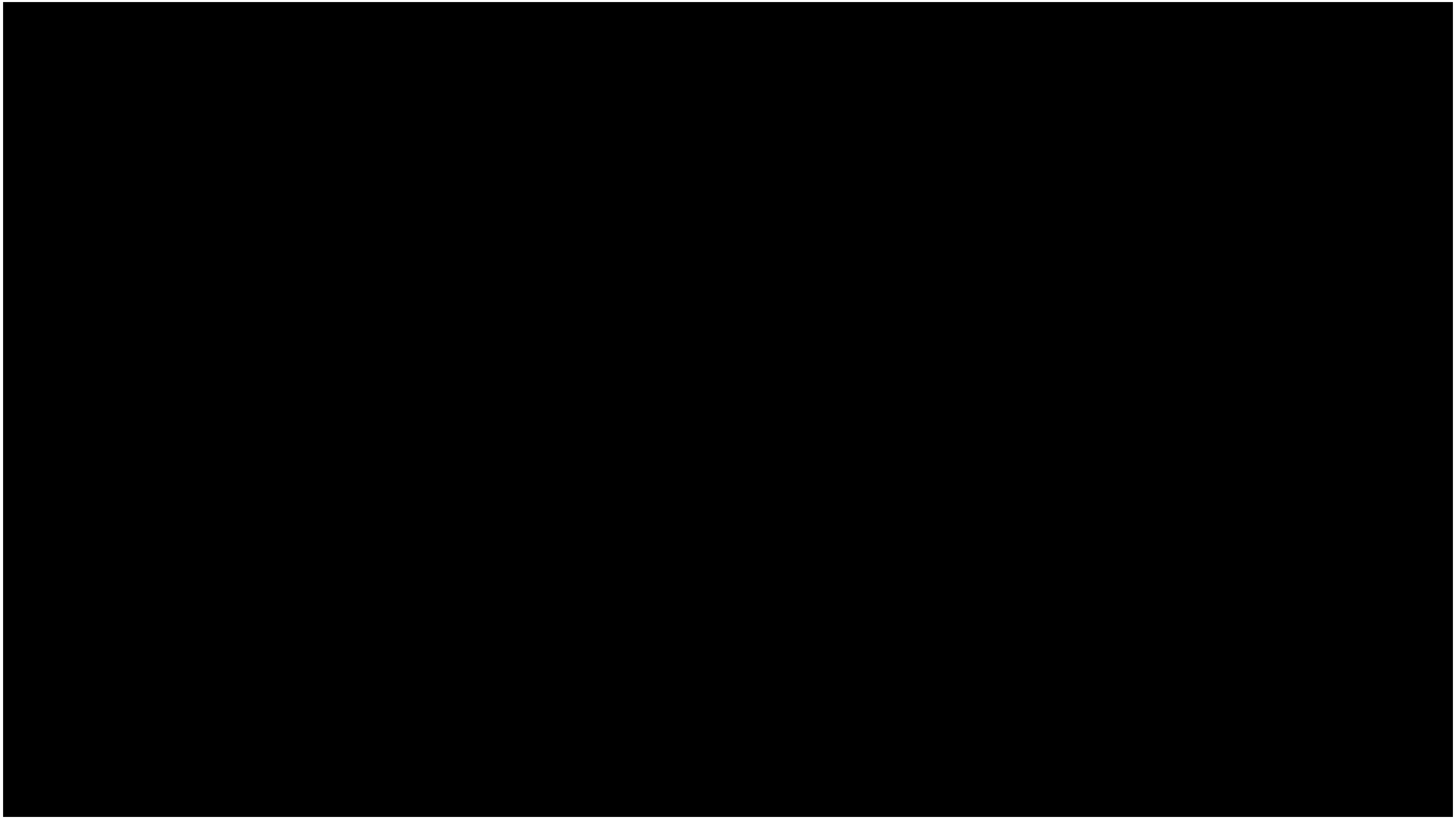
5. EEG and ERP



“associate the listener’s brainwaves with the subjective aesthetic pleasure induced by music”

“results indicate that signals from a restricted number of sensors (located over frontal and temporal brain areas) can be combined in a computable biomarker reflecting the listener's subjective music evaluation”

5. EEG and ERP



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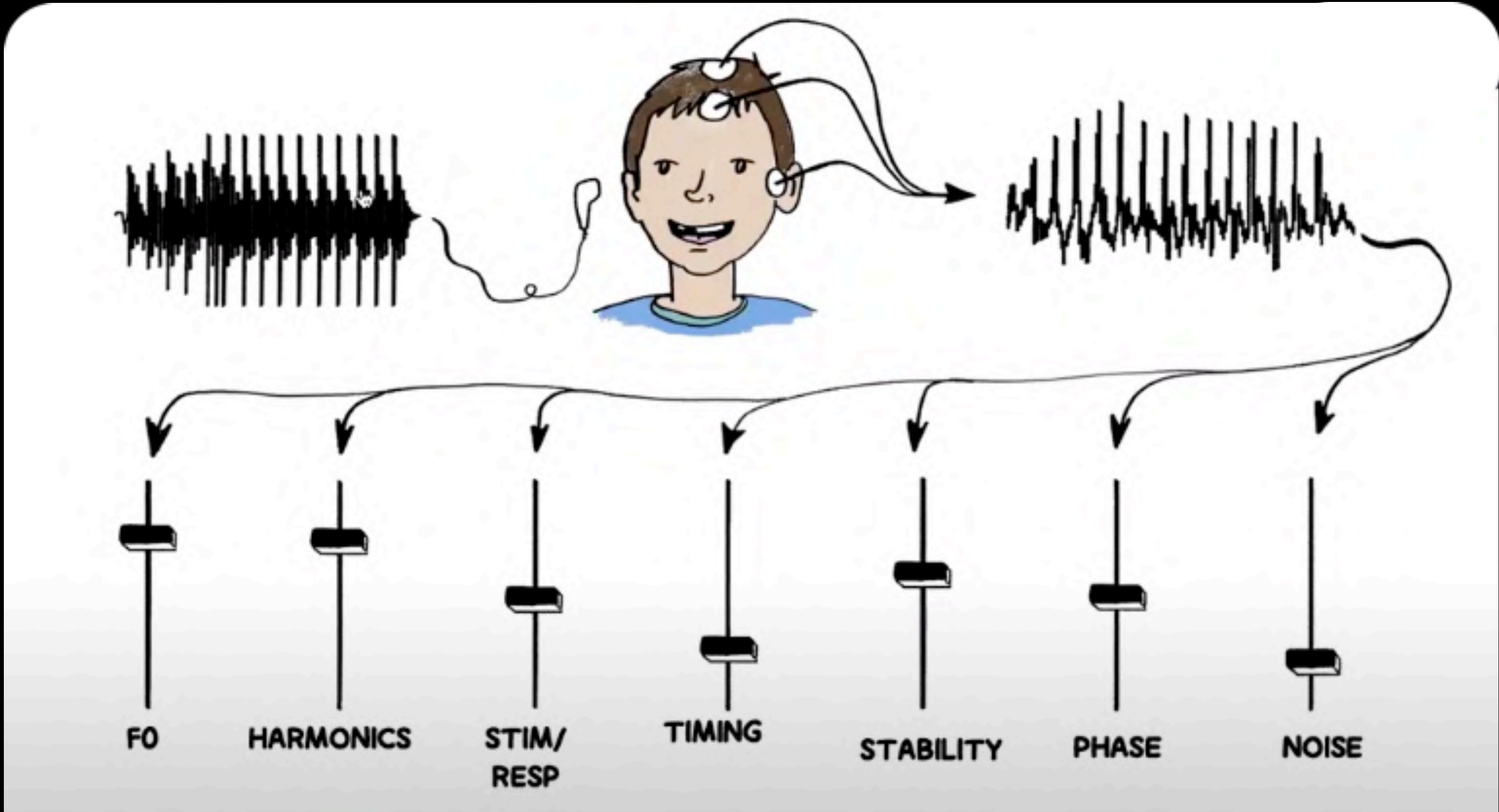
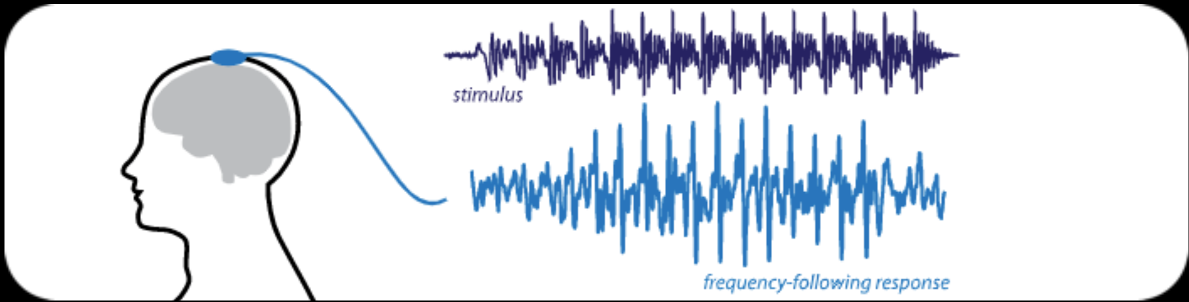
Frequency Following Response

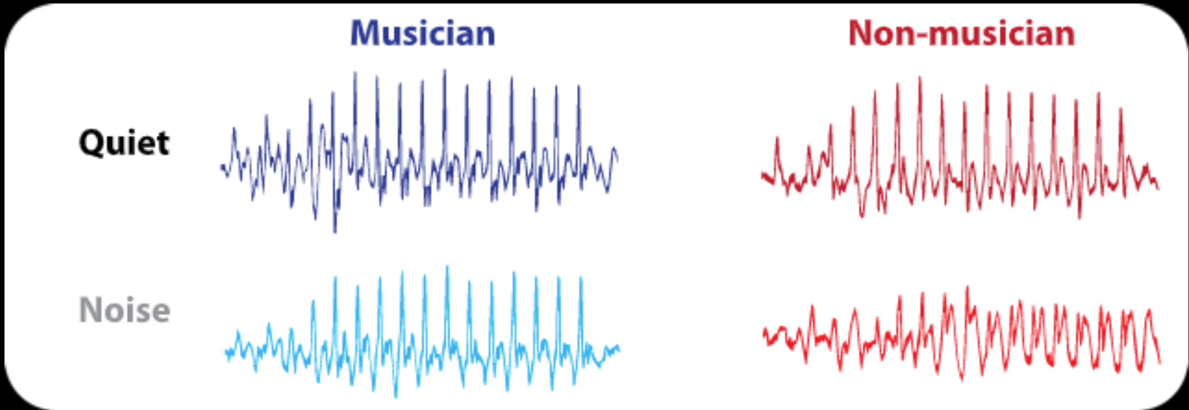


©Nina Kraus
Source: https://www.youtube.com/watch?v=37LUDdDGidM

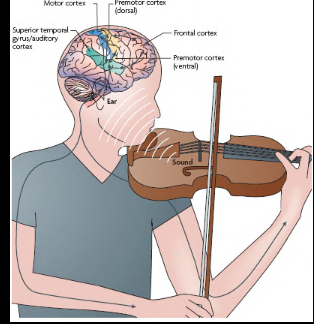
measure of auditory system precision

Frequency Following Response





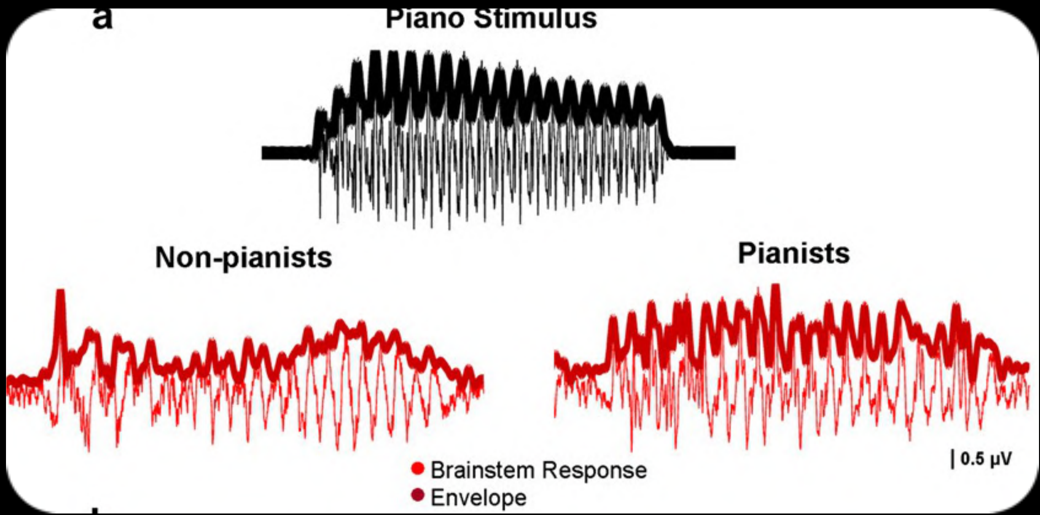
greater resiliency to the degrading effects of background



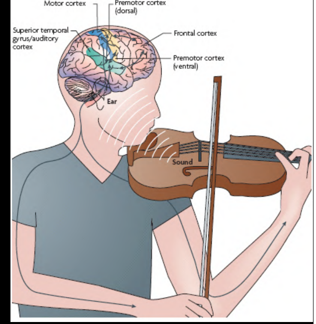
Functional Effects

- faster and stronger response from the brainstem to speech and music sounds (Musacchia et al., 2007; Wong et al., 2007; Strait et al., 2009)

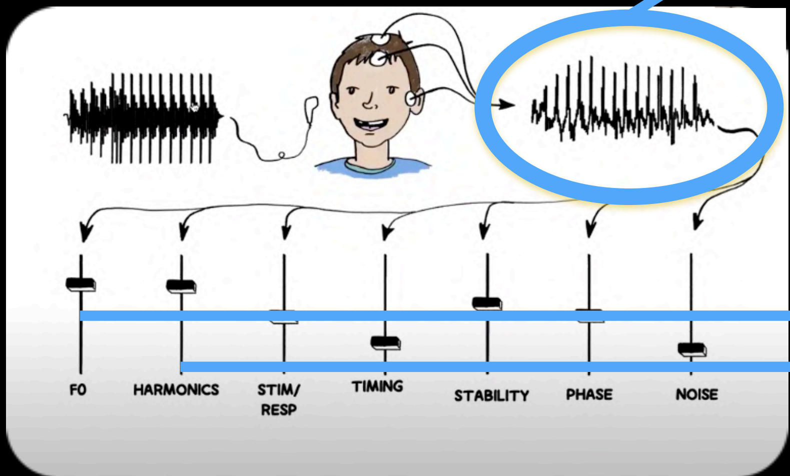
- stronger responses to sound changes, esp. of own instrument (Pantev et al., 1998; Tervaniemi et al., 2001; Schneider, P. et al., 2002; Strait et al., 2011)

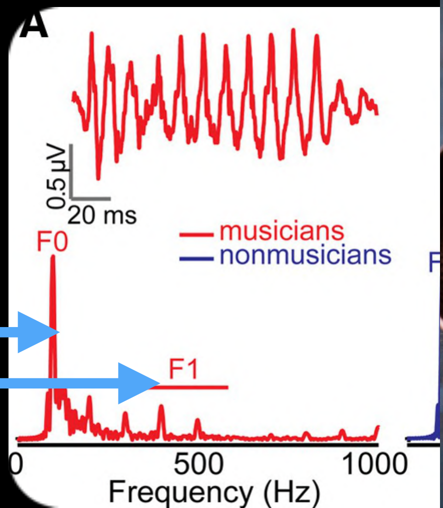


Functional Effects



- brain responses tend to correspond more accurately to the evoking stimulus and with more nuance (Weiss & Bidelman, 2015)

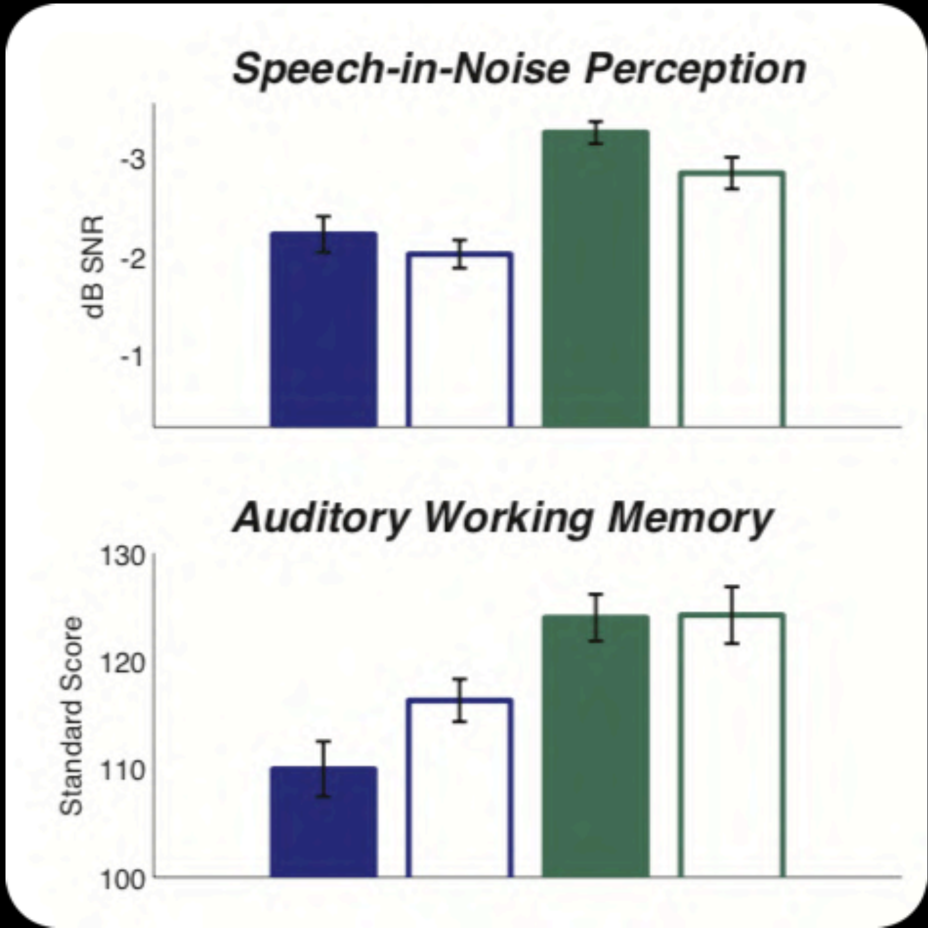




Long-term benefits

NMUS

NMUS (hearing loss)



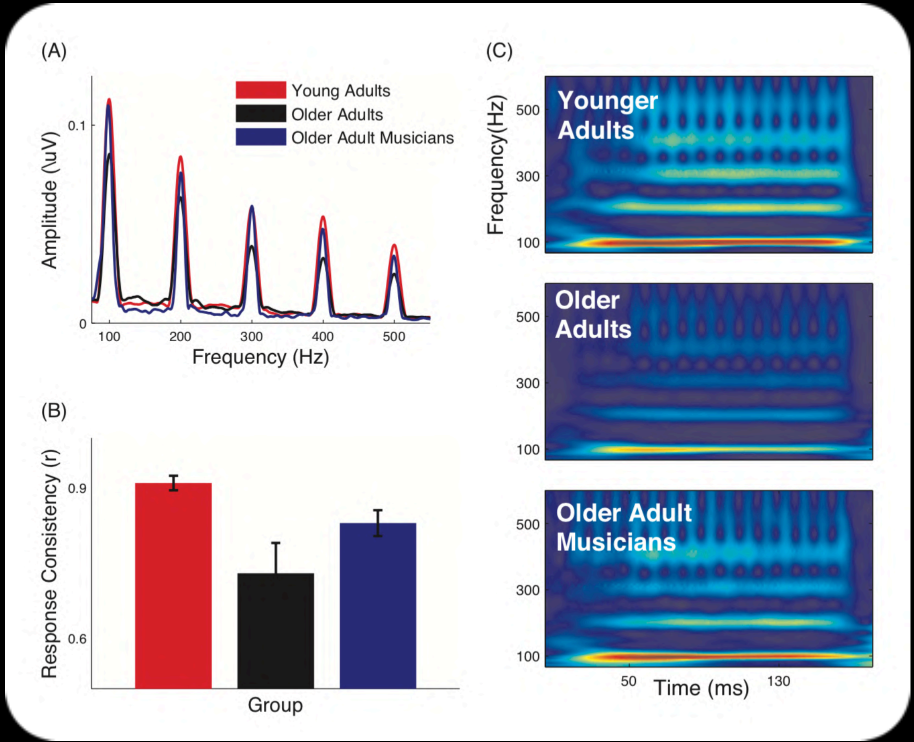
MUS

MUS (hearing loss)

Kraus & White Schwoch (2014) Music Training: Lifelong Investment to Protect the brain from aging and hearing loss

Long-term benefits

- lifelong musical expertise seems to reduce cognitive decline, builds some form of **cognitive reserve**



Kraus & White Schwoch (2014) Music Training: Lifelong Investment to Protect the brain from aging and hearing loss

Auditory System precision

"a biological looking glass into a child's literacy potential."

Nina Kraus 2015

so what does

auditory system precision

have to do

with learning?

Music and Language

discrimination of sounds

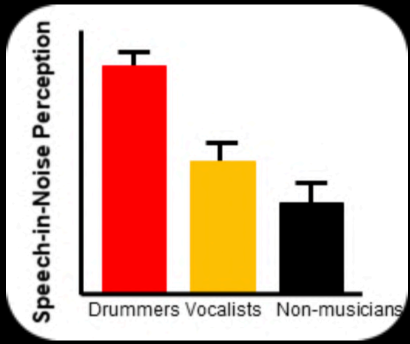
structured rhythmically over time

integrate them at various levels

evaluate intonation

Auditory System Precision and Literacy

- struggling readers have particular problems with auditory temporal processing (Ahissar et al. 2000)
- rhythm abilities linked to early and better reading skills (Woodruff Carr et al. 2014; Thomson & Goswami 2008)
- rhythmic patterns help a listener understand speech (Slater & Kraus, 2015)



Auditory System Precision and Literacy

- jazz drummers recruit language-specific areas for the processing of rhythmic structure (Herdener et al.,2012)
- music making found to improve communication skills by training aspects of rhythm
- literacy development proceeded smoothly in children whose oral language problems were resolved by age 5. 5 yrs (Bishop and Adams, 1990)

Auditory System Precision and Literacy

PLOS BIOLOGY

OPEN ACCESS PEER-REVIEWED

RESEARCH ARTICLE

Auditory Processing in Noise: A Preschool Biomarker for Literacy

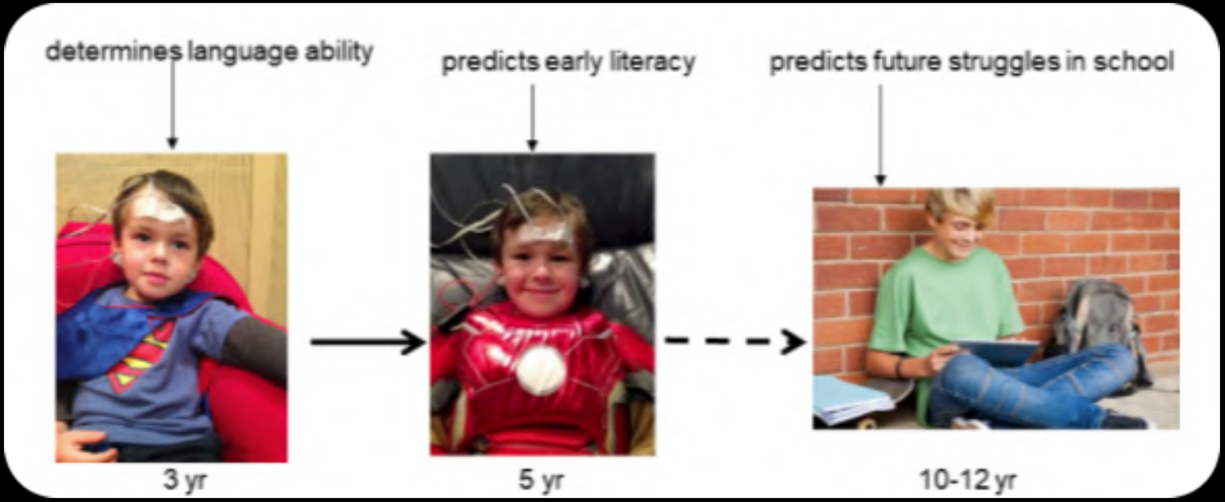
Travis White-Schwoch, Kali Woodruff Carr, Elaine C. Thompson, Samira Anderson, Trent Nicol, Ann R. Bradlow, Steven G. Zecker, Nina Kraus

Published: July 14, 2015 • https://doi.org/10.1371/journal.pbio.1002196

30-min neurophysiological assessment

Auditory System Precision and Literacy

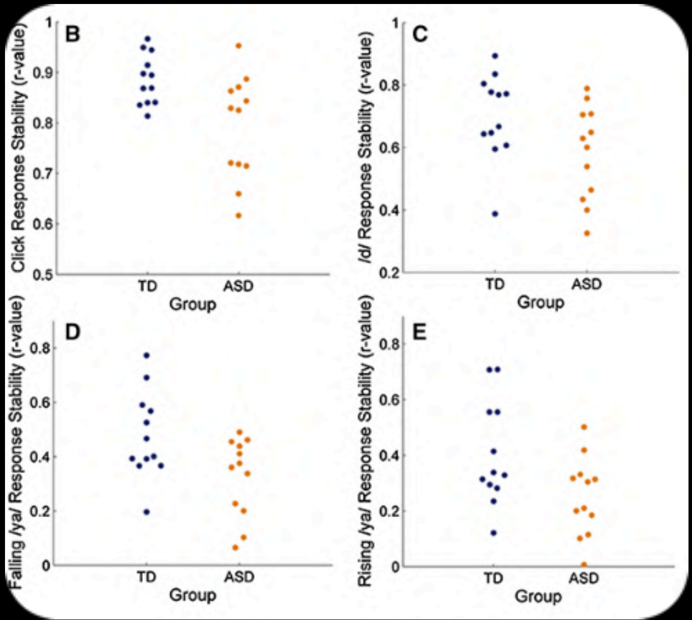
- 4 yrs: stronger neural processing emerged to be stronger readers after one year
- older children: reliably predict which of the children had received a diagnosis of a reading impairment.



source: https://brainvolts.northwestern.edu/

Music and Disabilities

- auditory processing differs in children with autism spectrum disorder (Otto-Meyer et al. 2017)



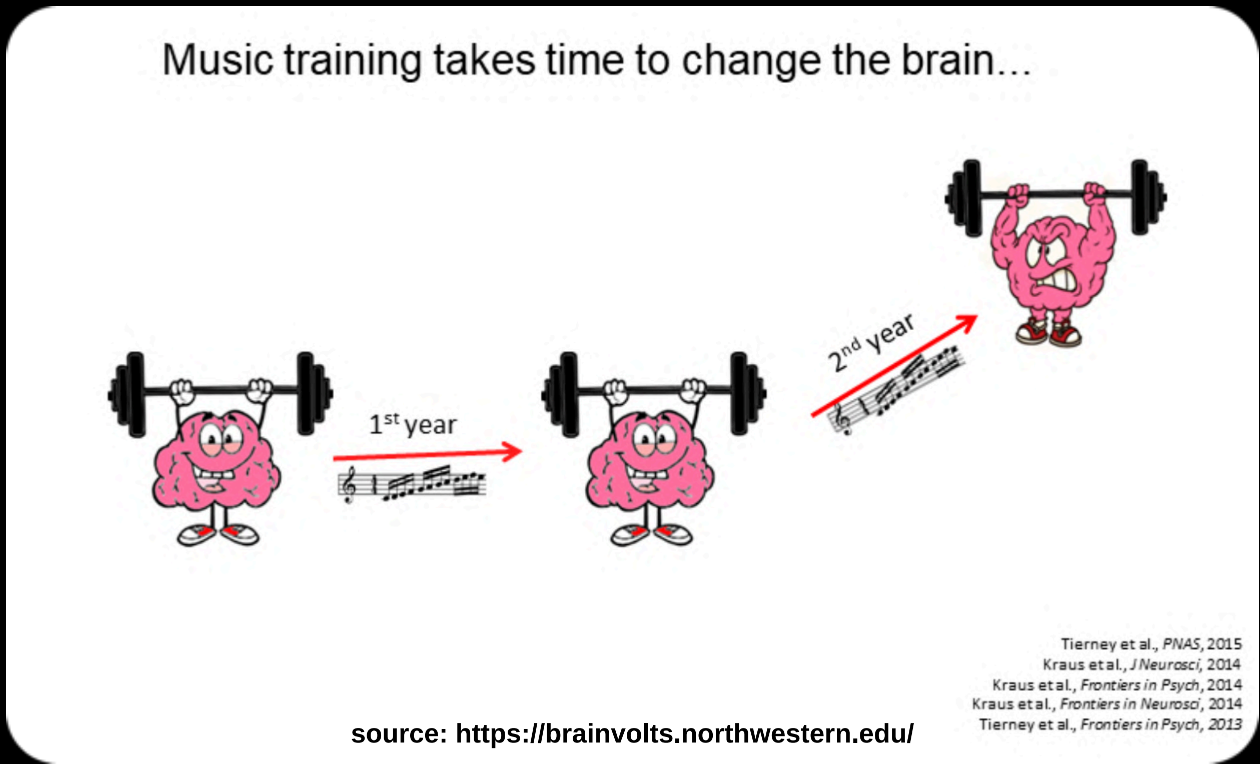
n=24 (7-13 years)

Music and Disabilities

- auditory processing stability differs in dyslexic children (Hornickel & Kraus. 2013)
- strong relation between timing, rhythm processing and reading abilities in dyslexic children (8-11 yrs) (Flaugnacco et al. 2014)
- 7 months of active music training (vs painting) improved reading skills in children with dyslexia (Flaugnacco et al. 2015)

Longitudinal Studies

- 7- 13 yrs: formal musical training during school age and less formal musical group activities in early childhood benefit the maturation of neural sound discrimination (Putkinen et al., 2015)



Longitudinal Studies

6-9 yrs old

2 hrs/week to ≥ 4 hrs/week

gang-reduction zones in LA

group music instruction vs waitlist

1 yr: ↑ perception of sentences in noise

2 yrs: ↑ neural differentiation of the syllables (better reading)

Musical Training alters brain development (neural encoding of speech) in at-risk adolescents

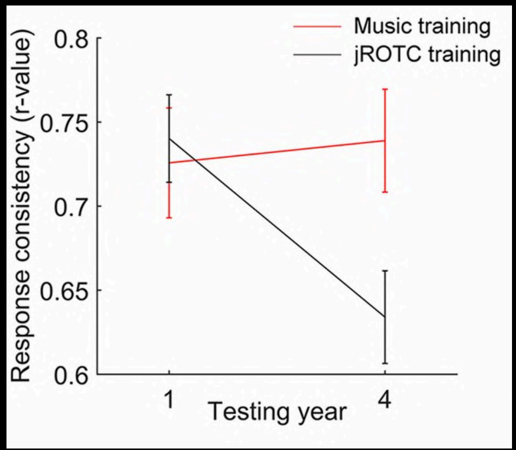
Slater J, Skoe E, Strait DL, O'Connell S, Thompson E, Kraus N. 2015. Music training improves speech-in-noise percep- tion: longitudinal evidence from a community-based music program. Behav Brain Res 291:244–52.

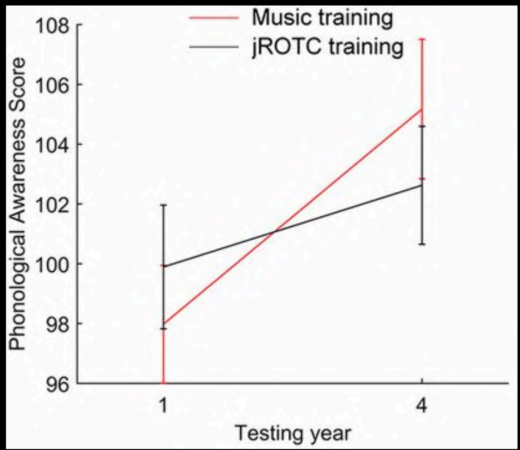
Longitudinal Studies

musical training

~14 yrs old (for 4 years)
self-discipline,
dedication,
determination

JROTC training



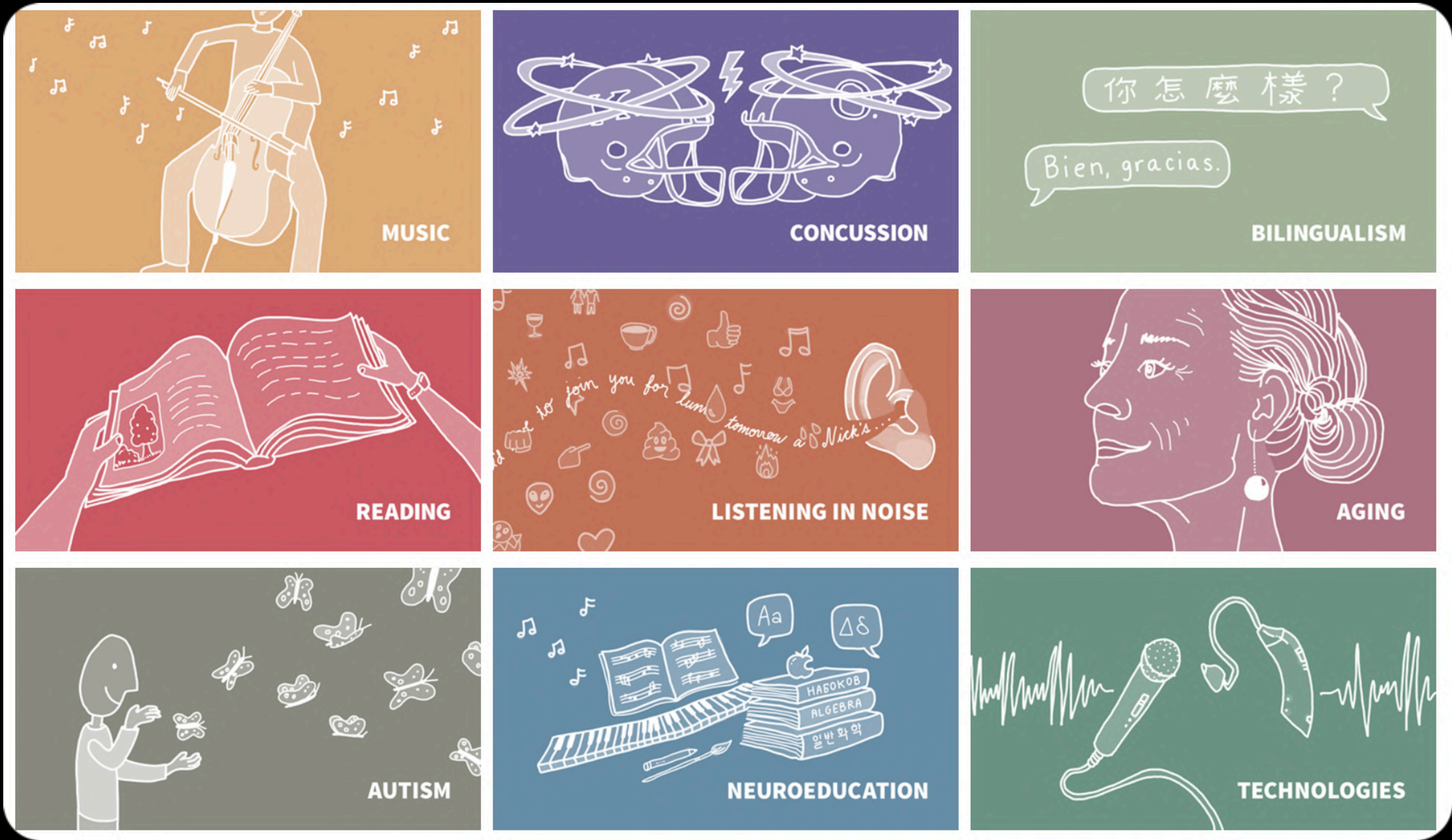


Music training initiated at least as late as high school still has the potential to improve sound processing in the brain

Slater J, Skoe E, Strait DL, O'Connell S, Thompson E, Kraus N. 2015. Music training improves speech-in-noise percep- tion: longitudinal evidence from a community-based music program. Behav Brain Res 291:244–52.

brainvolts

Prof. Nina Kraus



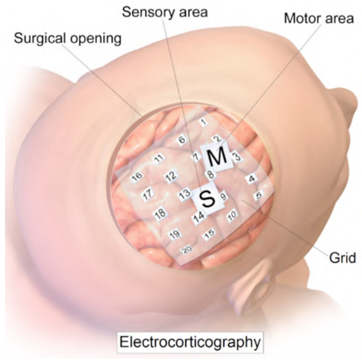
Finally…….

- (playing) music is special in allowing for far transfer
  - start early (~2-4 hrs/week)
  - continue for 2 years
- musical training for developmental/learning disorders
- you don’t have to be a professional musician but the more you play the more you profit

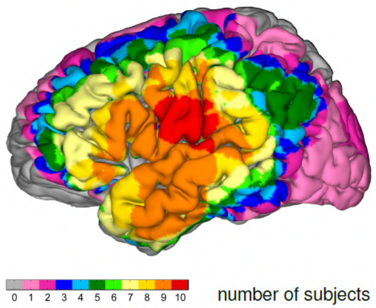
5. EEG and **ERP**

- problems
  - participants might have **changed attentiveness** during recording
  - brain responses are **prone to habituation**, i.e. amplitudes will be reduced the more familiar, or predictable, the often-repeated stimuli are
  - **individual variation lost** due to grand average ERPs

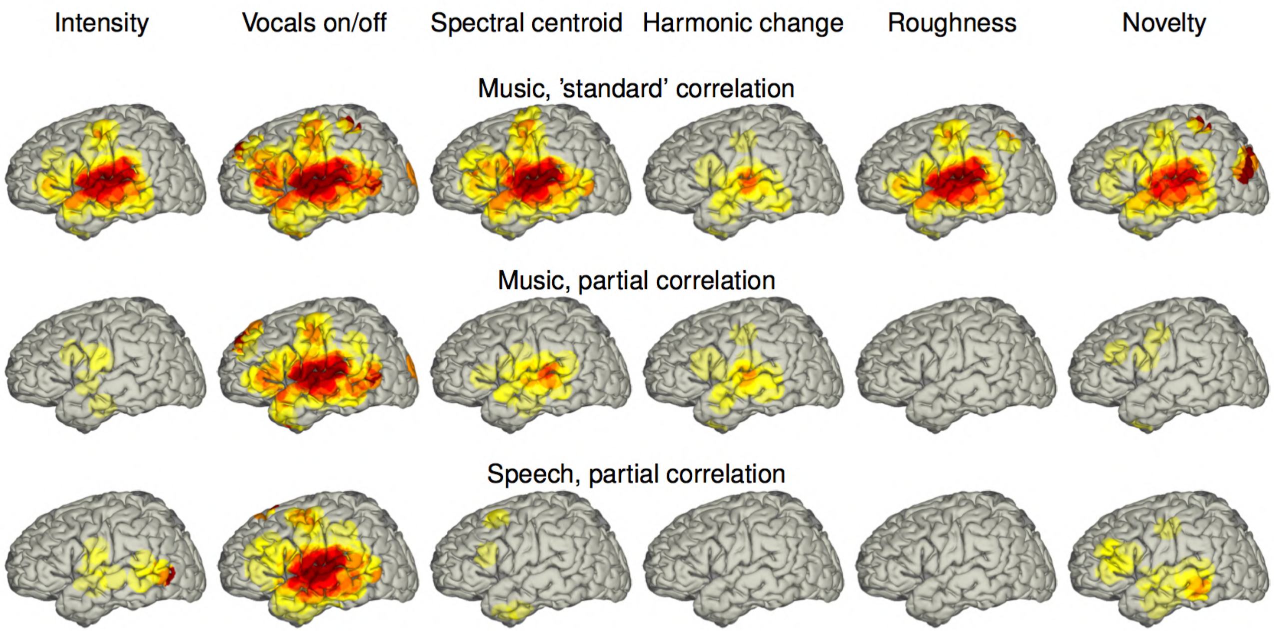
6. Electrocorticography (ECoG or iEEG)



- Electrodes in the brain
- Highly risky & invasive procedure typically used in epileptic patients to identify epileptogenic zones
- High spatial and temporal resolution



Sturm et al., 2015

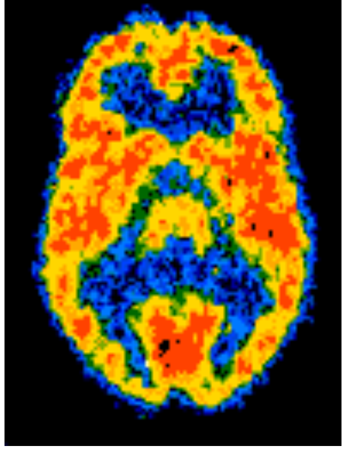


7. MEG

- provides the most accurate resolution of the timing of nerve cell activity - down to the millisecond,
- can separate hemispheres well, has potential also for sound source location analysis
- not available in all hospitals and research centers
- Possible to do for all age groups including foetuses

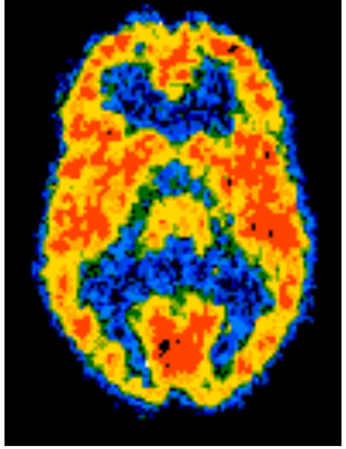
- Problem: low SN ratio

8. PET



- positron emission tomography (1970s)
- observe metabolism - energy consumption (oxygen and glucose) serves as an indicator to precisely localize brain activity
- Injection of radioactive substance
  - only one recording per male adult per year
- active cells consume the radioactive glucose
- PET can also be used to track neurotransmitters

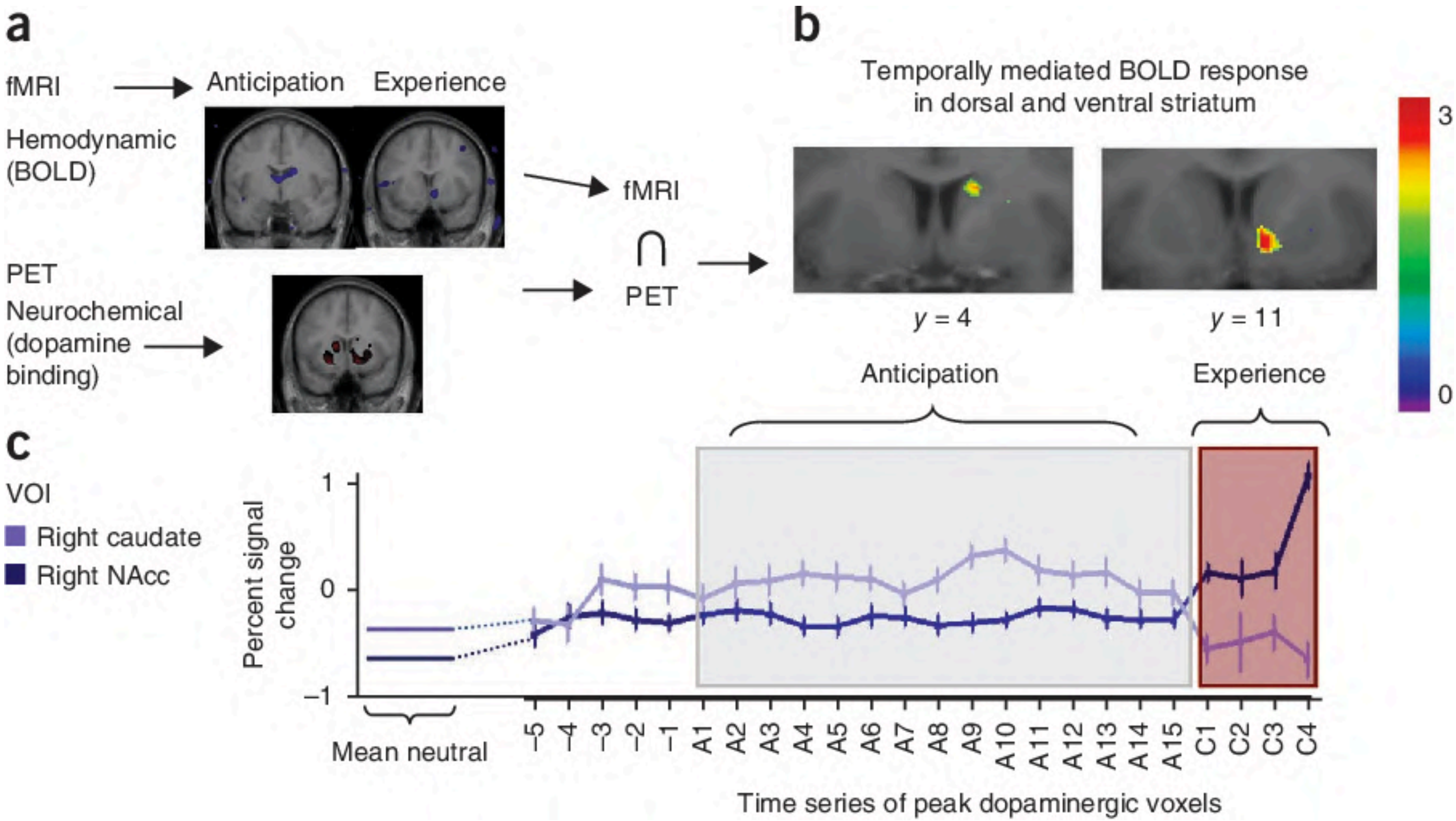
PET



- quite accurate spatial resolution
- temporal resolution: upto 30 minutes

- Problems:
  - Only slow metabolic activity can be imaged
  - Exposure to radiation
  - Very Expensive to run

8. PET



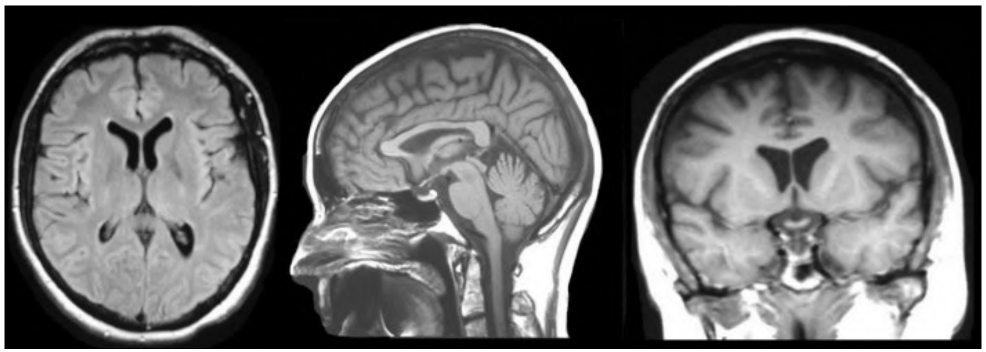
Salimpoor, V. N., Benovoy, M., Larcher, K., Dagher, A., & Zatorre, R. J. (2011). Anatomically distinct dopamine release during anticipation and experience of peak emotion to music. Nature Neuroscience, 14(2), 257–262. doi:10.1038/nn.2726

8. MRI and fMRI

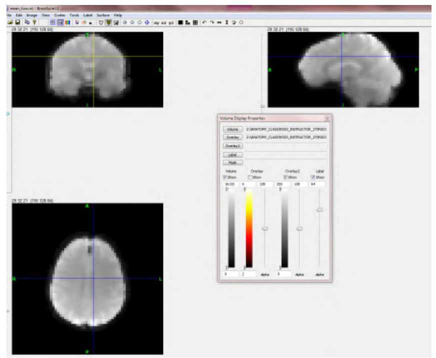
- MRI or magnetic resonance imaging is structural imaging (”picture” of brain tissue - anatomy)
- fMRI is functional imaging, this is what the public knows to be ”brain imaging” (metabolic activity)

Structure vs **Function**

MRI

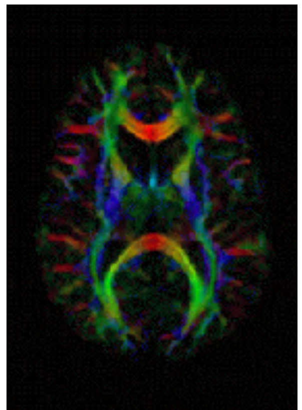


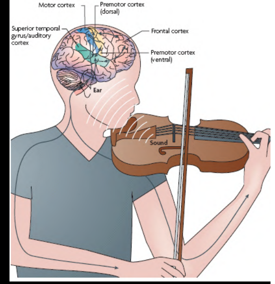
fMRI



MRI and diffusion MRI

- Picture of brain tissue with different parameters emphasizing
  - Gray matter volume, thickness, etc.
  - White matter structures
  - White matter fiber directions, crossings and density

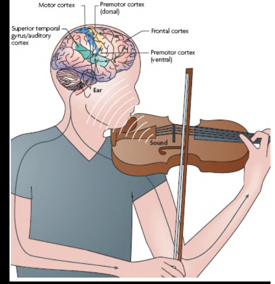




Structural Effects

- increased grey and white matter volume in brain areas associated with auditory, motor, and cognitive skills

  (Amunts et al., 1997; Anvari et al., 2002; Bengtsson et al., 2005; Chan et al., 1998; Elbert et al., 1995; Fujioka et al., 2004, 2006; Gardiner et al., 1996; Gaser & Schlaug, 2003; Hyde et al., 2009; Jäncke et al., 1997, 2000; Koelsch et al., 1999, 2003; Meister et al., 2005; Moreno et al., 2008; Pantev et al., 1998; Schellenberg, 2004; Schlaug et al., 1995; Schneider et al., 2002; Sluming et al., 2002; Tervaniemi et al., 2001)



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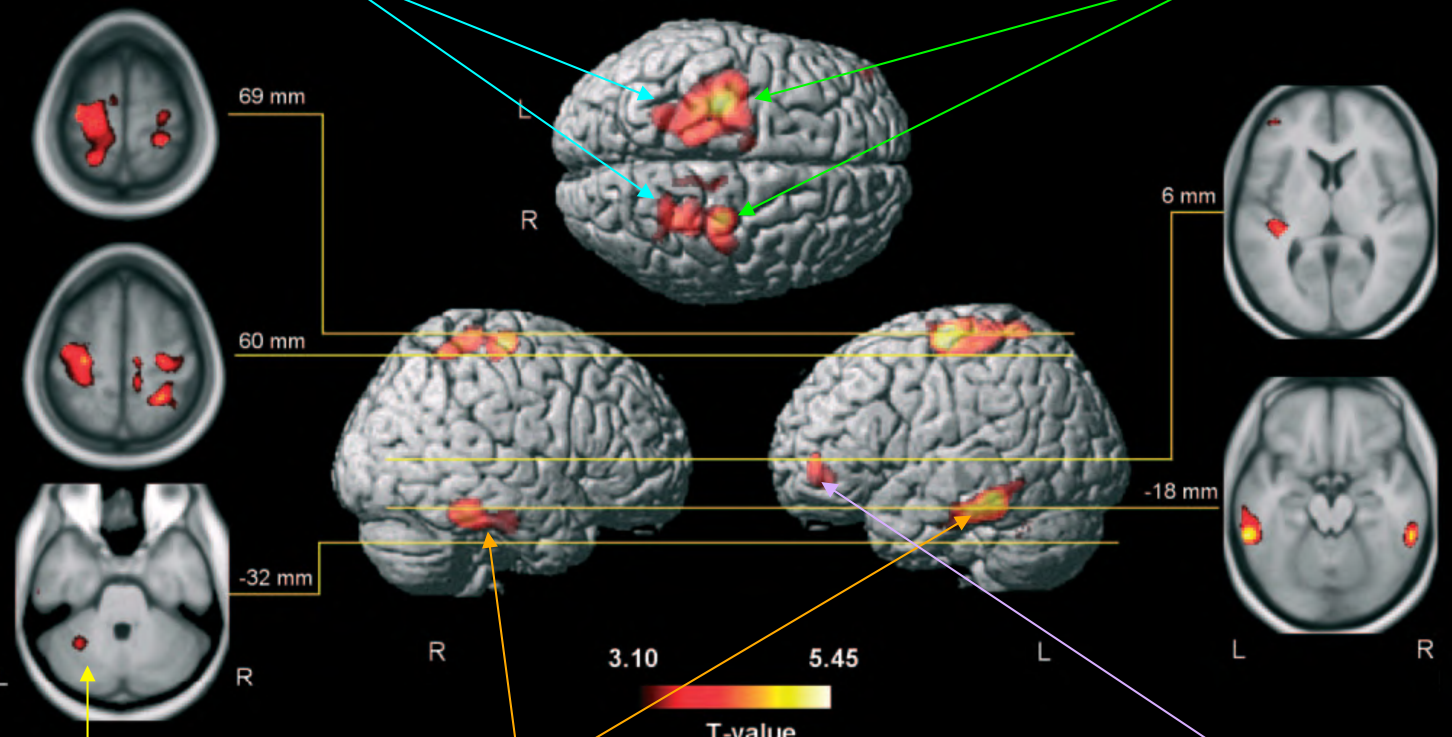

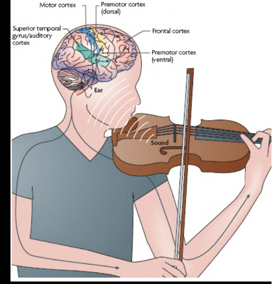

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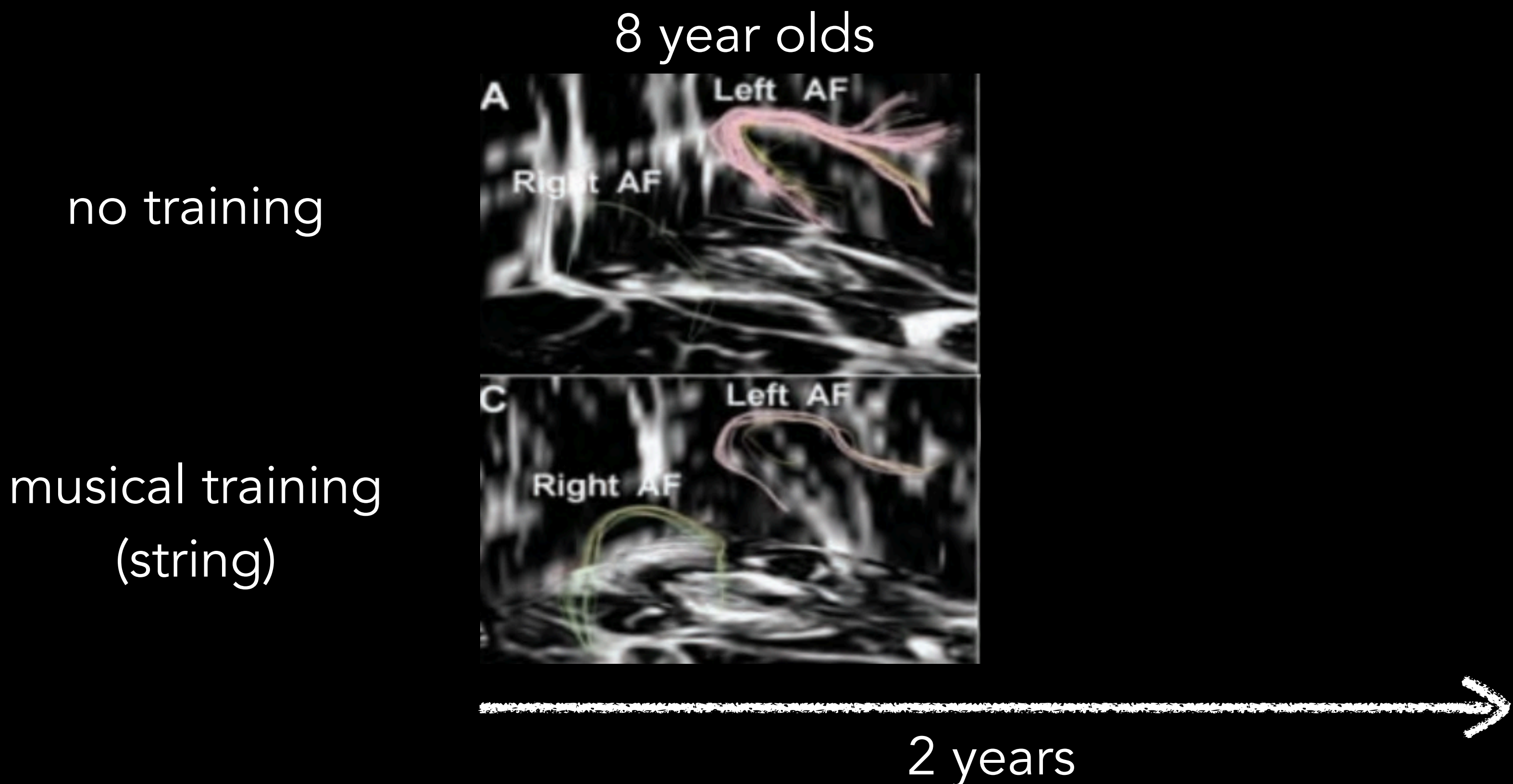
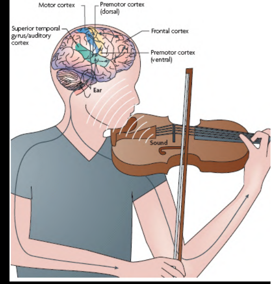


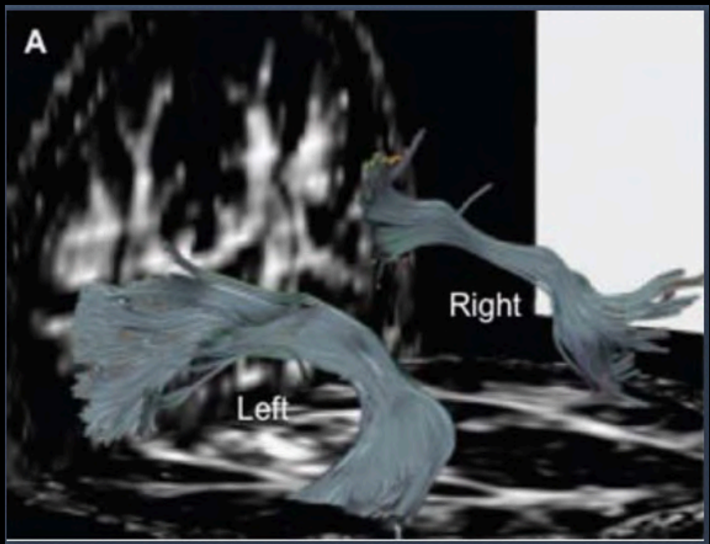
Schlaug et al. 2010. **Music making as a tool for promoting brain plasticity across the life span**. *Neuroscientist.*



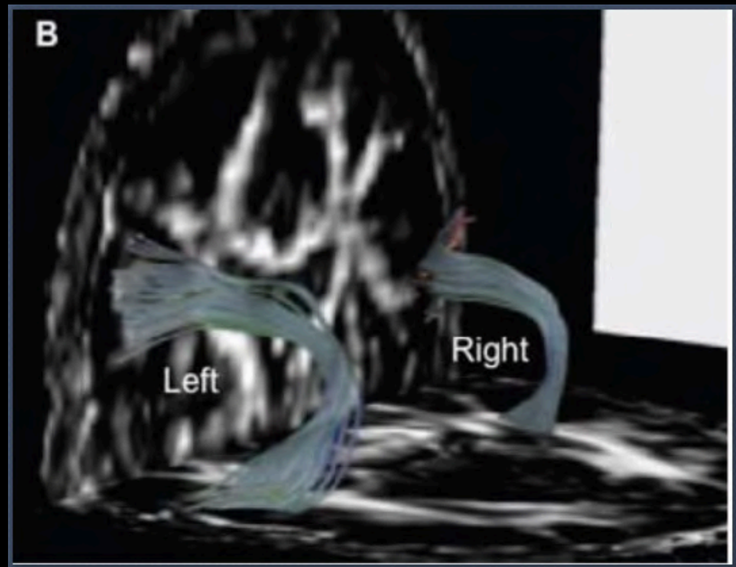
Structural Effects

- increased grey and white matter volume in brain areas associated with auditory, motor, and cognitive skills

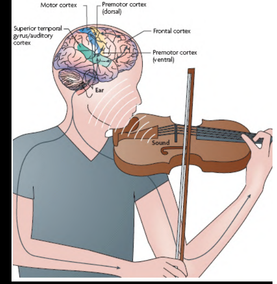
65-year old instrumental **musician**



63-year old **non-musician**



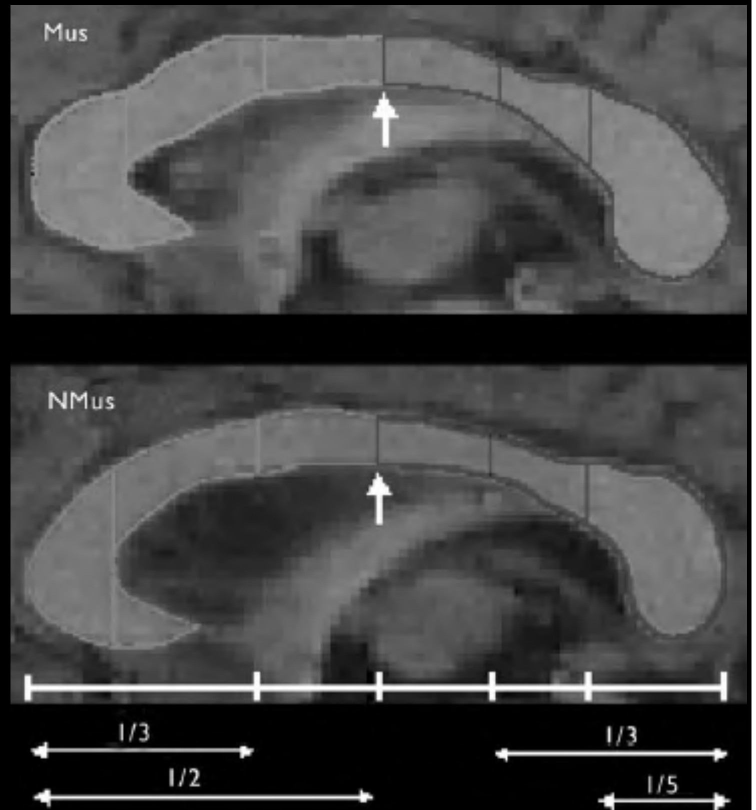
Schlaug et al. 2010. **Music making as a tool for promoting brain plasticity across the life span**. *Neuroscientist.*

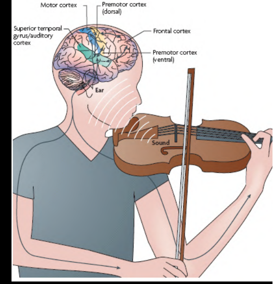


Structural Effects

- corpus callosum (connecting the left and right cortical areas) is larger in musicians (Schlaug et al. 1995; Lee et al. 2003)

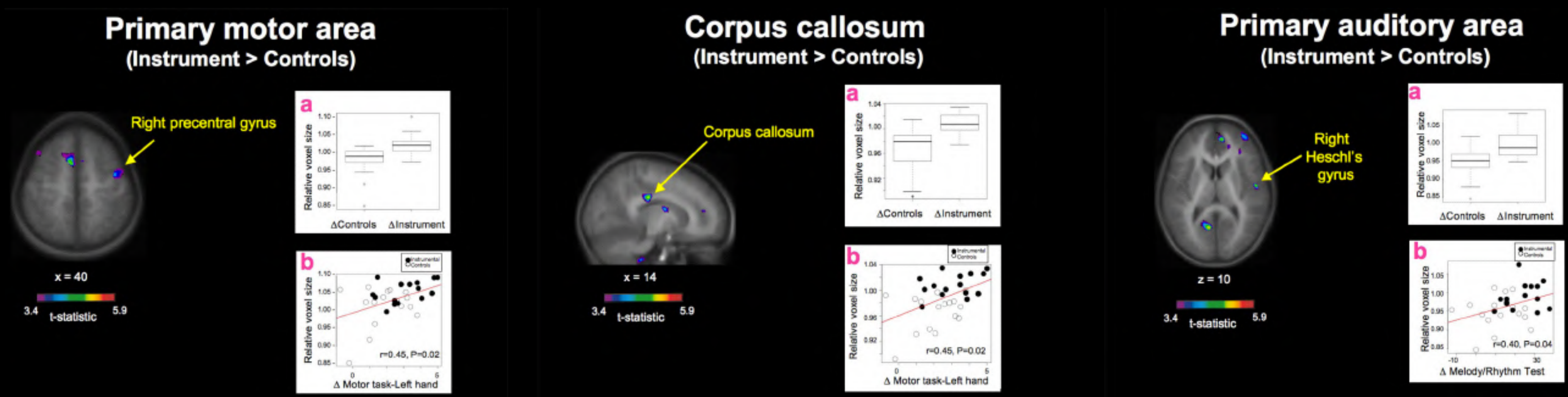
- the amount of practice is directly related to the volume of the white matter tracts in different regions for each age period (Bengtsson et al., 2005).

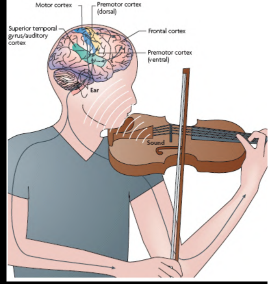




Structural Effects

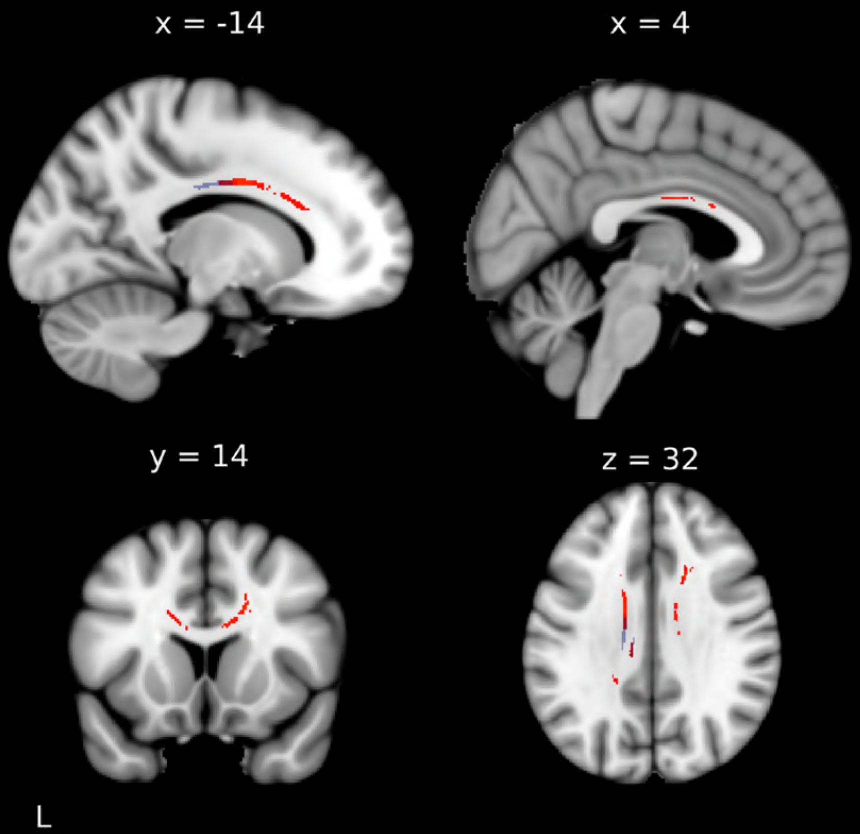
- 6(~) years old develop changes in motor cortex, corpus callosum and auditory cortex in **15 months** of piano lessons (Hyde et al., 2009).





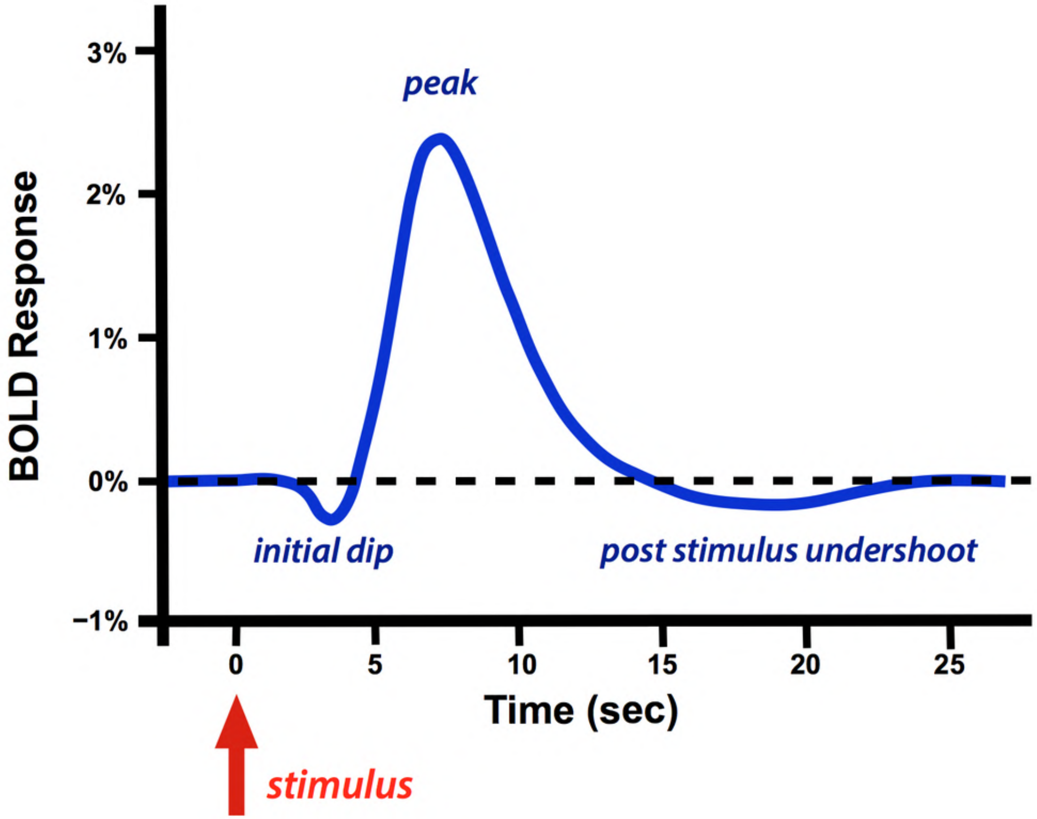
Structural Effects

- Training **before the age of 7 years** results in greater changes in white-matter connectivity (Steele et al., 2013)



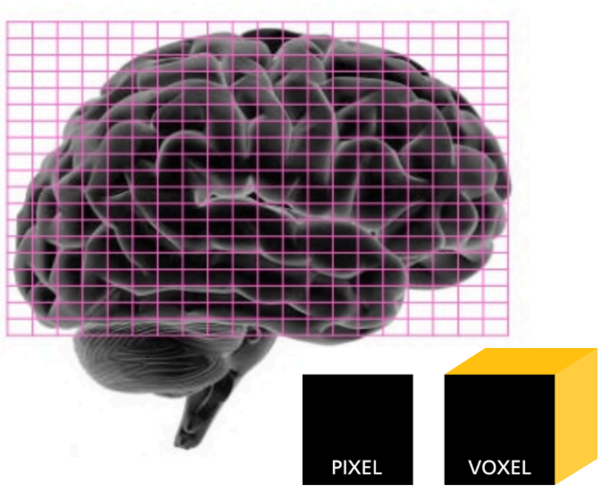
fMRI

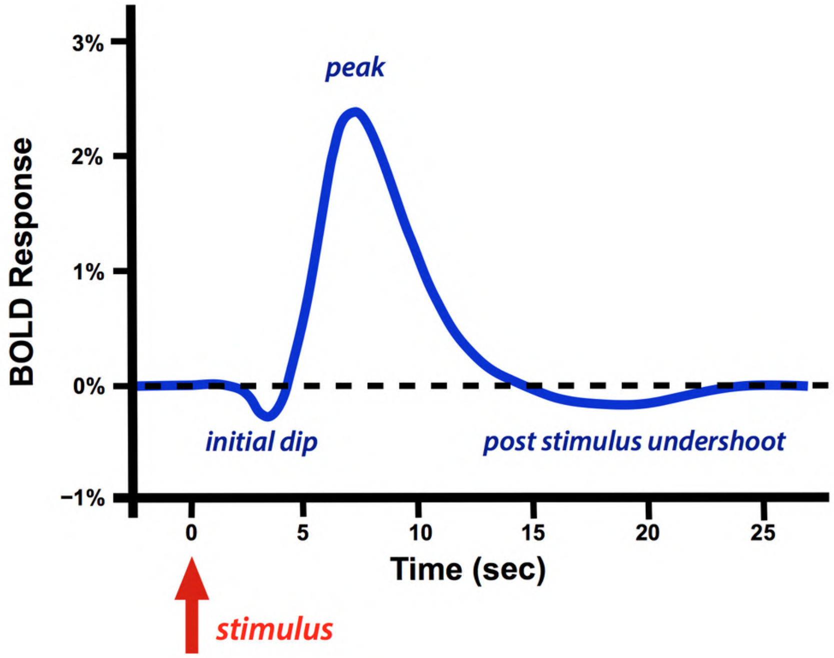
- picture of changes in blood oxygenation level



fMRI

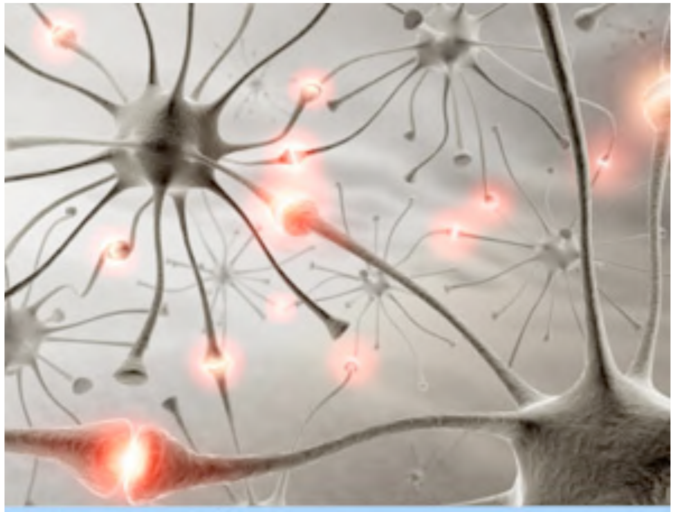
- picture of changes in blood oxygenation level
- very accurate spatially (~2,00,000 voxels)





BOLD Signal

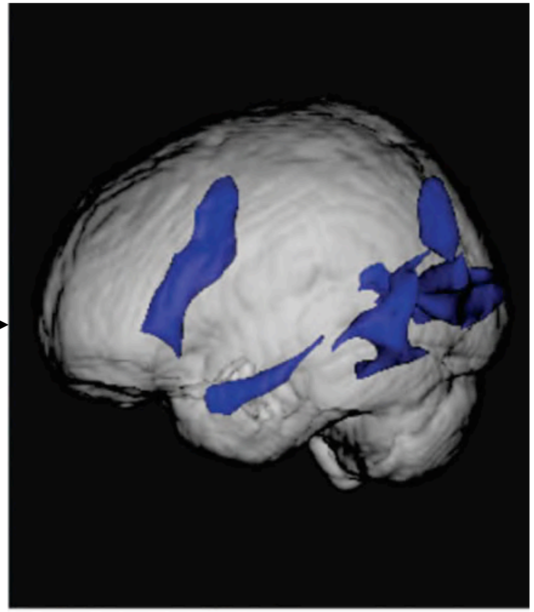
Blood **O**xygenation **L**evel **D**ependent contrast



Brain neurons firing

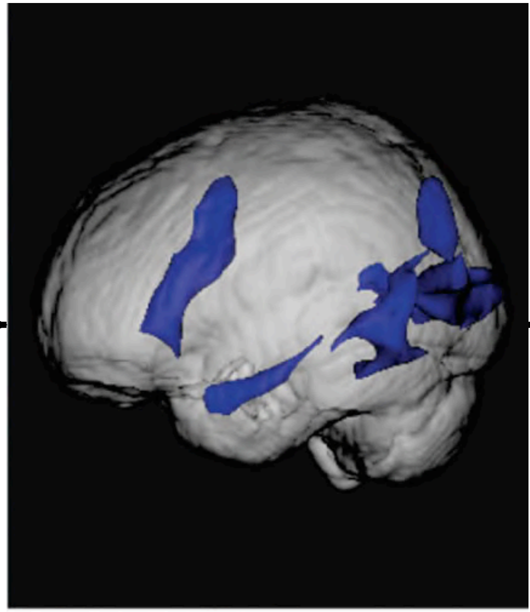
BOLD Signal

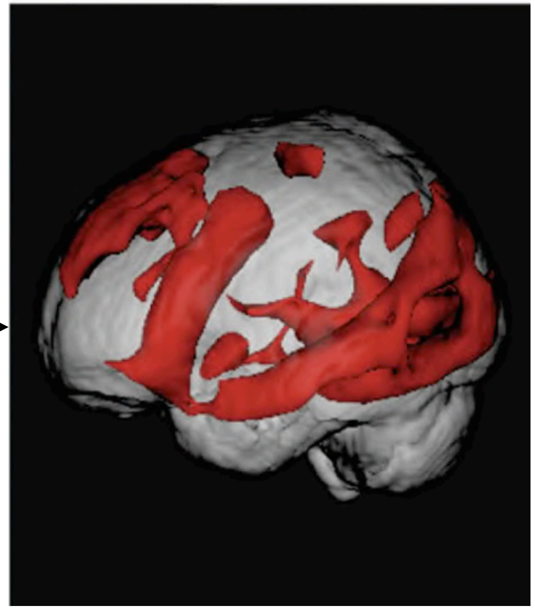
Blood **O**xygenation **L**evel **D**ependent contrast



BOLD Signal

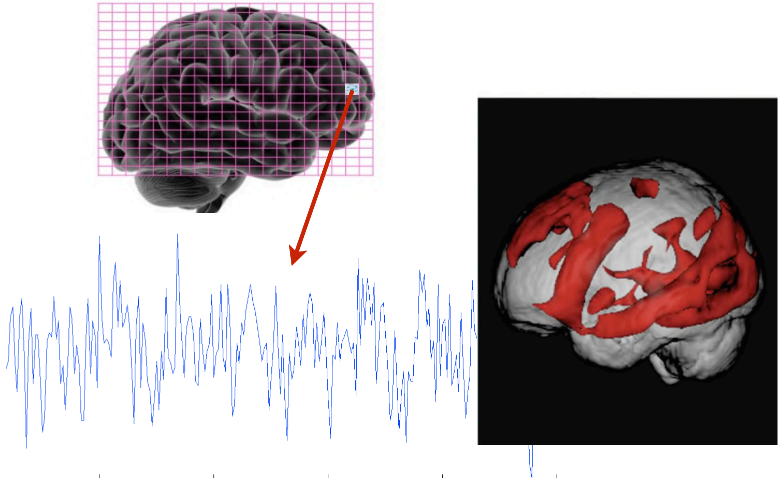
Blood **O**xygenation **L**evel **D**ependent contrast



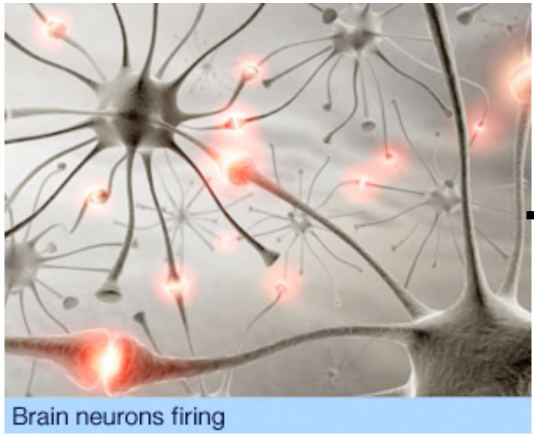


BOLD Signal

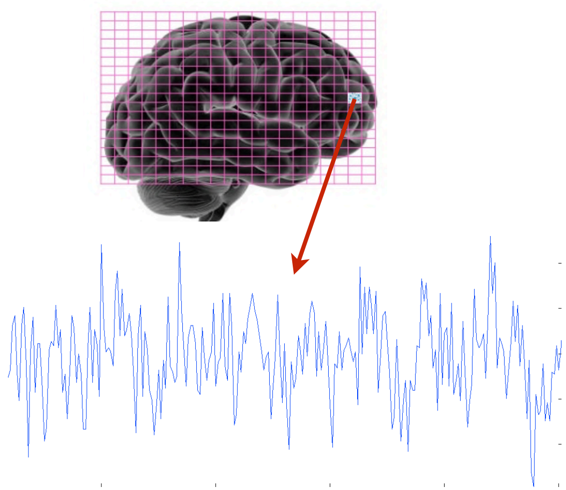
Blood **O**xygenation **L**evel **D**ependent contrast



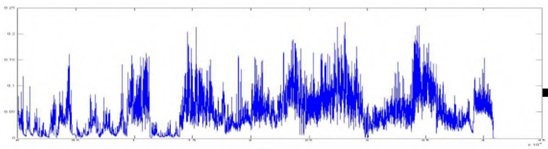
A ‘Signals and Systems’ approach



neural response

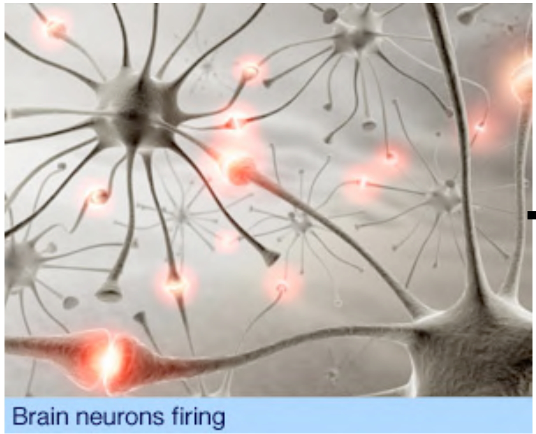


BOLD response



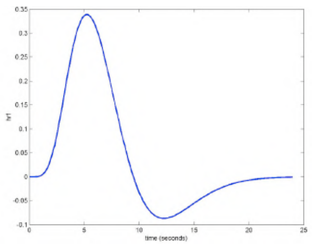
Acoustic features

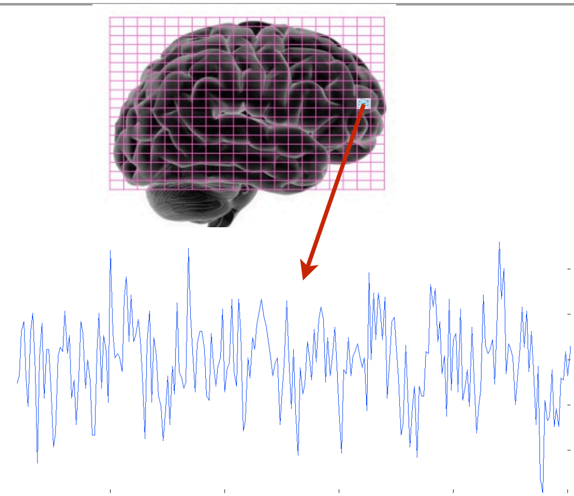
A ‘Signals and Systems’ approach



neural response

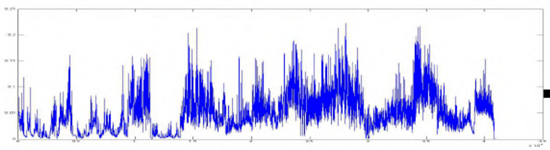
$$h(n)$$





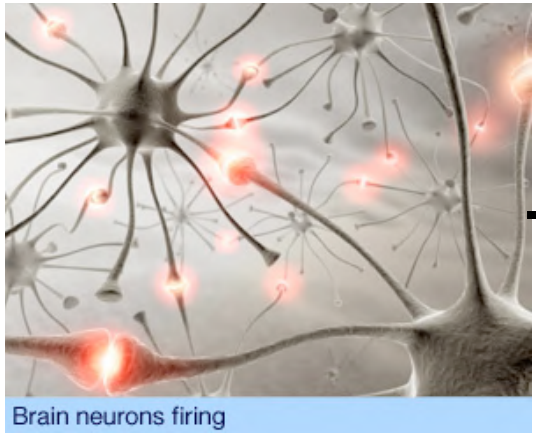
BOLD response

$$x(n)$$



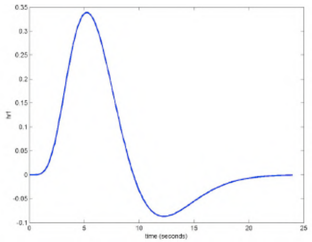
Acoustic features

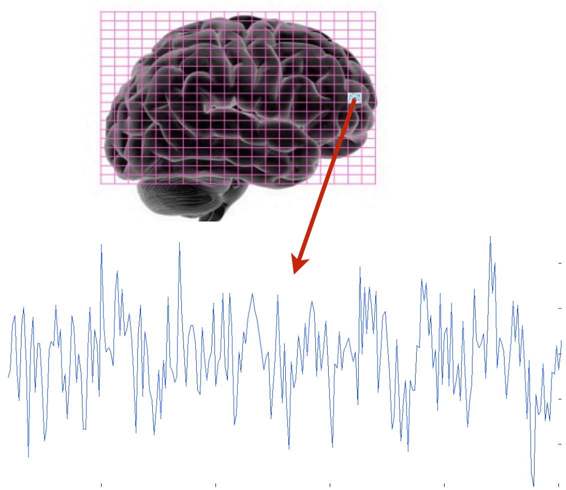
A ‘Signals and Systems’ approach



neural response

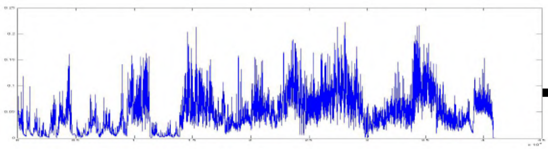
$$h(n)$$





BOLD response

$$x(n)$$



Acoustic features

$$x(n) * h(n)$$

Overview of Research in Neuromusicology (fMRI)

current and future trends

- paradigm: from controlled to naturalistic
- viewpoint: from segregation to integration
- universality: from invariance to variance
- modelling: from encoding to decoding and simulation

current and future trends

- paradigm: from controlled to naturalistic
- viewpoint: from segregation to integration
- universality: from invariance to variance
- modelling: from encoding to decoding and simulation

How SCARED is this person?

1	2	3	4	5

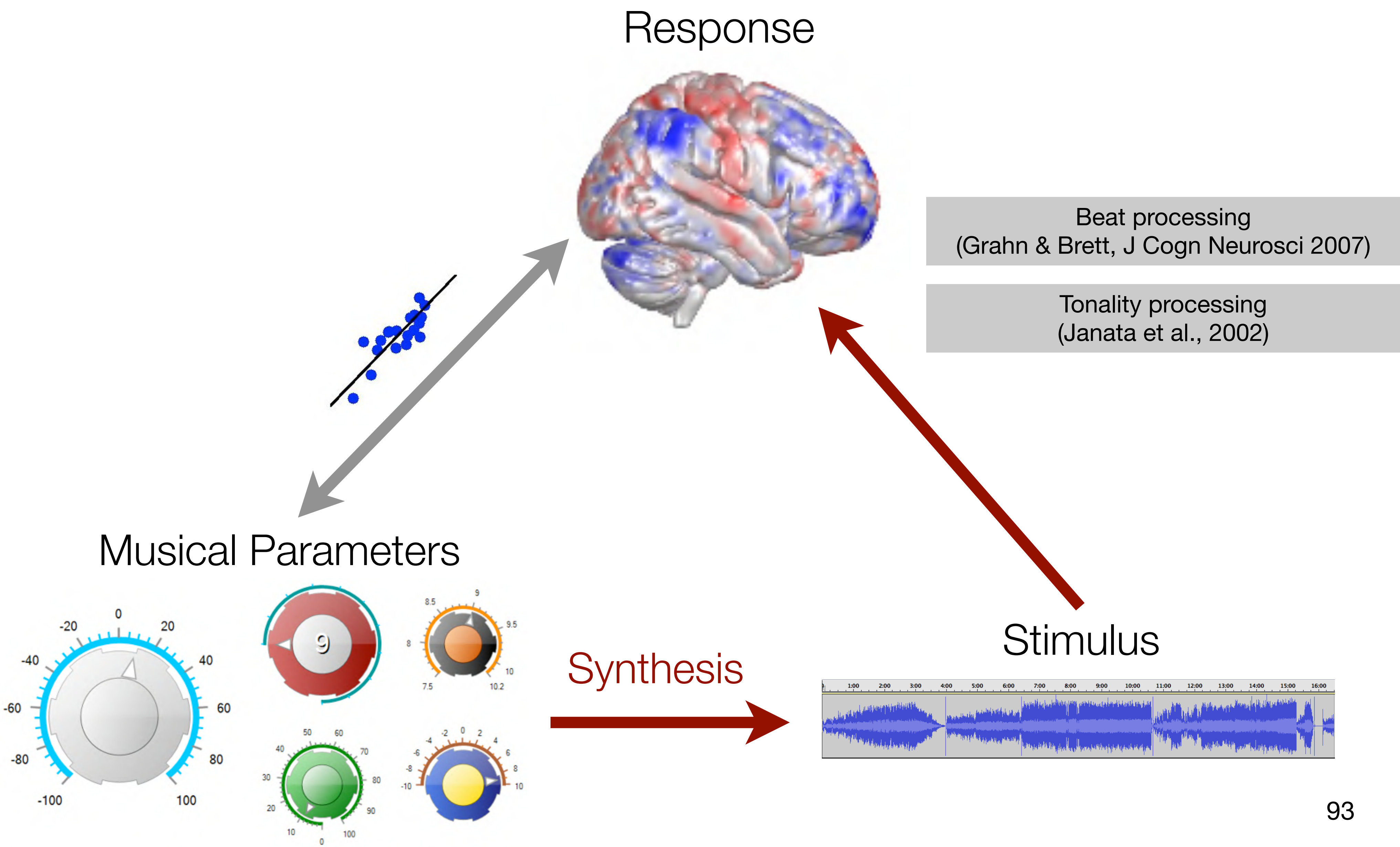
Not SCARED — Very SCARED

How SCARED is this person?

1	2	3	4	5

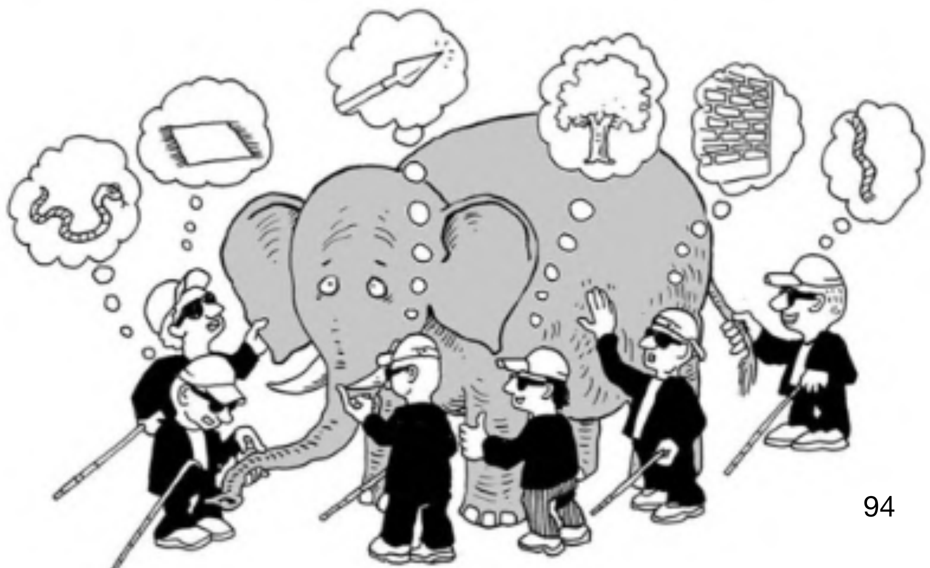
Not SCARED — Very SCARED

Musical feature processing in the brain
CONTROLLED PARADIGM

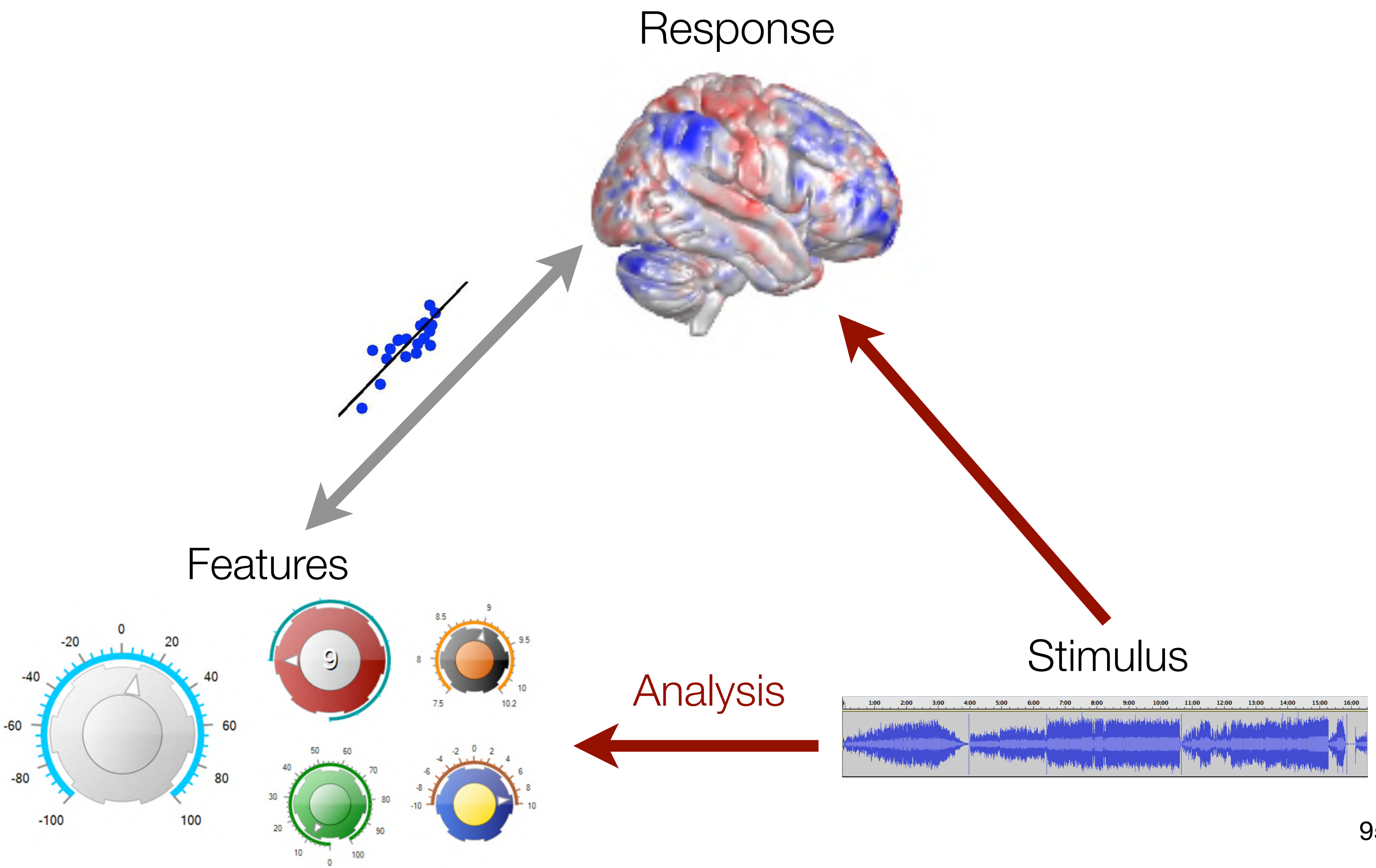


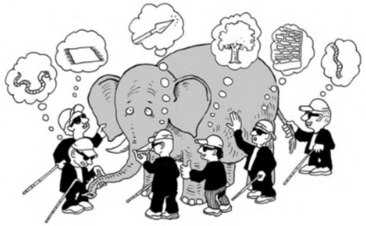
what is missing?

- in real music many musical elements are changing simultaneously
    - timbre, rhythm, melody, harmony, ...
- while listening we process these elements in parallel and integrate them into coherent percepts
- the total can be more than the sum of its parts



Musical feature processing in the brain
NATURALISTIC PARADIGM

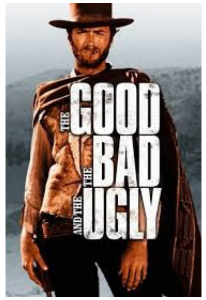




paradigm: from controlled to naturalistic

Context Matters

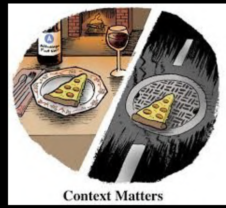
- visual (neurocinematics) (Hasson et al. 2004)

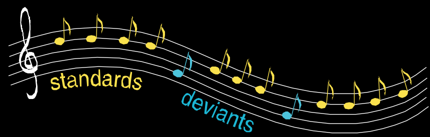
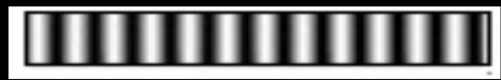
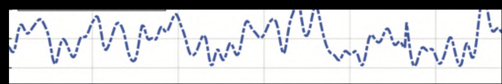


- empathy networks (Vemuri & Surampudi., 2015)

- music (Alluri et al. 2012; 2013; 2015; 2017; Burunat et al., 2016,2017; Toiviainen et al., 2013; 2019; 2021; Sachs et al. 2019……)

traditional vs **naturalistic** paradigm



	stimuli	presentation
traditional		
naturalistic		

Music and the Brain

Functional Neuroimaging Studies in the Naturalistic Paradigm

Which brain areas respond to individual musical features during continuous listening?

Study 1: Brain responses to tango

Alluri, V., Toiviainen, P., Jääskeläinen, I. P., Glerean, E., Sams, M., & Brattico, E. (2012). Large-scale brain networks emerge from dynamic processing of musical timbre, key and rhythm. NeuroImage, 59, 367-3689.

Stimulus

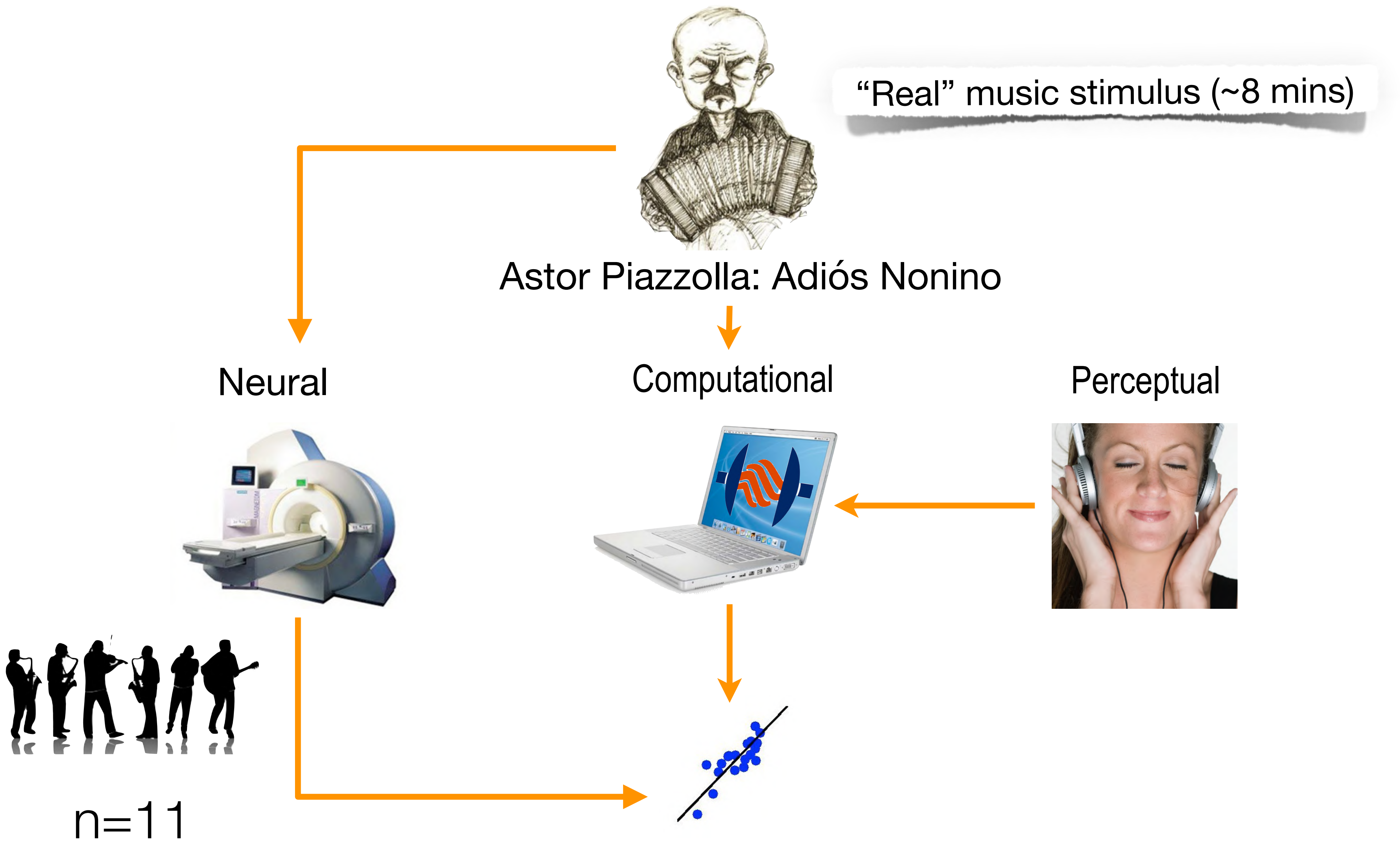
?

Stimulus

?

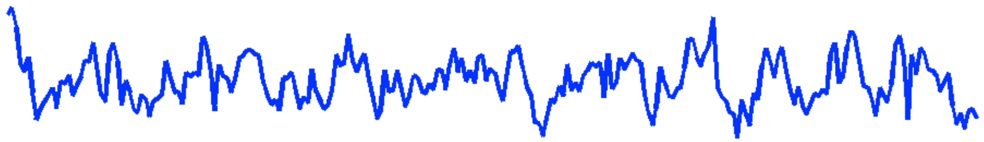
- variation in acoustic content
- no lyrics
- long enough considering sampling rate of scanner
- unfamiliar

Brain Responses to Tango



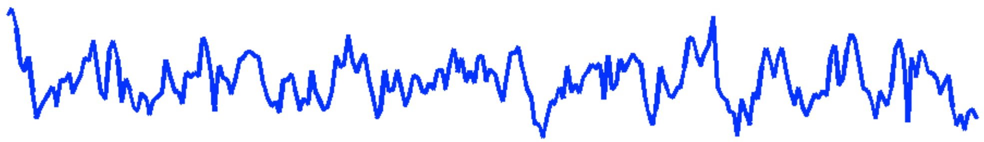
BOLD contrast time-series/voxel

- NIfTI Toolbox



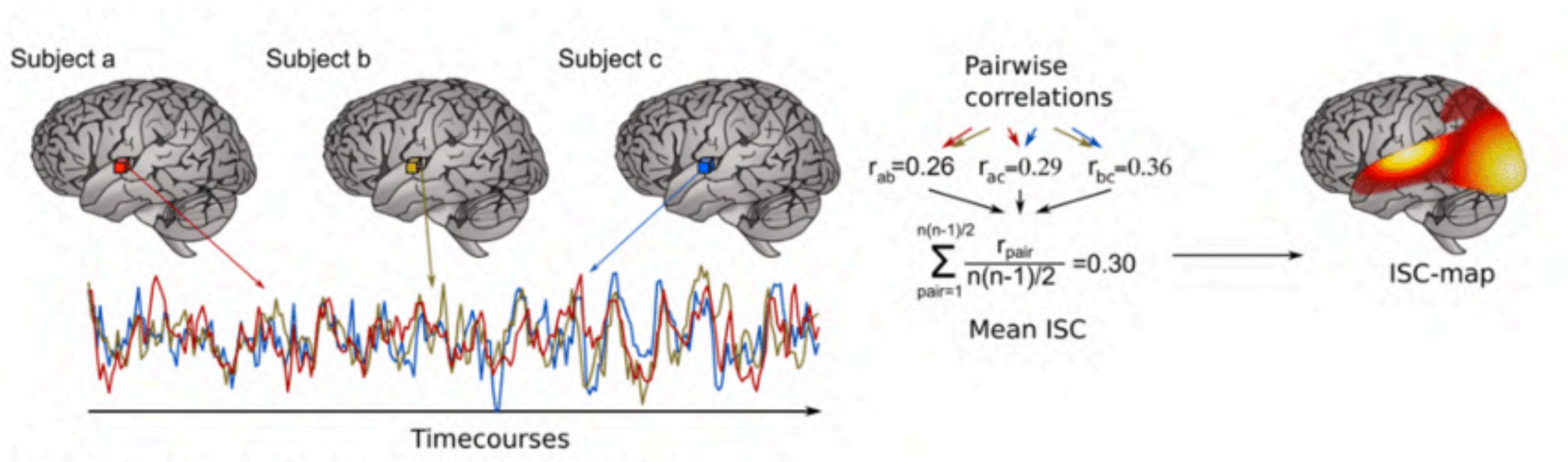
- High-pass filtering

  (128 sec scanner drift)



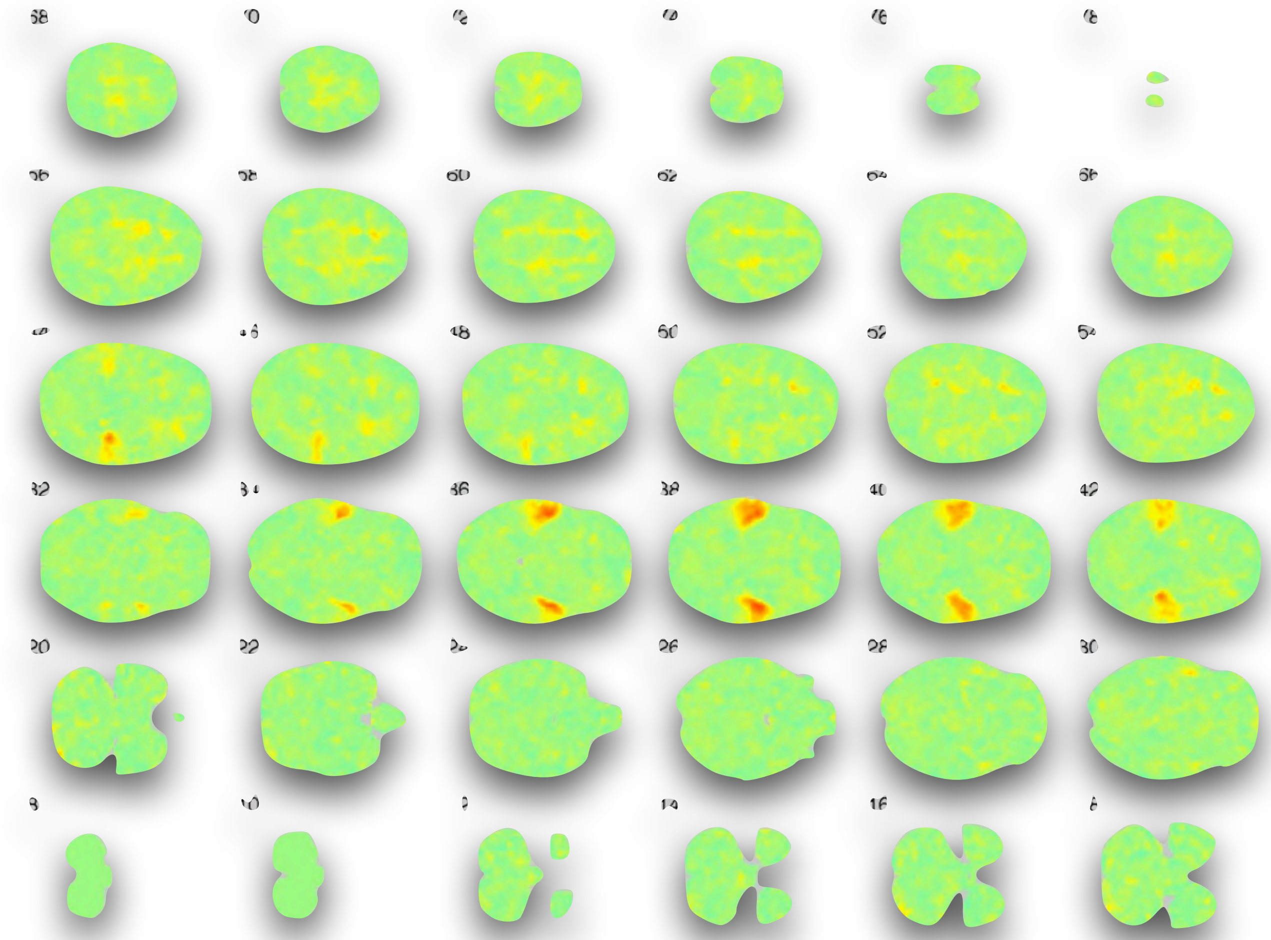
- Gaussian smoothing

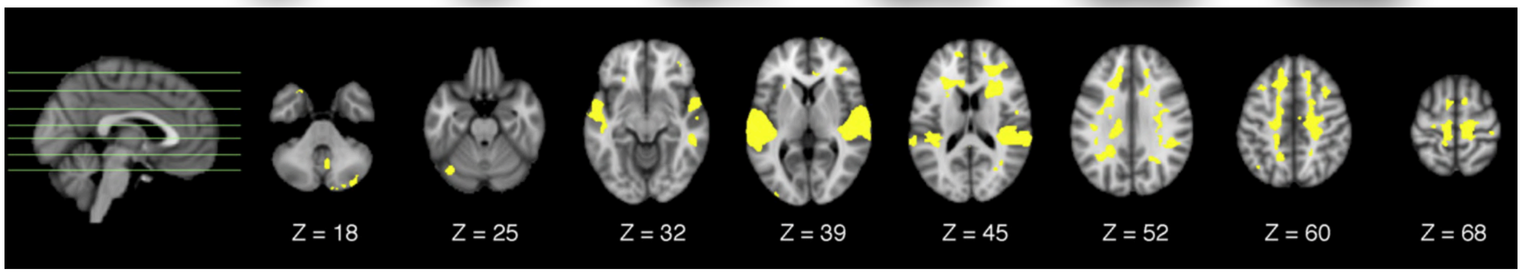
Inter-subject Correlation



Inter-subject Correlation

$r_{max} = 0.63$





Features

?

Acoustic Feature Extraction

Loudness

Timbral

43 features

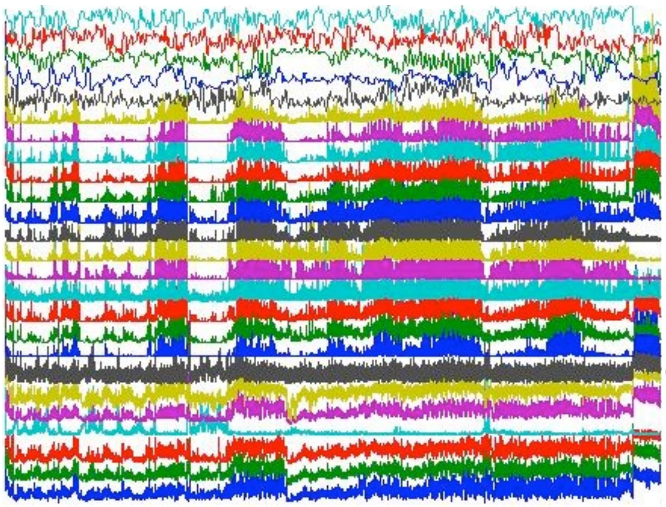
Rhythmical

Tonal

Processing Musical Features for fMRI

Feature Extraction

25 features



Loudness
Root Mean Square Energy
Timbre
Zero Crossing Rate
Spectral Centroid
High Energy – Low Energy Ratio
Spectral Spread
Spectral Entropy
Spectral Roll-off
Spectral Flux
Spectral Flatness
Roughness
Sub-band Flux (10)

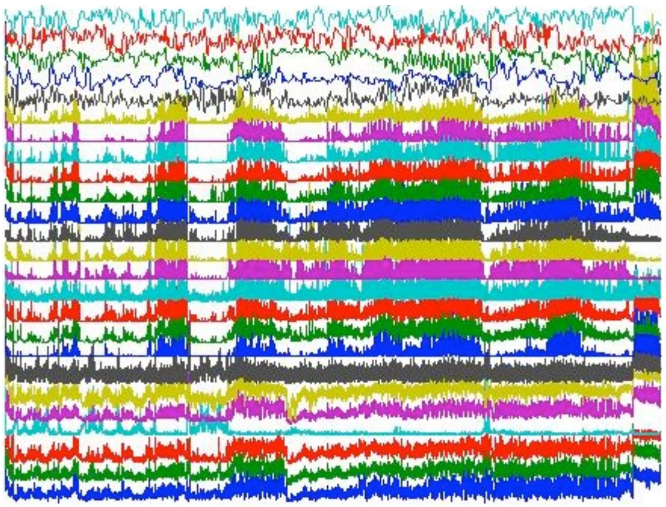
Tonality
Mode
Key Clarity
Rhythm
Fluctuation Centroid
Fluctuation Entropy
Pulse Clarity

Processing Musical Features for fMRI

Feature Extraction

Convolution with HRF

25 features



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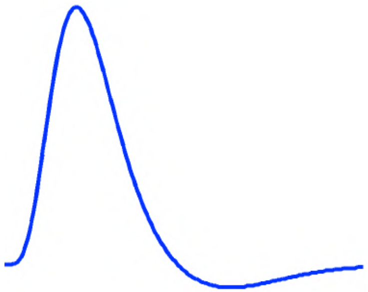

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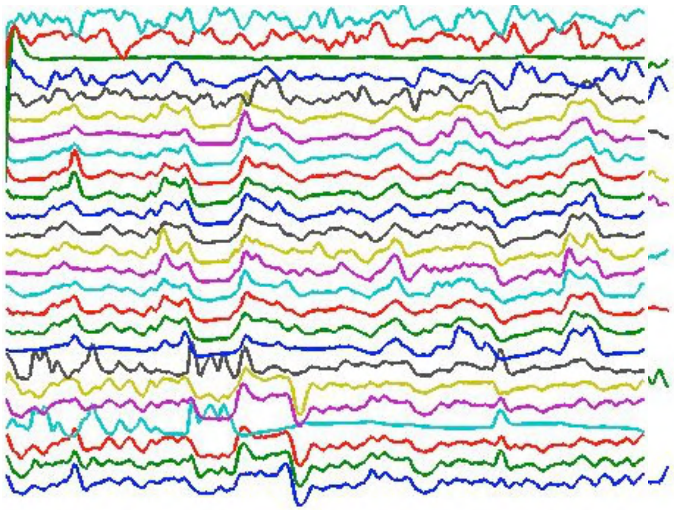
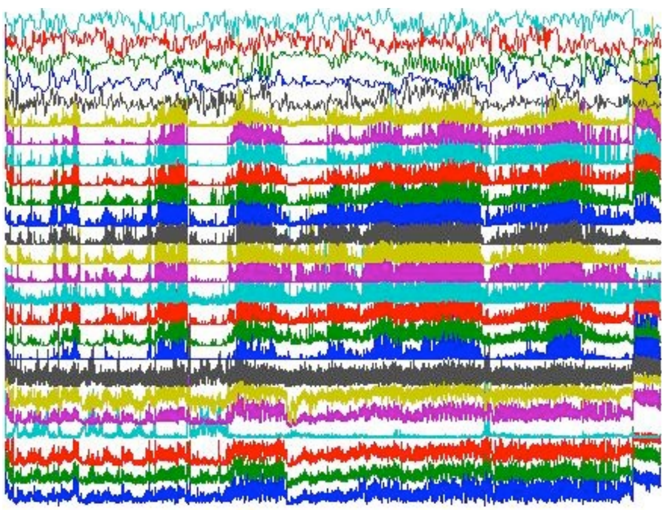
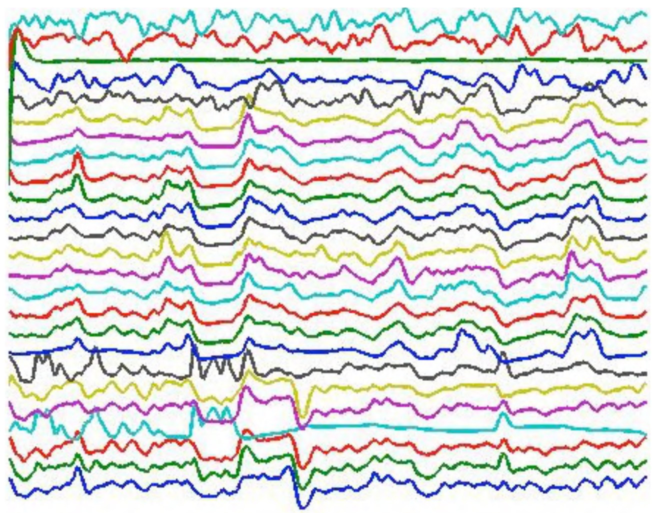
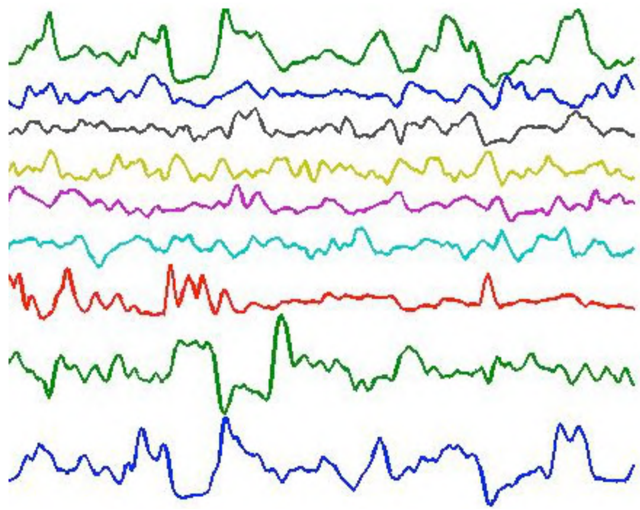


Processing Musical Features for fMRI

Feature Extraction	Convolution with HRF	PCA
25 features		9 PCs

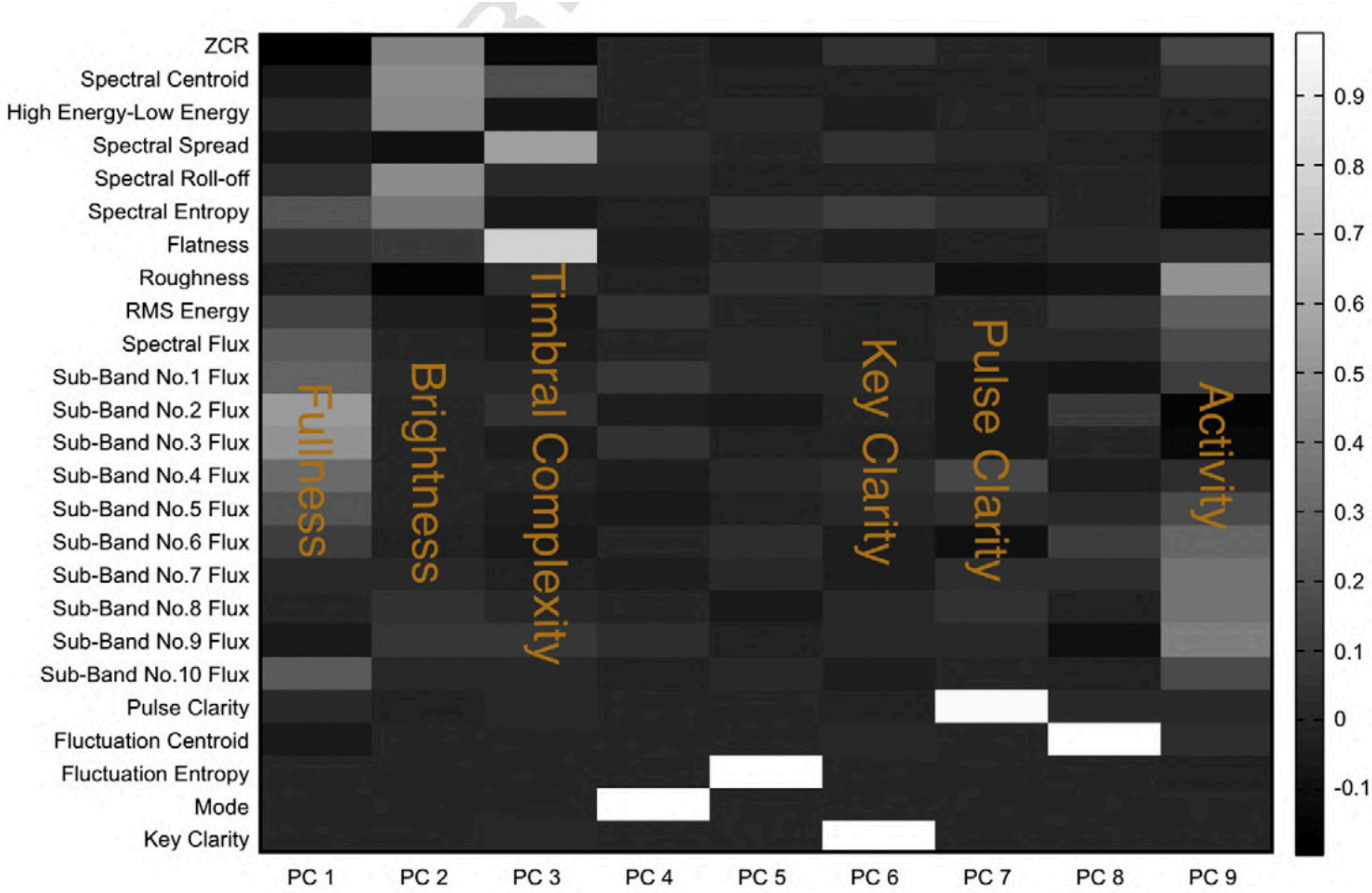




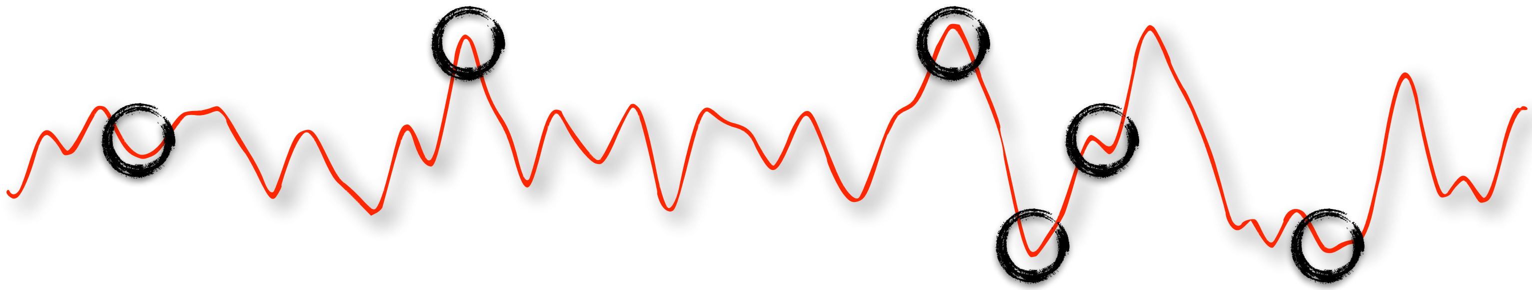


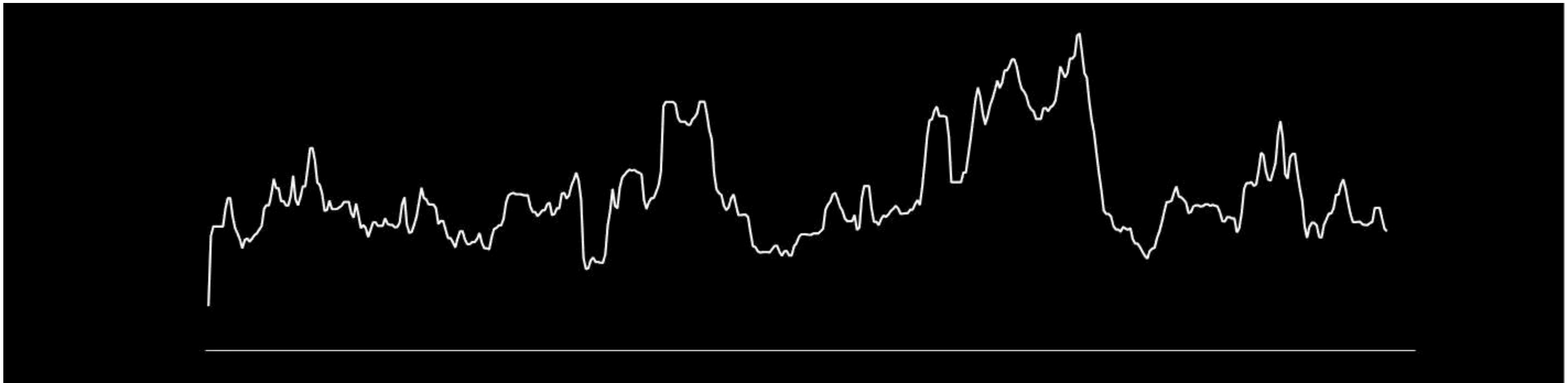
Perceptual validation -> 6 PCs retained

Loading/Weight Matrix

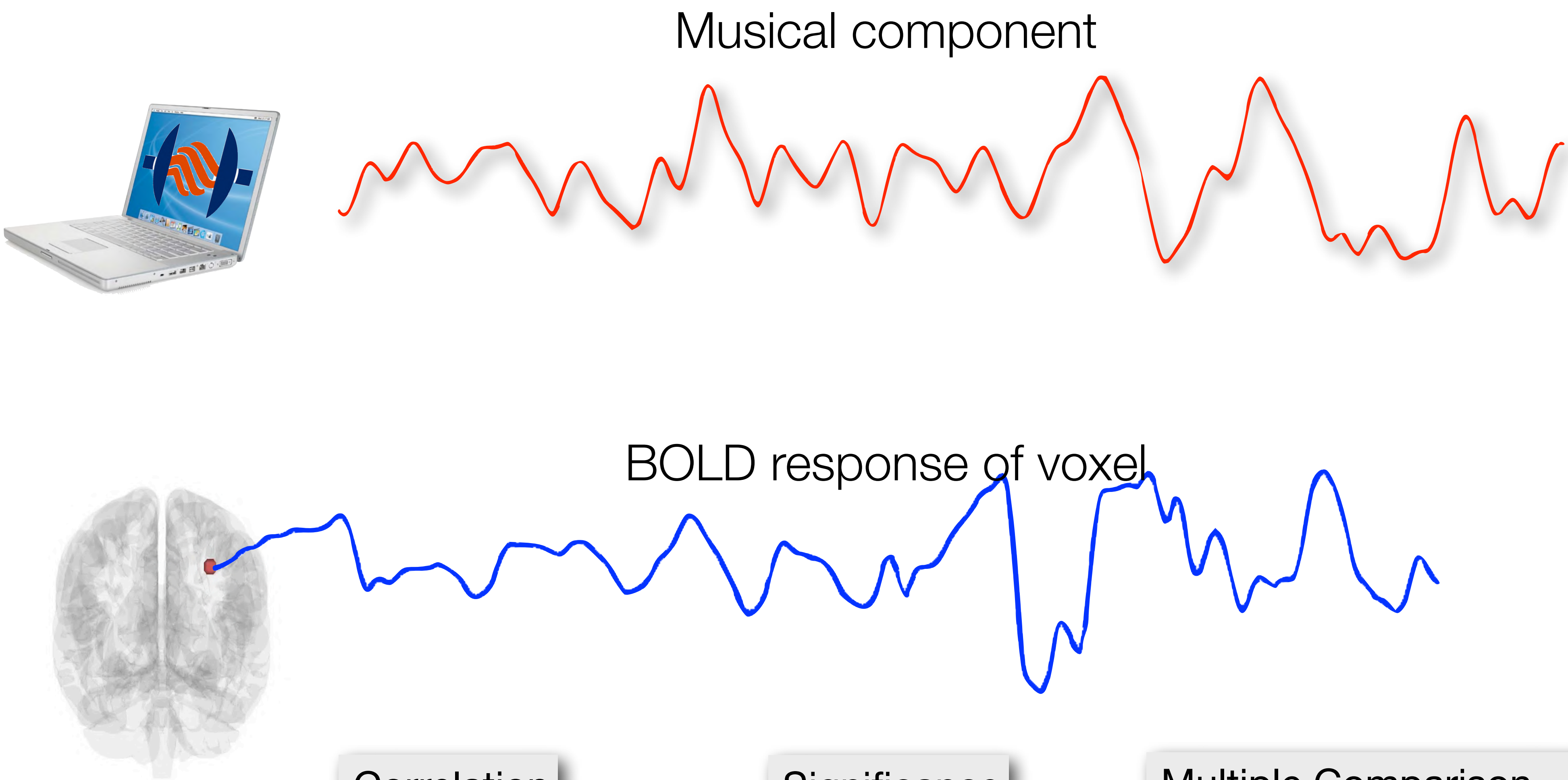


Listening Experiment



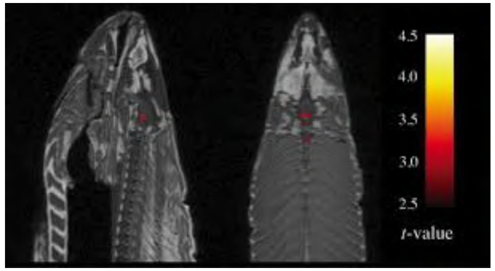


Voxel-Wise Correlation Analysis



Correlation Coefficient → Significance Estimation → Multiple Comparison Correction

non-parametric statistical tests



voxelwise inference

(temporal autocorrelation)

- effective degrees of freedom (Pyper and Peterman,1998)
- permutation tests - phase randomization (Ebisuzaki, 1997)

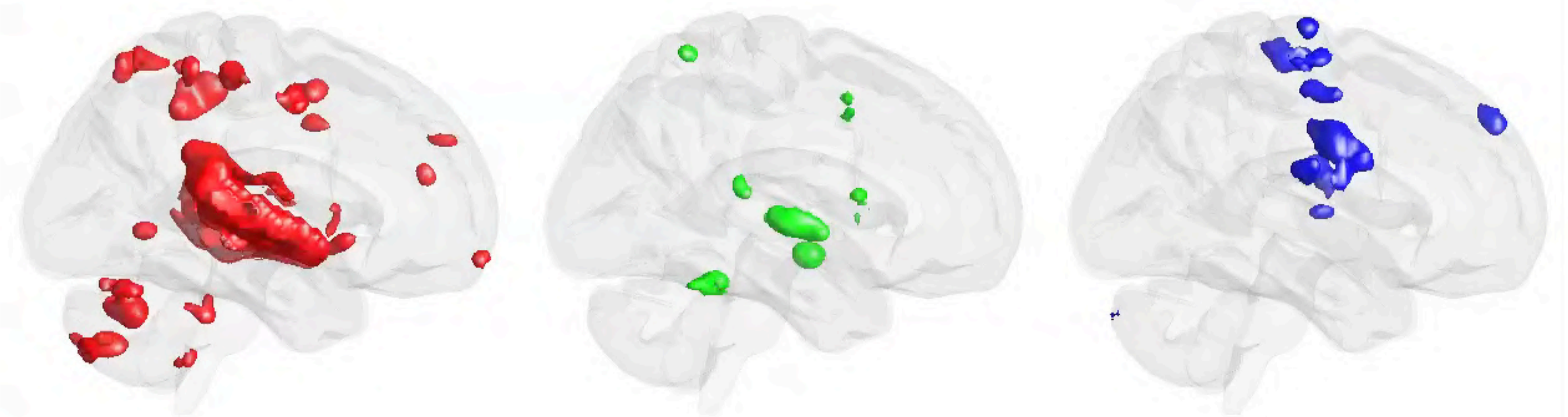
clusterwise inference

(spatial autocorrelation)

- spatial smoothness (Ledberg, Akerman, & Roland, 1998)
- bootstrapping (Efron, 1979)

Results

- **in line** with previous findings using controlled settings
- **additional** brain areas recruited



- **timbre**: auditory cortex, cerebellar cognitive areas, somatosensory & DMN-related cortical areas
- **rhythm**: motor areas(SMA), limbic areas (putamen, amygdala, insula)
- **tonality**: motor areas (rolandic operculum, SMA), mirror-neuron related areas (BA9)

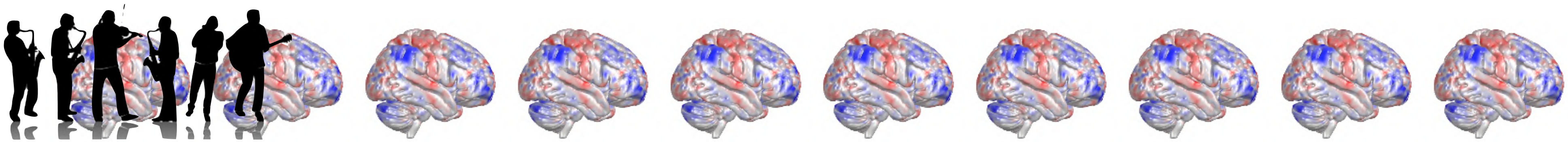
reliability?

validity?

new paradigm

reliability, replicability and repeatability

Alluri, V., Toiviainen, P., Lund, T., Wallentin, M., Vuust, P., Nandi, A. K., Ristaniemi, T., & Brattico, E. (2013). From Vivaldi to Beatles and back: predicting brain responses to music. NeuroImage, 83, 627-636.



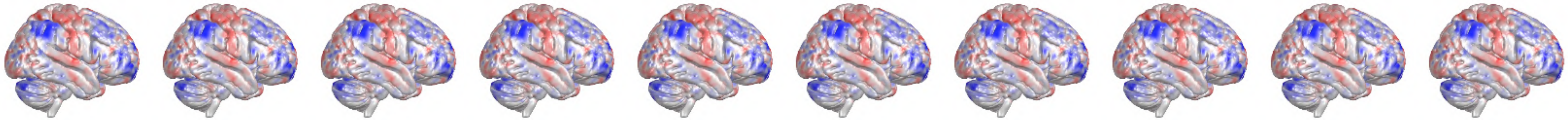
Burunat, I., Toiviainen, P., Alluri, V., Bogert, B., Ristaniemi, T., Sams, M., & Brattico, E. (2016). The reliability of continuous brain responses during naturalistic listening to music. NeuroImage, 124, 224–231.

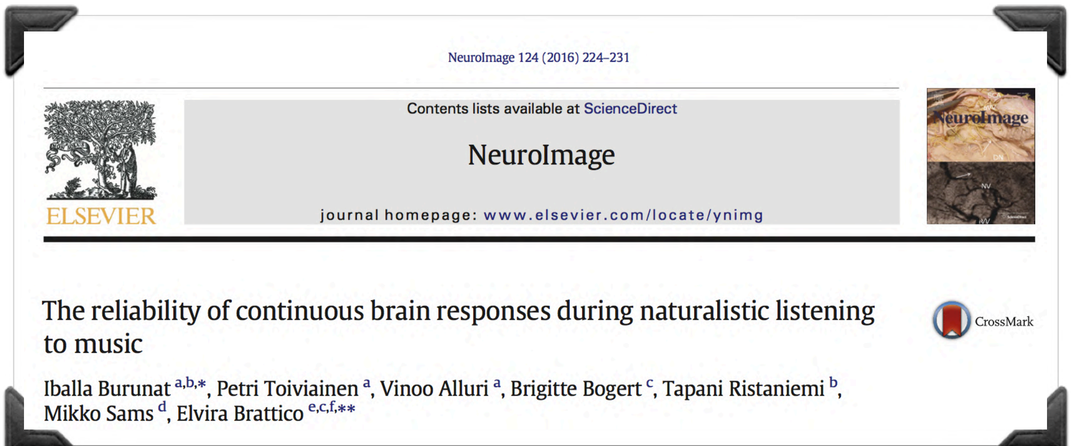
segregation

correlation

How accurately can neural correlates be replicated for musical features?

Study 2: Reproducible neuroscience with real-life experiments





NeuroImage 124 (2016) 224–231

Contents lists available at ScienceDirect

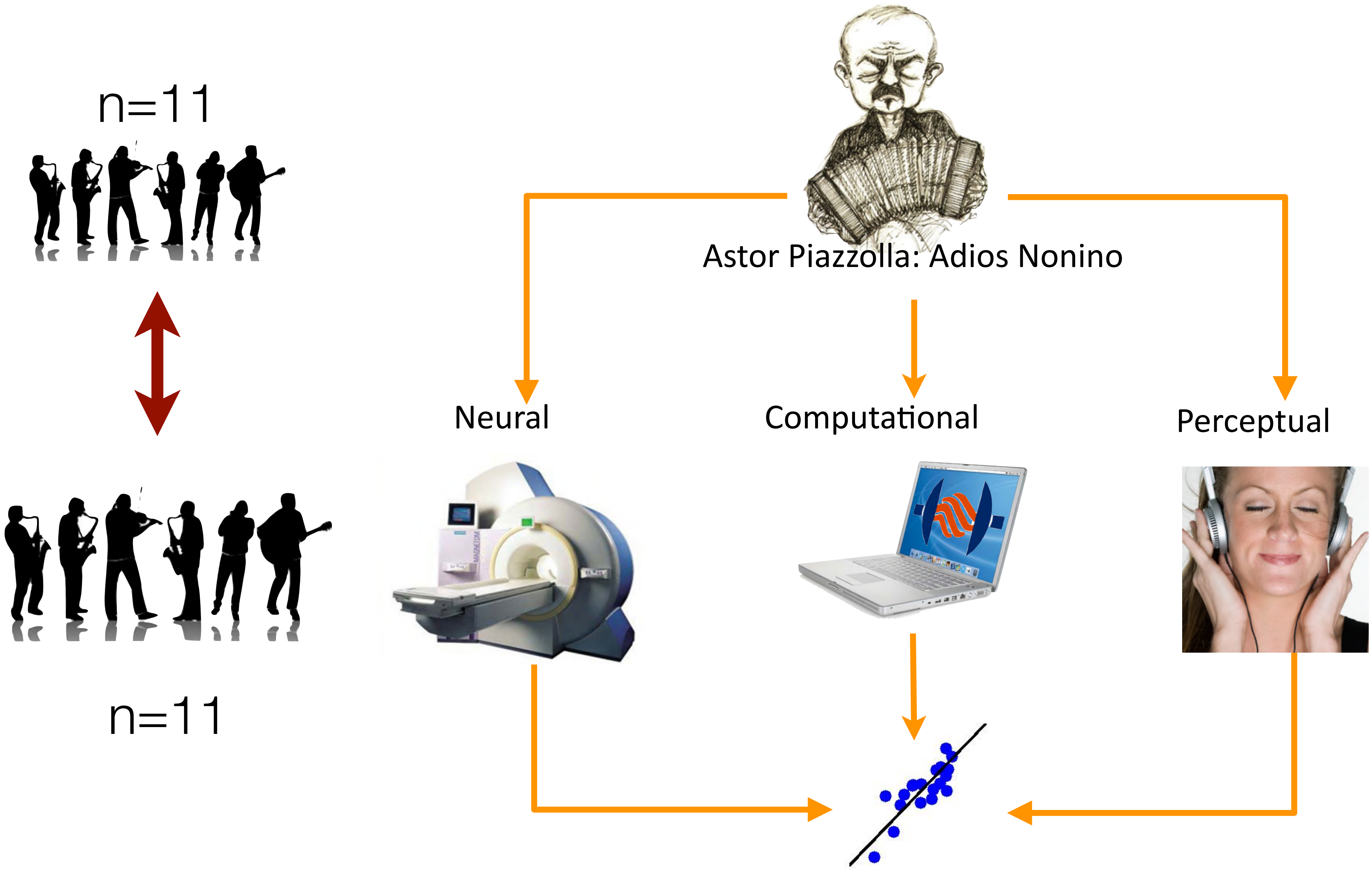
NeuroImage

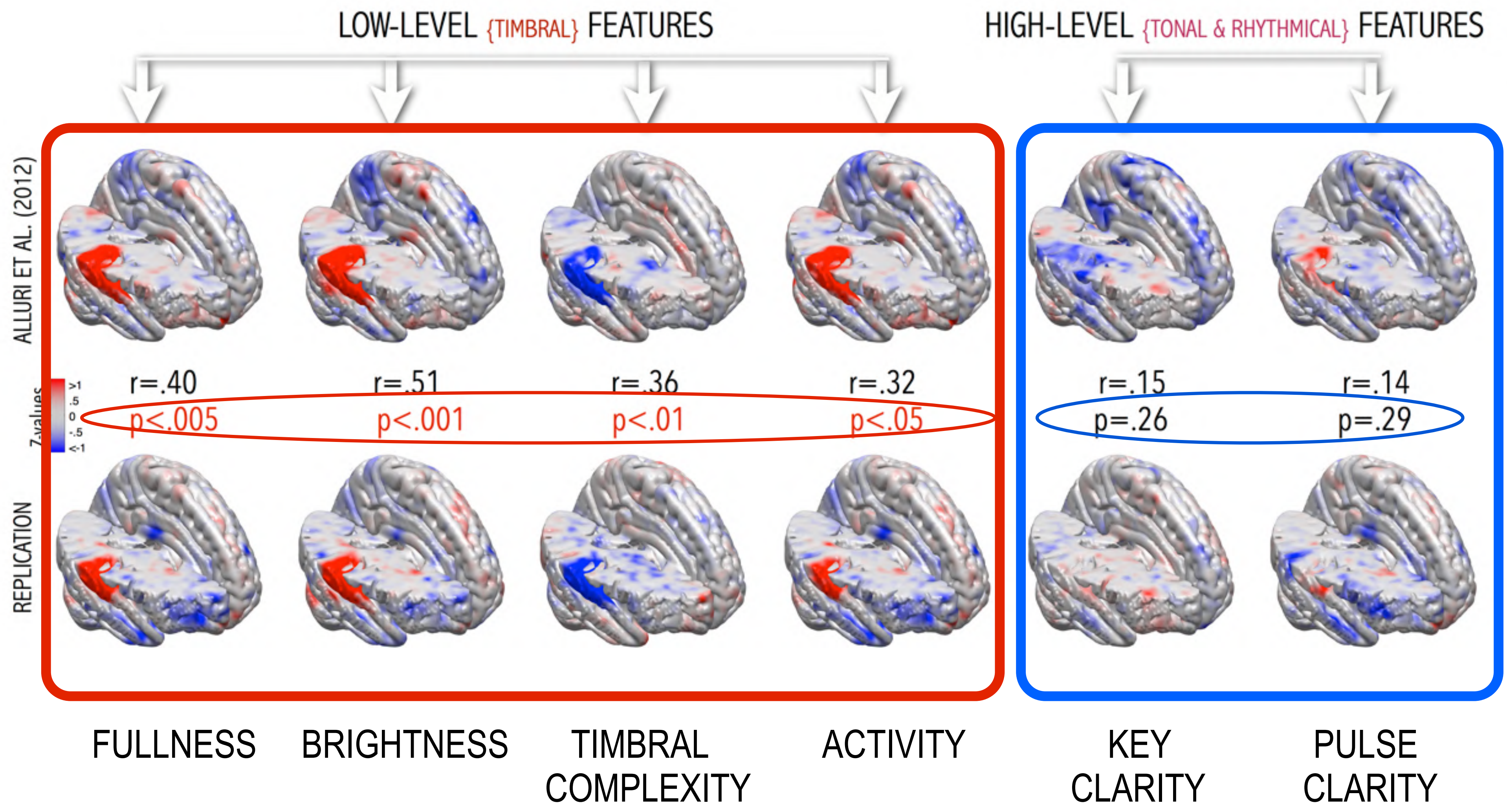
journal homepage: www.elsevier.com/locate/ynimg

The reliability of continuous brain responses during naturalistic listening to music

Iballa Burunat [a,b,*], Petri Toiviainen [a], Vinoo Alluri [a], Brigitte Bogert [c], Tapani Ristaniemi [b], Mikko Sams [d], Elvira Brattico [e,c,f,**]

Experimental Setup





RELIABILITY MEASURE I: CORRELATION BETWEEN SPATIAL MAPS

For which brain areas can the activation be predicted across different musical stimuli? Generalizability of the encoding models?

Study 3: This is your brain on Vivaldi and Beatles

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From Vivaldi to Beatles and back: Predicting lateralized brain responses to music

Vinoo Alluri [a,b,*], Petri Toiviainen [a,1], Torben E. Lund [c,2], Mikkel Wallentin [c,f,3], Peter Vuust [c,d,2,3], Asoke K. Nandi [e,b,5], Tapani Ristaniemi [b,4], Elvira Brattico [a,g,h,6]

Study 3: This is your brain on Vivaldi and Beatles

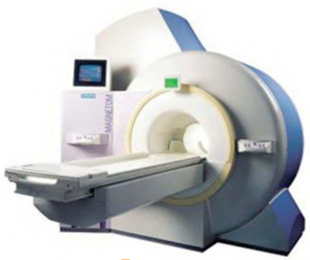
"Real" music stimuli (~16mins each)

Abbey Road

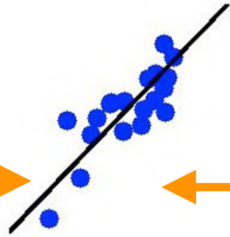
Medley

Neural

Acoustic

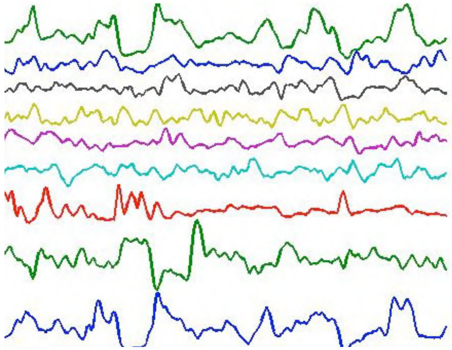


n=15



Encoding Models

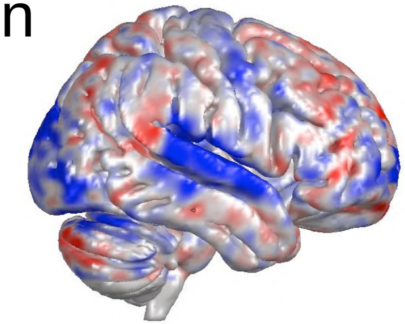
Musical components



$$\mathbf{PC}_{\mathrm{A}} = \mathbf{F}_{\mathrm{A}}\mathbf{L}_{\mathrm{A}}$$

Voxel-wise
PC Regression

$$V_{\mathrm{A}}^{i} \approx \mathbf{PC}_{\mathrm{A}}\mathbf{b}_{\mathrm{A}}^{i}$$



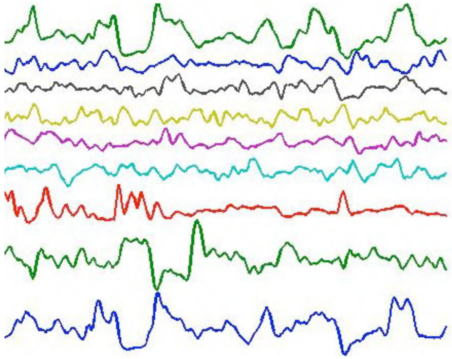
measured

$\mathbf{F}$ = acoustic features

$\mathbf{L}$ = loading matrix

Encoding Models

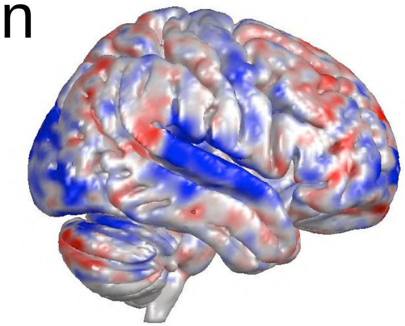
Musical components



$$\mathbf{PC}_{\mathrm{M}} = \mathbf{F}_{\mathrm{M}}\mathbf{L}_{\mathrm{M}}$$

Voxel-wise
PC Regression

$$V_{\mathrm{M}}^{i} \approx \mathbf{PC}_{\mathrm{M}}\mathbf{b}_{\mathrm{M}}^{i}$$



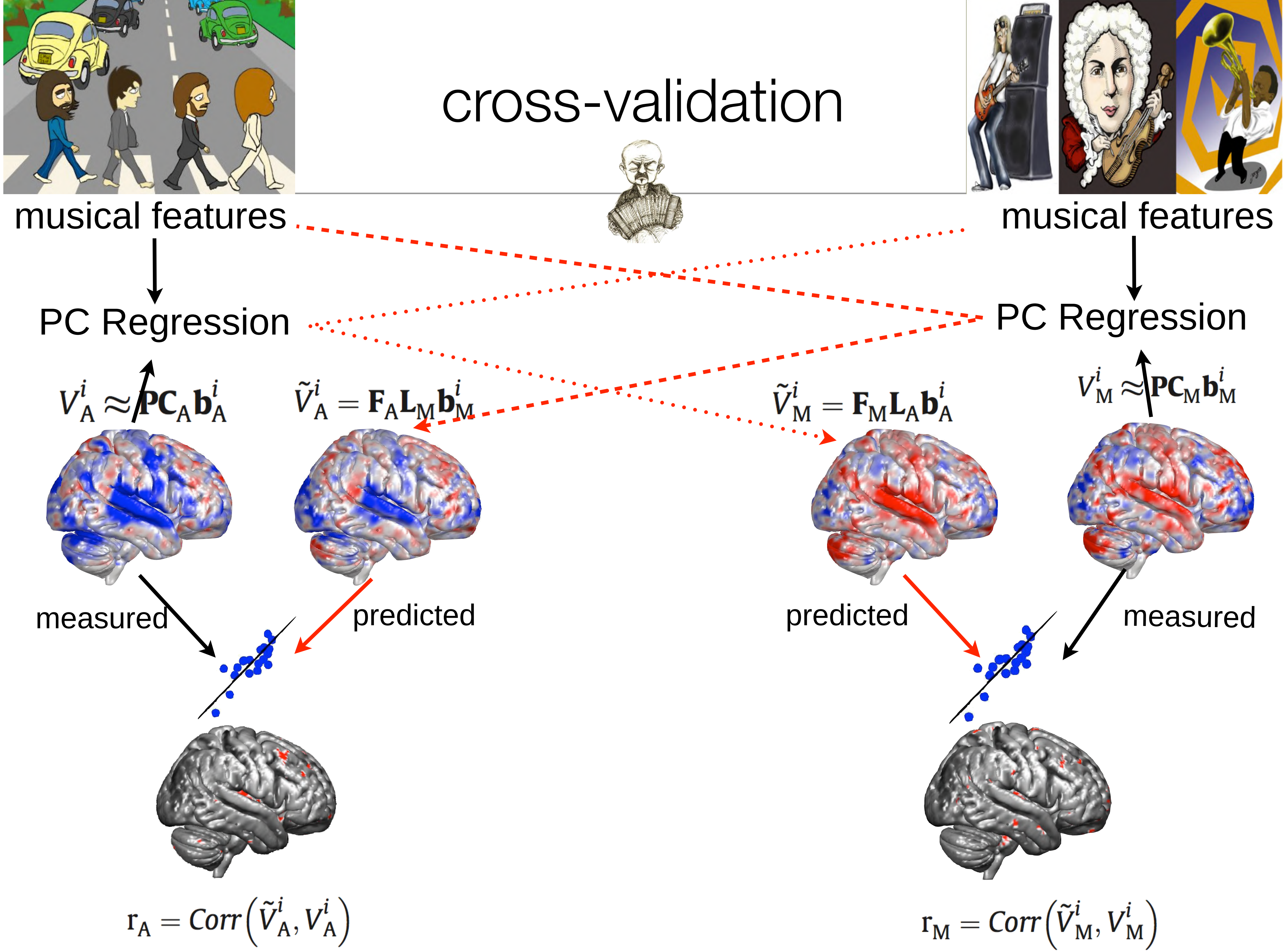
measured

$\mathbf{F}$ = acoustic features

$\mathbf{L}$ = loading matrix

Encoding Results

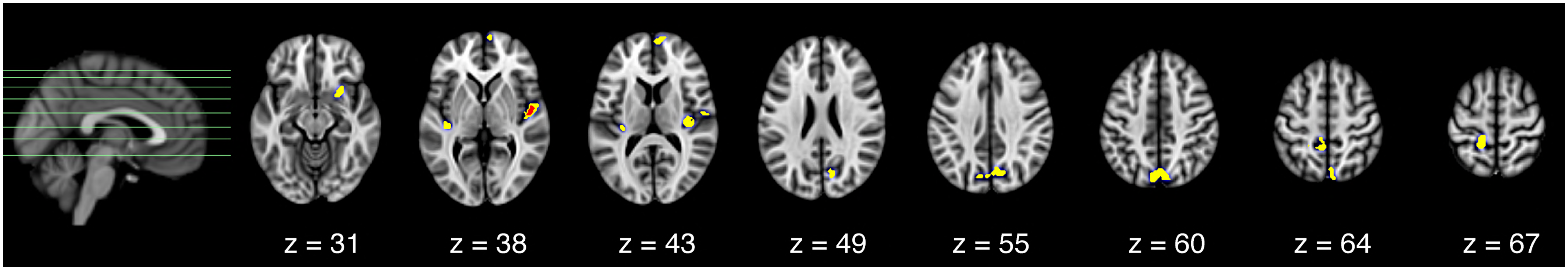
- Brain activations can be predicted in auditory, and motor, and orbitofrontal regions
- Right anterior STG best predicted by musical features
- Activations in limbic and cerebellar regions only predictable for Abbey Road



cross-validation
musical features
musical features
PC Regression
PC Regression
$V_A^i \approx \mathbf{PC}_A \mathbf{b}_A^i$
$\tilde{V}_A^i = \mathbf{F}_A \mathbf{L}_M \mathbf{b}_M^i$
$\tilde{V}_M^i = \mathbf{F}_M \mathbf{L}_A \mathbf{b}_A^i$
$V_M^i \approx \mathbf{PC}_M \mathbf{b}_M^i$
measured
predicted
predicted
measured
$r_A = Corr\left(\tilde{V}_A^i, V_A^i\right)$
$r_M = Corr\left(\tilde{V}_M^i, V_M^i\right)$

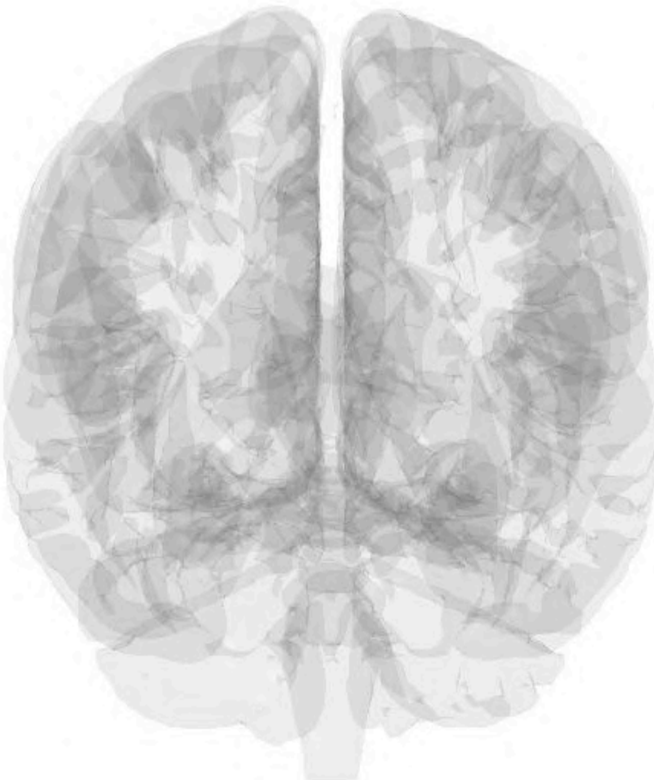
Encoding Cross-validation Results

- Brain activations can be predicted in auditory, and motor, and orbitofrontal regions
- Right anterior STG best predicted by musical features
- Activations in limbic and cerebellar regions only predictable for Abbey Road
- **Cross-validation**: **STG(R)**
  - **auditory** (bilateral AC), **motor** (putamen, postcentral gyrus, paracentral lobule), **DMN** (precuneus, superior MFG)



Cross-validation Results

- The presence of lyrics confounds processing of musical features in left hemisphere



Instrumental vs instrumental Instrumental vs vocal

current and future trends

- paradigm: from controlled to naturalistic
- viewpoint: from segregation to integration
- universality: from invariance to variance
- modelling: from encoding to decoding and simulation

two views into brain function

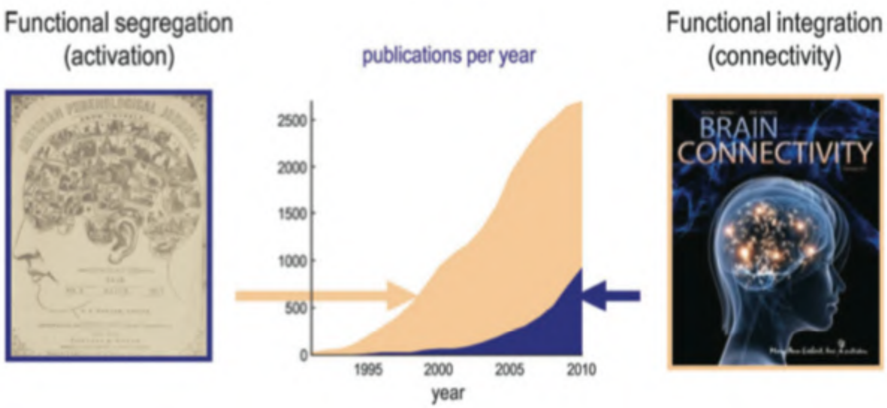
segregation

- identification of local regions that are specialized for a particular task

integration

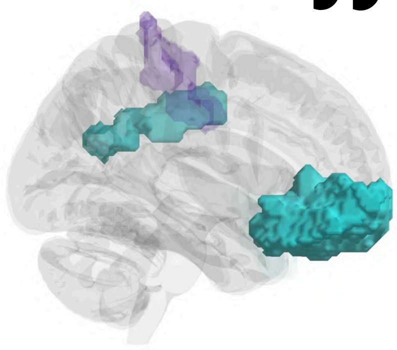
- identification of interactions between regions that allow integrated function

- increased interest in brain integration



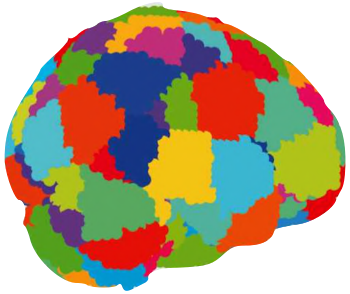
Friston 2011. Functional and Effective Connectivity: A Review. *Brain Connectivity*, Vol 1. DOI: 10.1089/brain.2011.0008

"blobology"

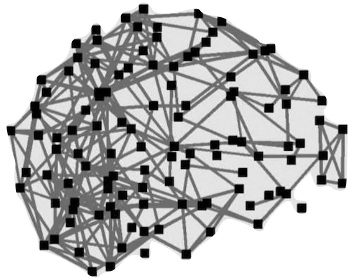


brain functioning viewpoints

Activations

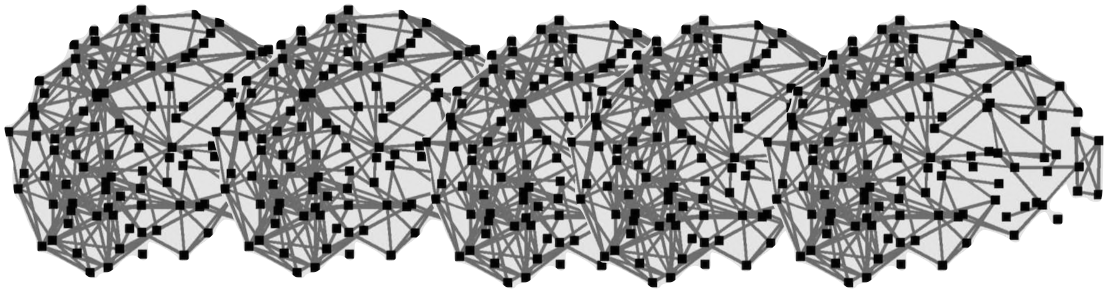


Integration



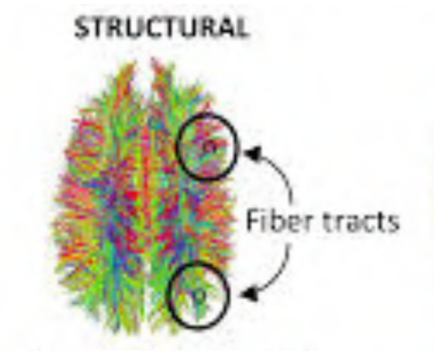
“Connectome”

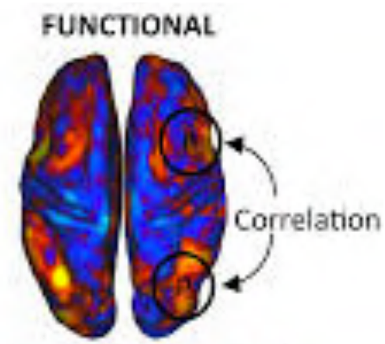
Dynamic Integration

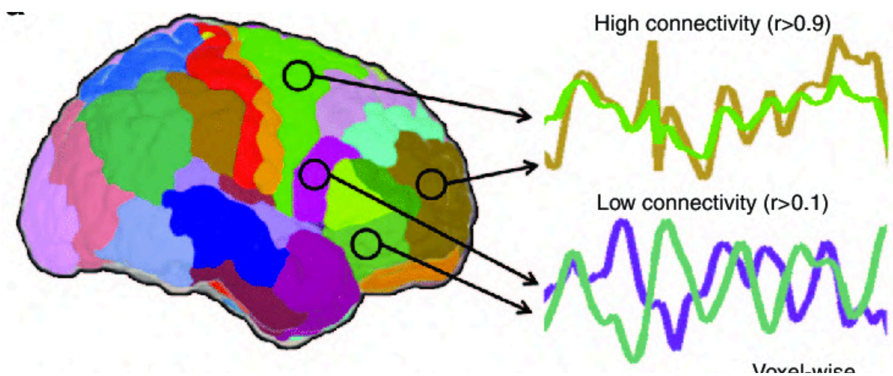


“Chronnectome”

Integration: Connectivity

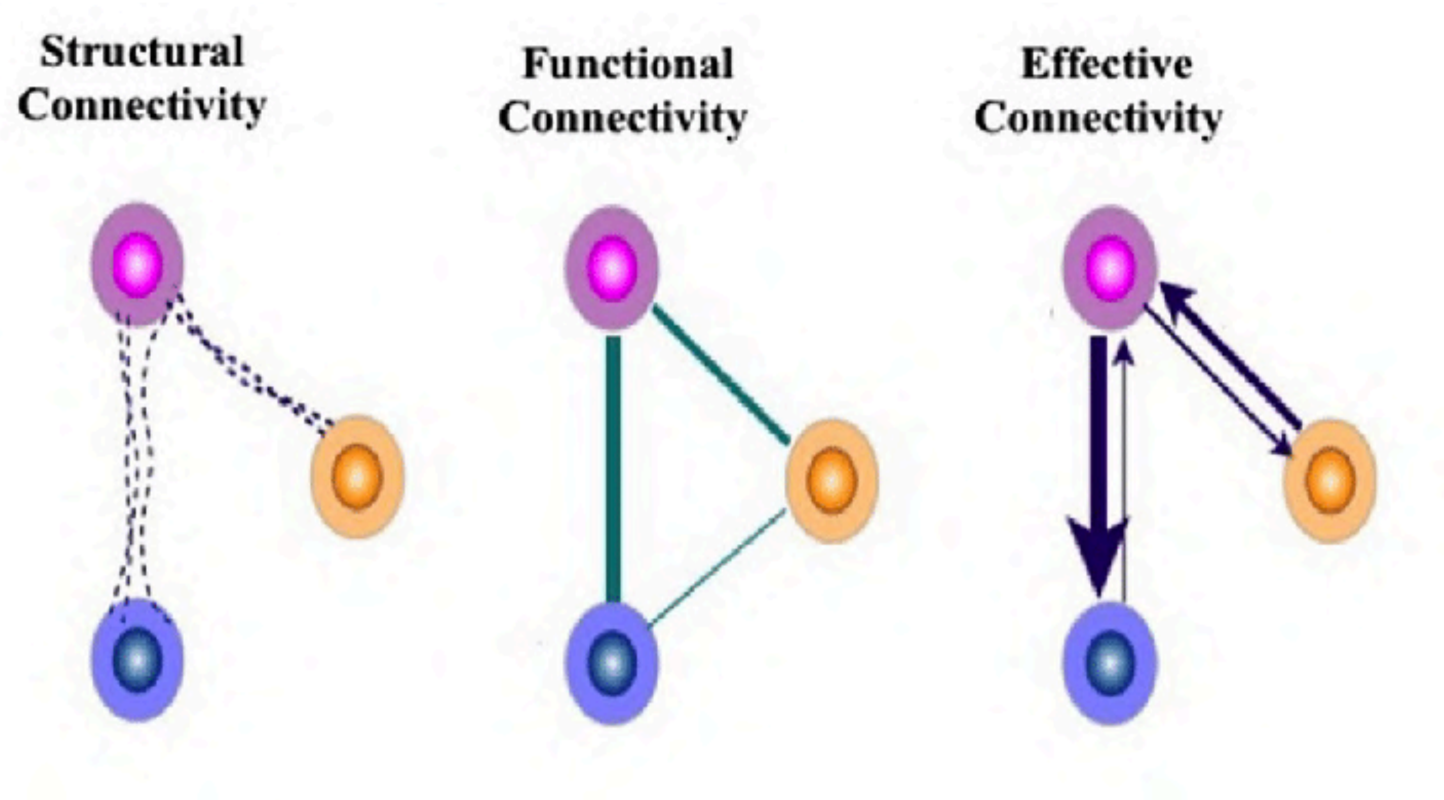






Structural vs **Functional**

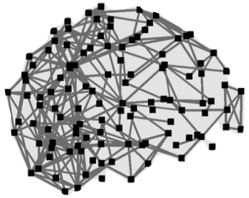
Connectivity

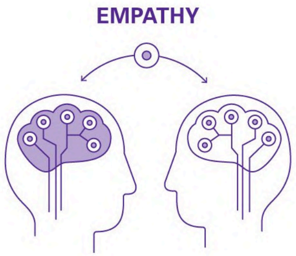


Some examples later

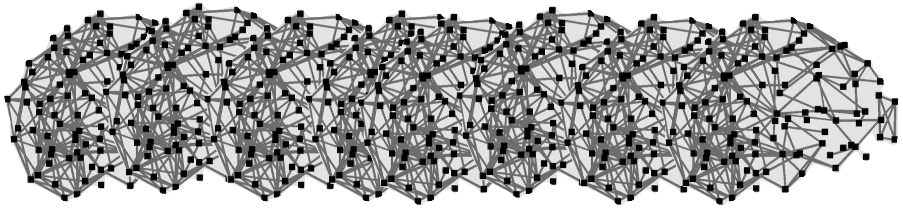
Activations

Static Functional Connectivity





Dynamic Functional Connectivity



functional integration

integration	phenomenon	assumptions	methods
functional connectivity	temporal correlation between regions	exploratory data-driven non-causal whole-brain	seed correlation PCA ICA Graph Analysis
effective connectivity	effect of one region on another	confirmatory hypothesis-driven causal brain regions	PPI SEM DCM Granger Causality

current and future trends

- paradigm: from controlled to naturalistic
- viewpoint: from segregation to integration
- universality: from invariance to variance
- modelling: from encoding to decoding and simulation

invariance

- traditionally focused on invariant features
  - to what extent are brain processes invariant across individuals?
- intersubject-variability regarded as noise
- intrasubject-variability not always feasible

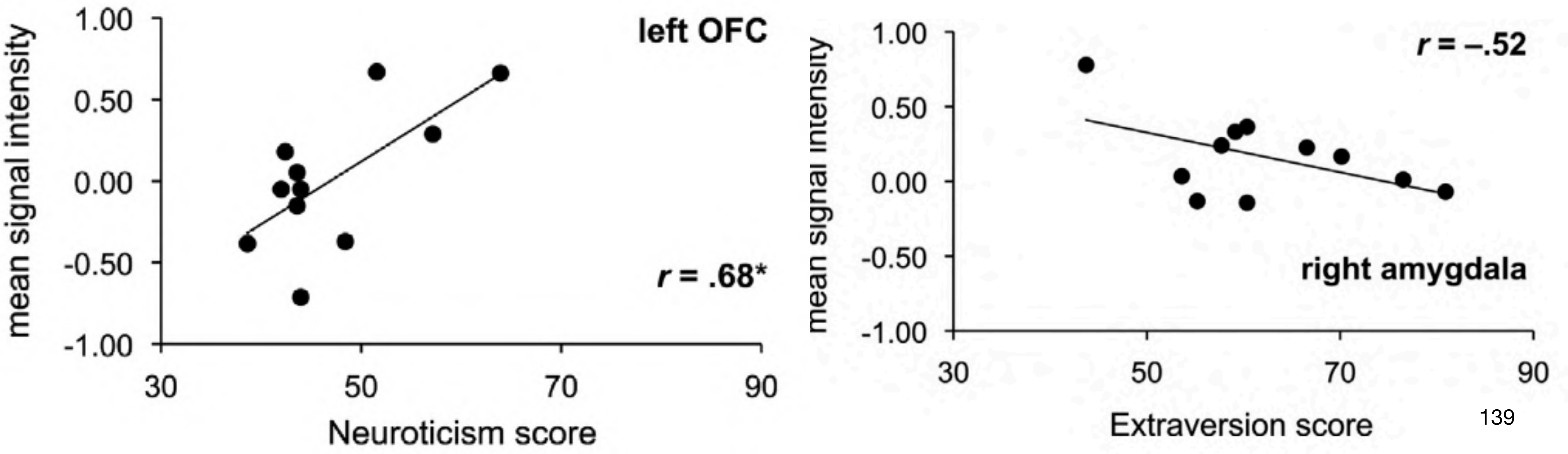
inter-subject variance

- individual differences and factors that cause them
  - genetic: personality traits, gender, handedness, musical aptitude
  - acquired: culture, training, history of illness, familiarity, preference

Personality matters!

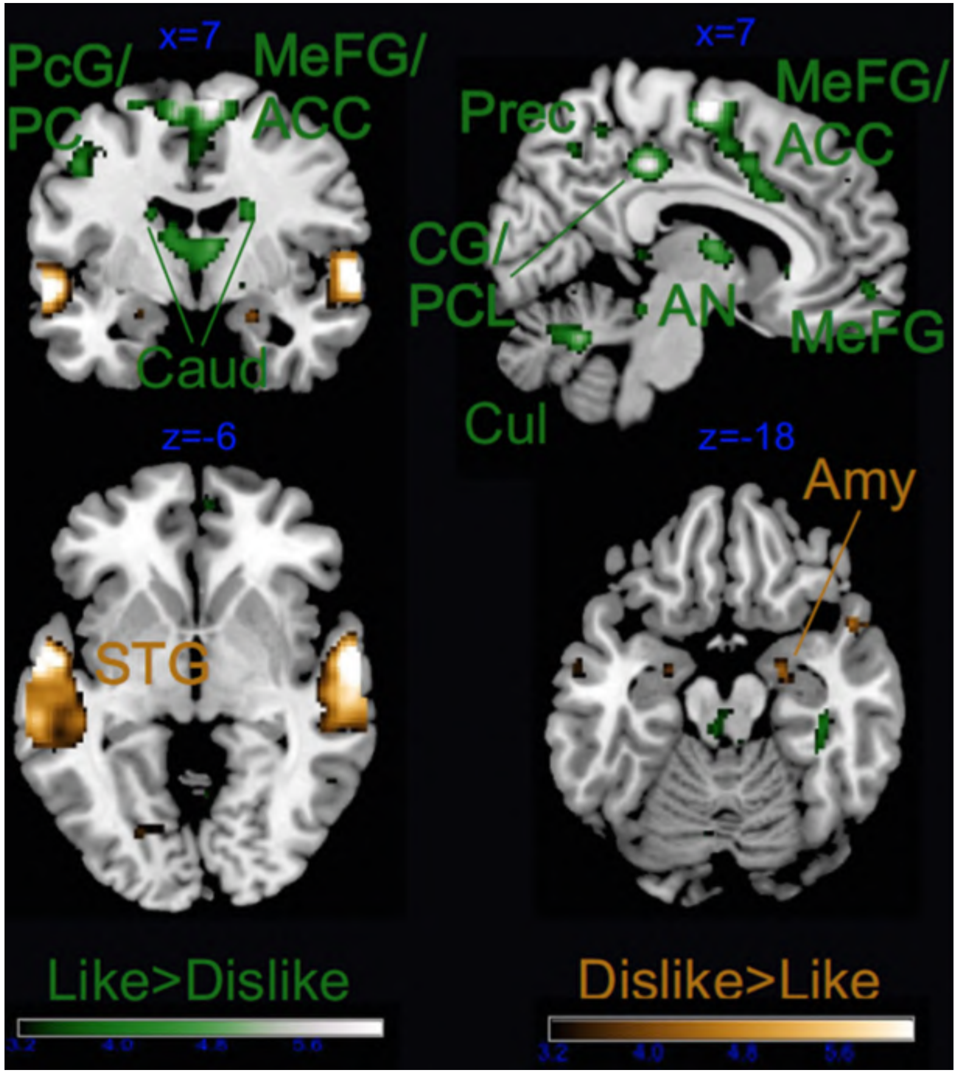
- personality modulates brain responses to musical emotions (Park et al 2013)

  - amygdala, orbitofrontal cortex, insula, basal ganglia more activated by happiness in neurotic listeners



preference: "It's Sad but I Like It"

- preference of music modulates brain activations (Brattico, Bogert, Alluri, Tervaniemi, Eerola & Jacobsen *Frontiers in Human Neuroscience 2016)*
  - cortico-thalamo-striatal reward circuit and motor areas more active during liked music
  - the auditory cortex and the right amygdala more active during disliked music

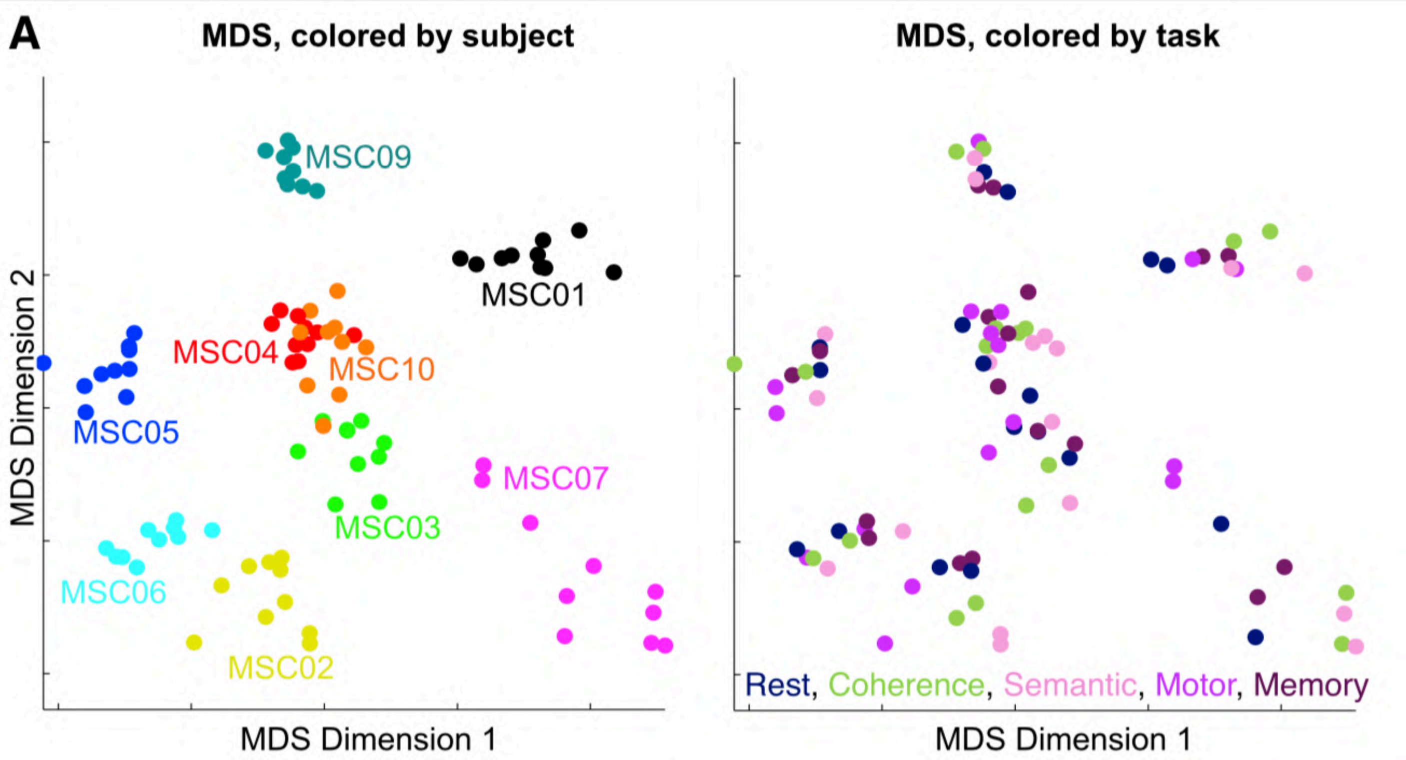


intra-subject variance

- single subject, same task, different day
  - eg: mood, attentiveness, interest

intra-subject variance

- Midnight Scan Club (MSC) dataset - (functional connectivity)



Gratton et al. 2018

intra-subject variance

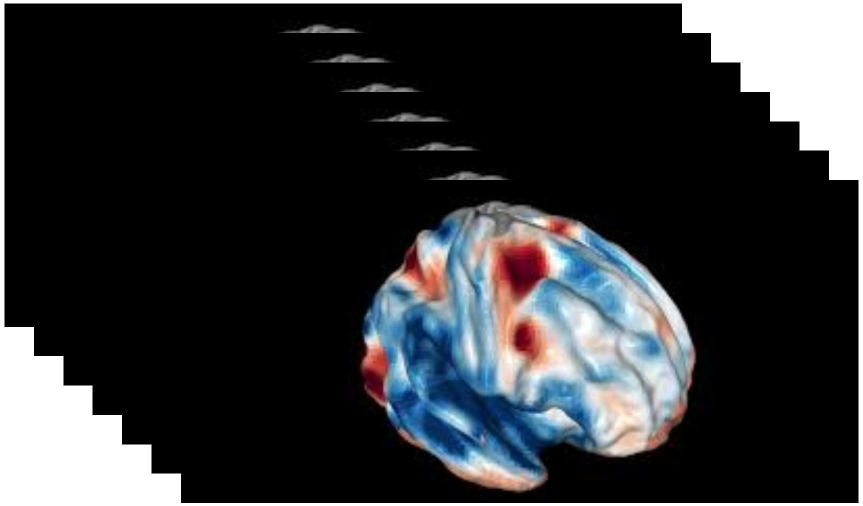
- presence of largely stable functional networks
- **large individual-specific variations**
- moderate variations across task states

- suited for unearthing biomarkers for intrinsic traits/ conditions
    - individual stable traits (ex: personality, empathy)
    - disease

Gratton et al. 2018

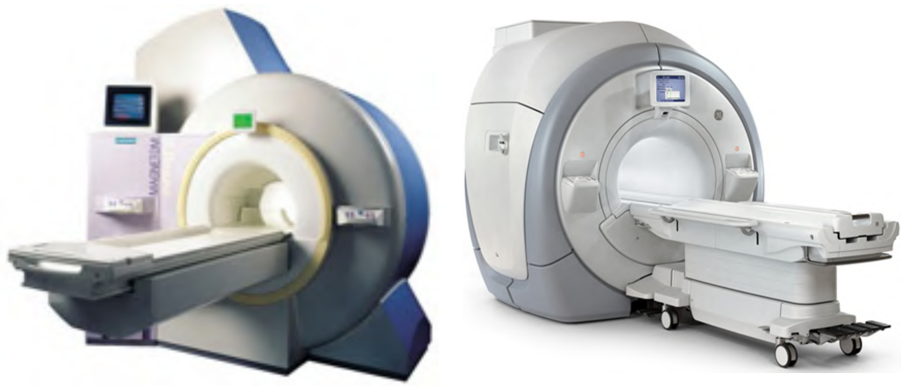
ex: intra-subject variance

- single subject, same task, different day (7 days)
- which regions do you think we would find similar responses in across sessions?



between-measurement variance

- to what extent are results replicable across measurements?
- not many replication studies as of yet



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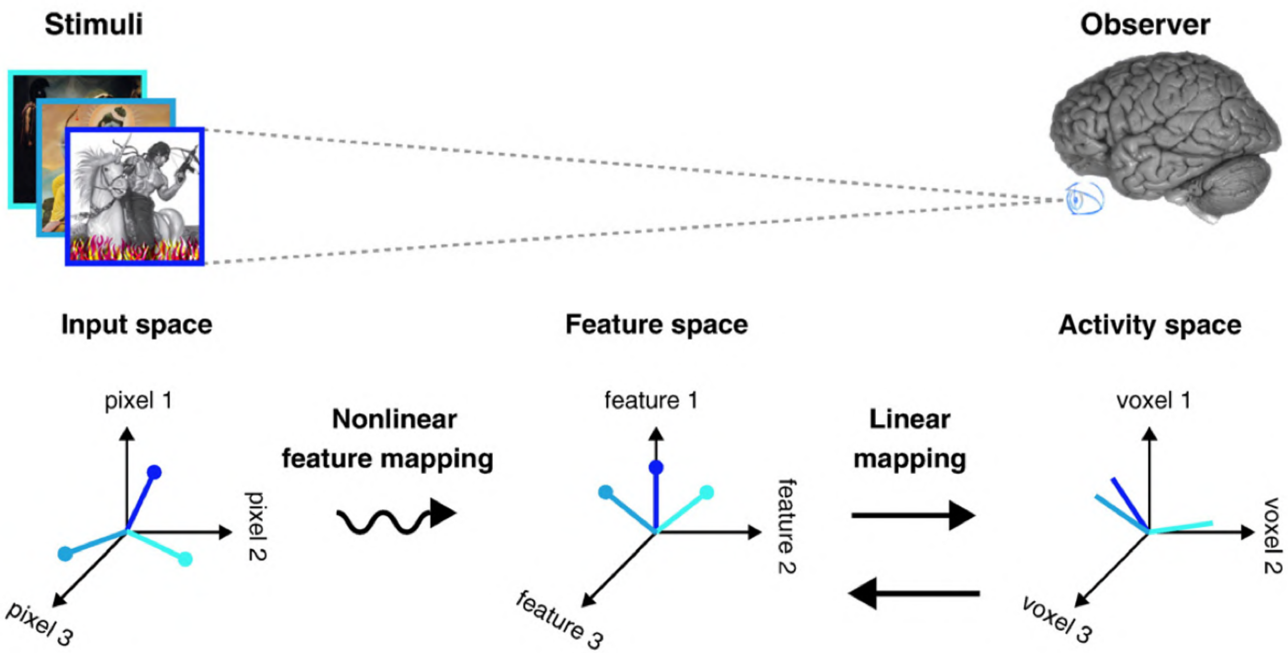
encoding vs decoding

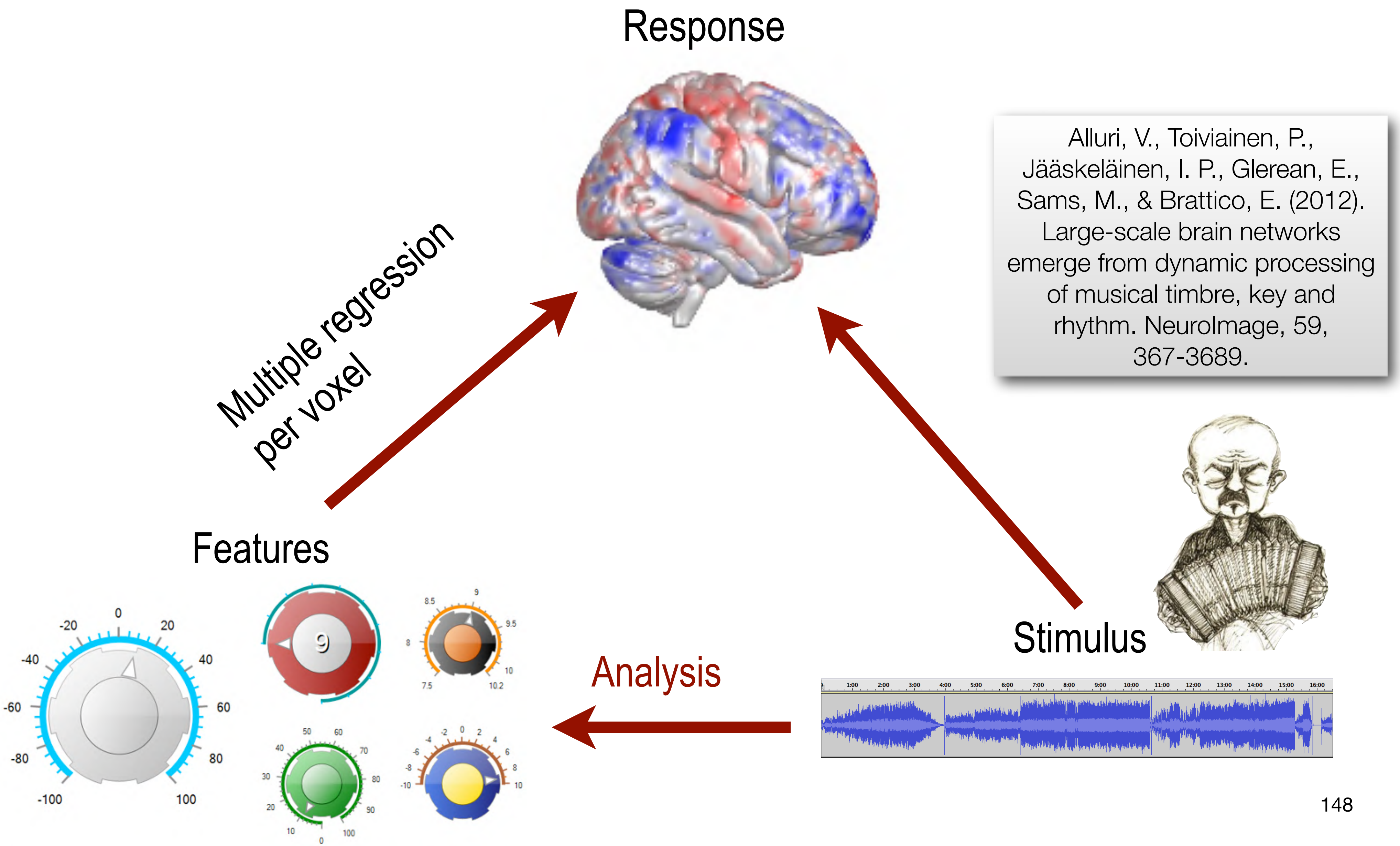
- encoding: forward inference
  - from stimulus features to brain activation
- decoding: reverse inference
  - from brain activation to stimulus features



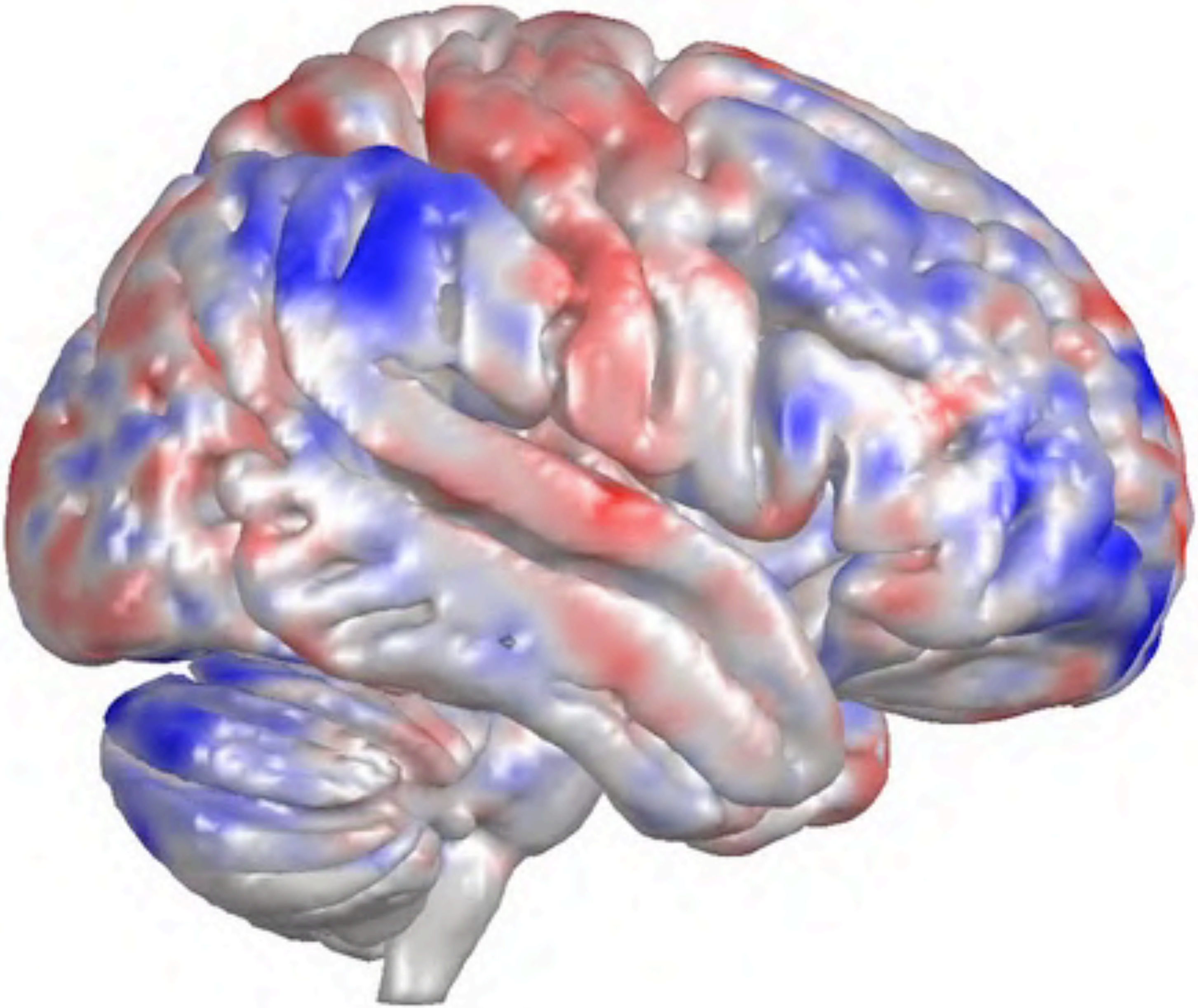
Naselaris, Kay, Nishimoto, Gallant. (2011). Encoding and decoding in fMRI. NeuroImage, 56, 400-410.

"Brain-reading"

encoding music

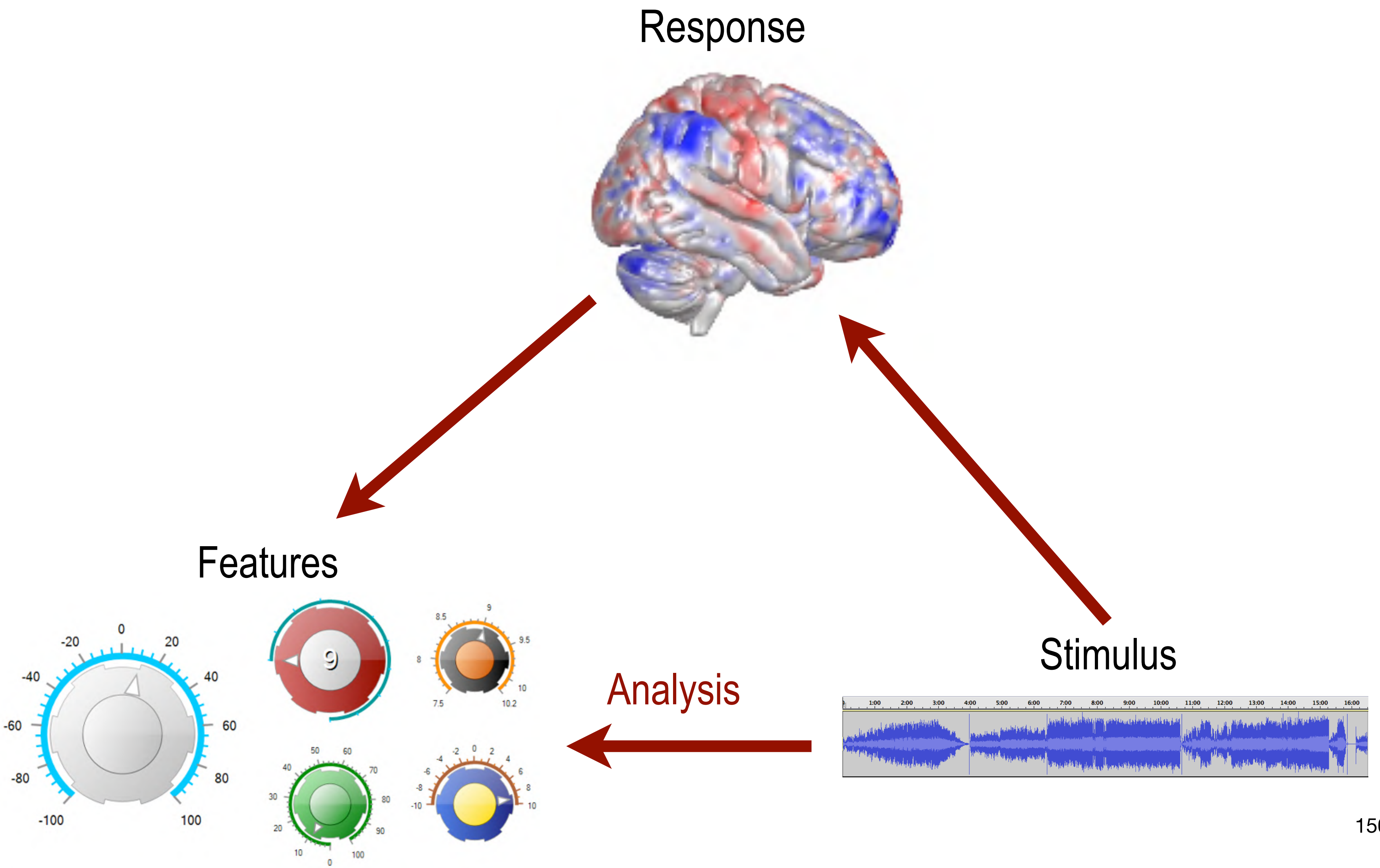


Alluri, V., Toiviainen, P., Jääskeläinen, I. P., Glerean, E., Sams, M., & Brattico, E. (2012). Large-scale brain networks emerge from dynamic processing of musical timbre, key and rhythm. NeuroImage, 59, 367-3689.

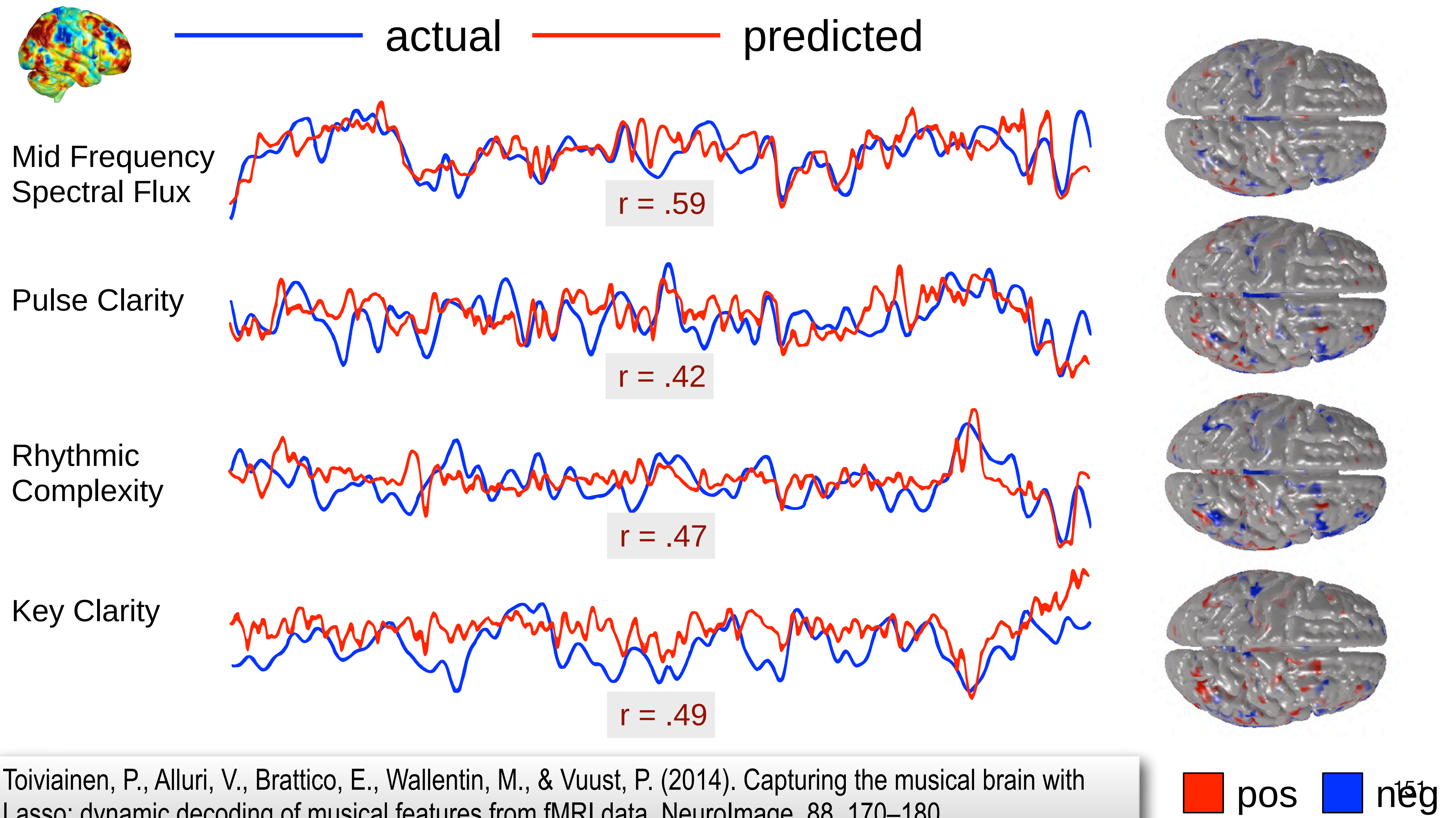


Alluri, V., Toiviainen, P., Jääskeläinen, I. P., Glerean, E., Sams, M., & Brattico, E. (2012). Large-scale brain networks emerge from dynamic processing of musical timbre, key and rhythm. NeuroImage, 59, 367-3689.

decoding music

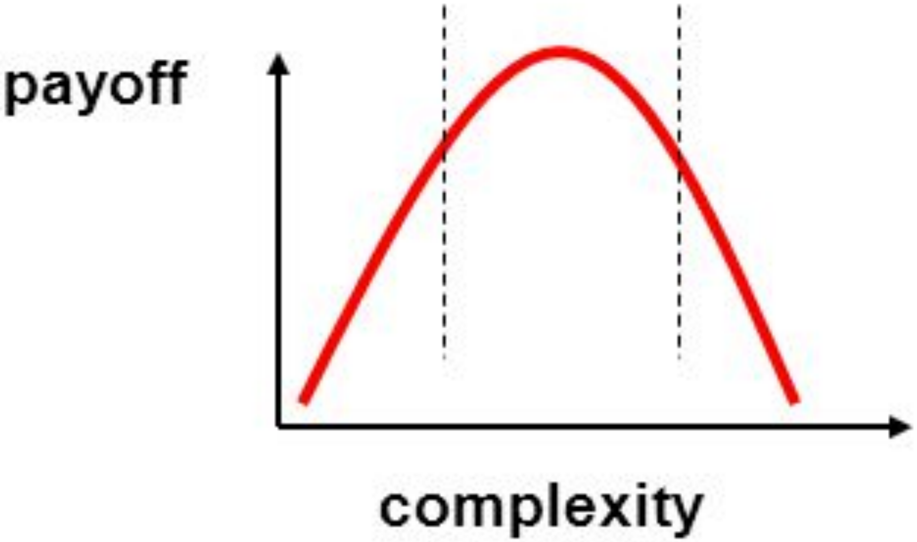


Decoding Musical Features (Example)



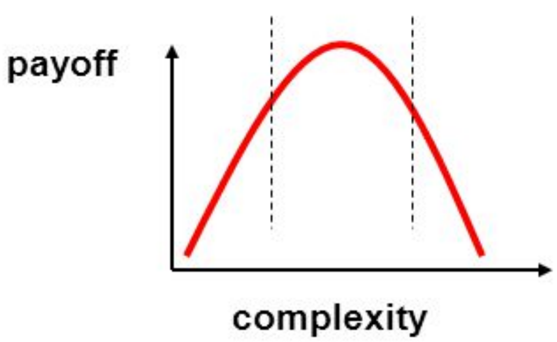
Toiviainen, P., Alluri, V., Brattico, E., Wallentin, M., & Vuust, P. (2014). Capturing the musical brain with Lasso: dynamic decoding of musical features from fMRI data. NeuroImage, 88, 170–180.

Medawar zone

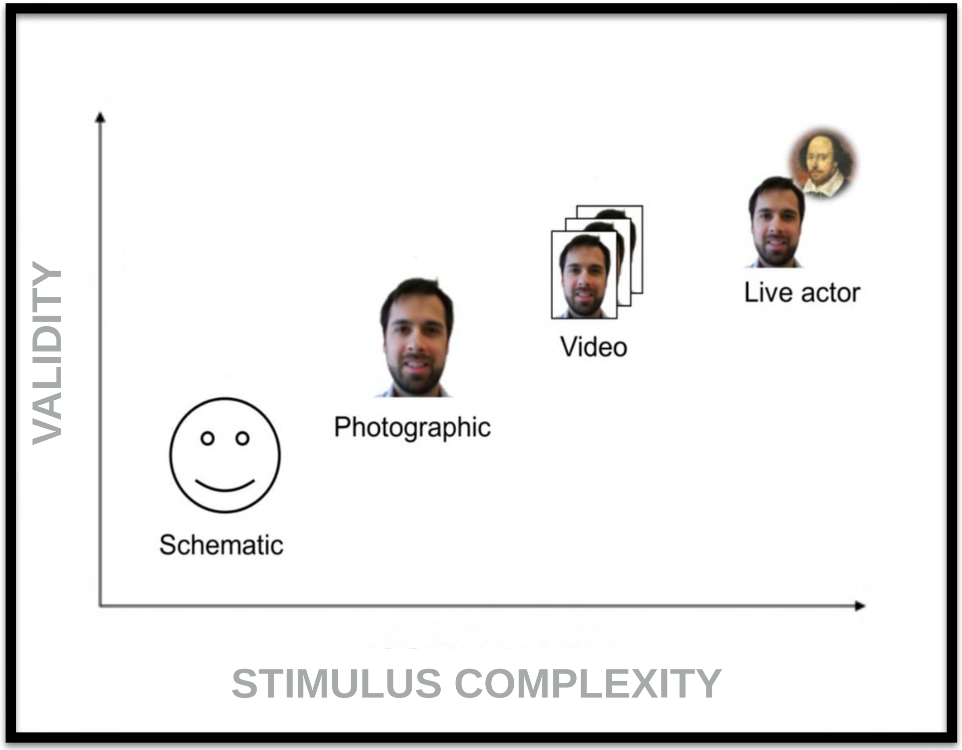


$$\boldsymbol{payoff} = f(\boldsymbol{ecological\ validity}, \boldsymbol{model\ interpretability})$$

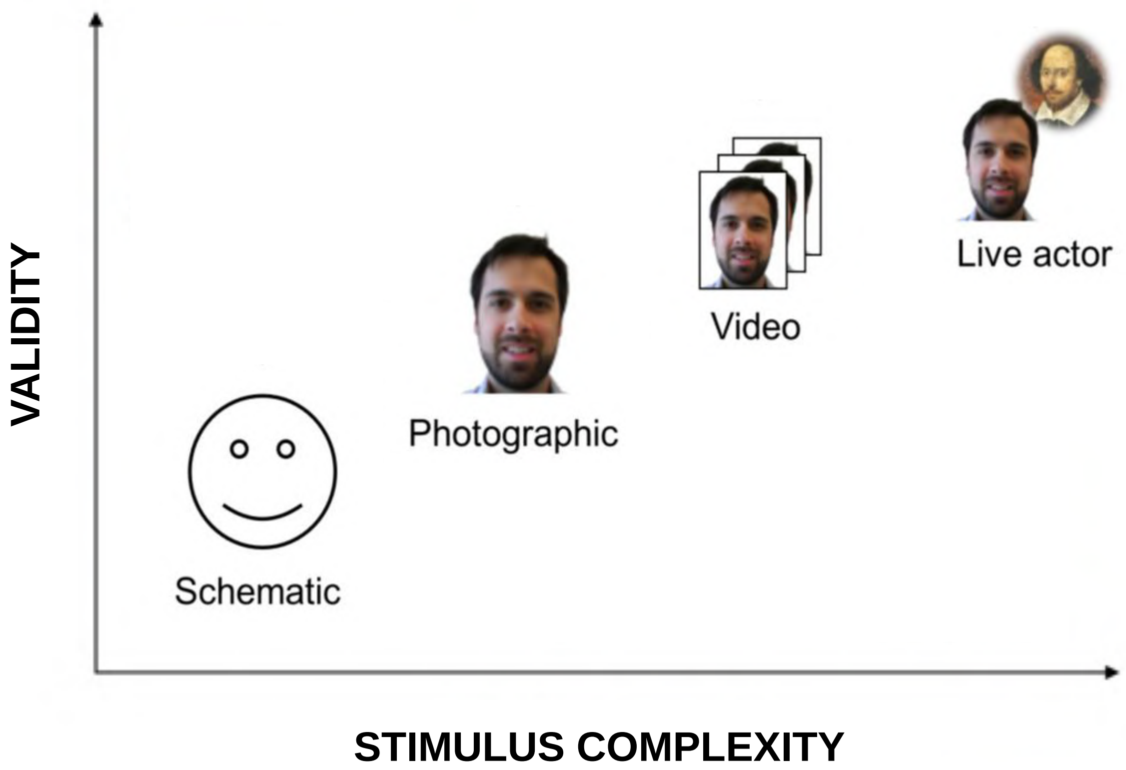
Medawar zone



$$\boldsymbol{payoff} = f(\boldsymbol{ecological\ validity}, \boldsymbol{model\ interpretability})$$

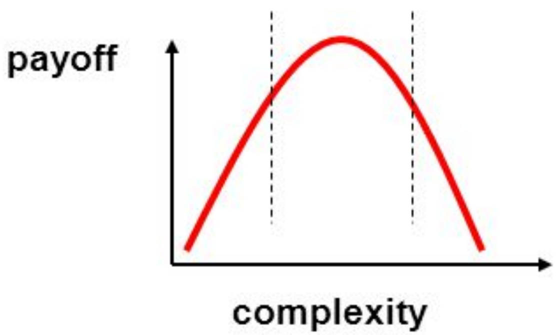


$$payoff = f(ecological\ validity, model\ interpretability)$$

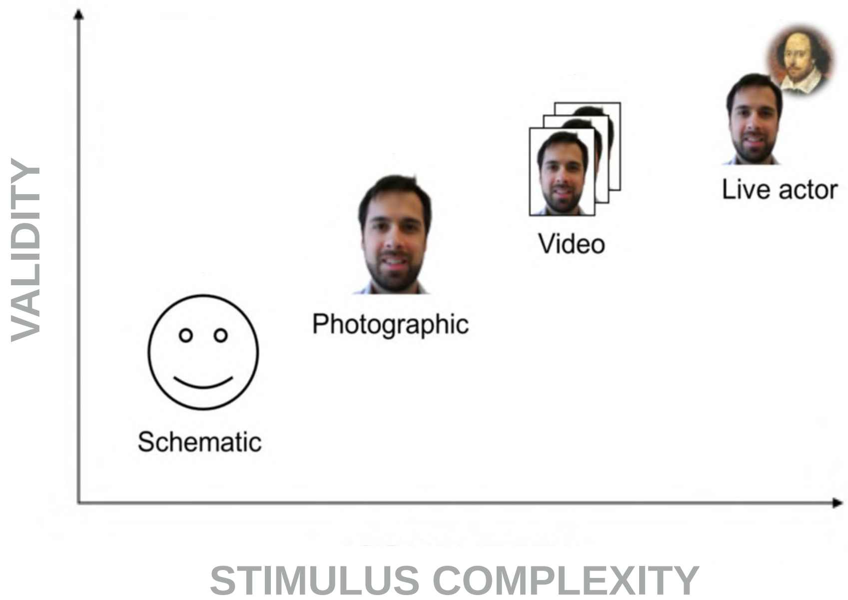


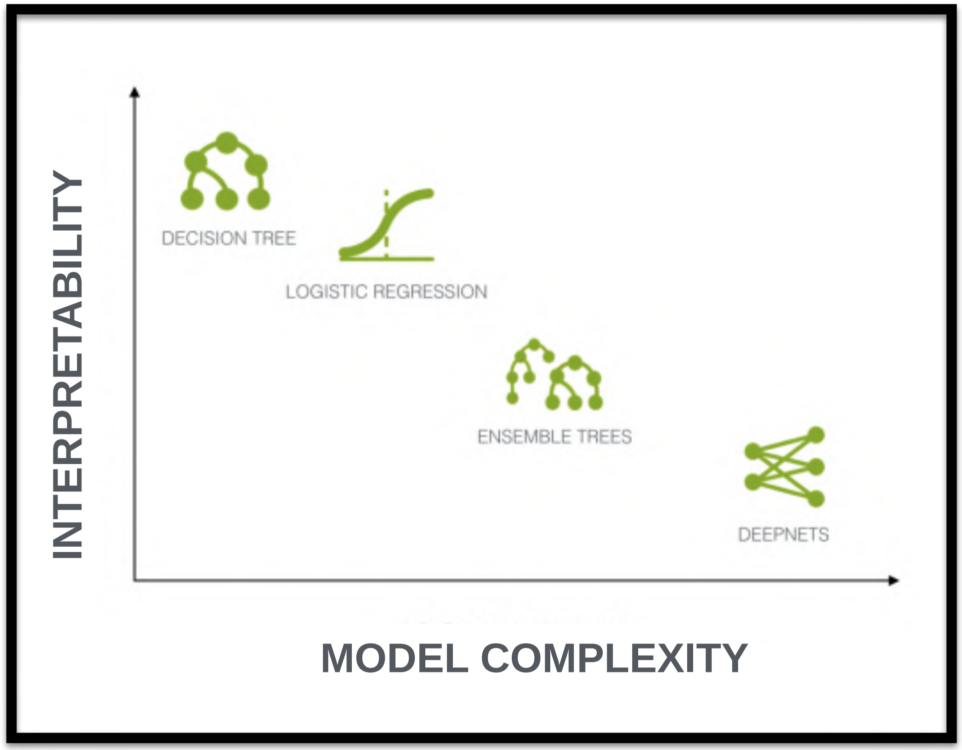
controlled naturalistic

Medawar zone

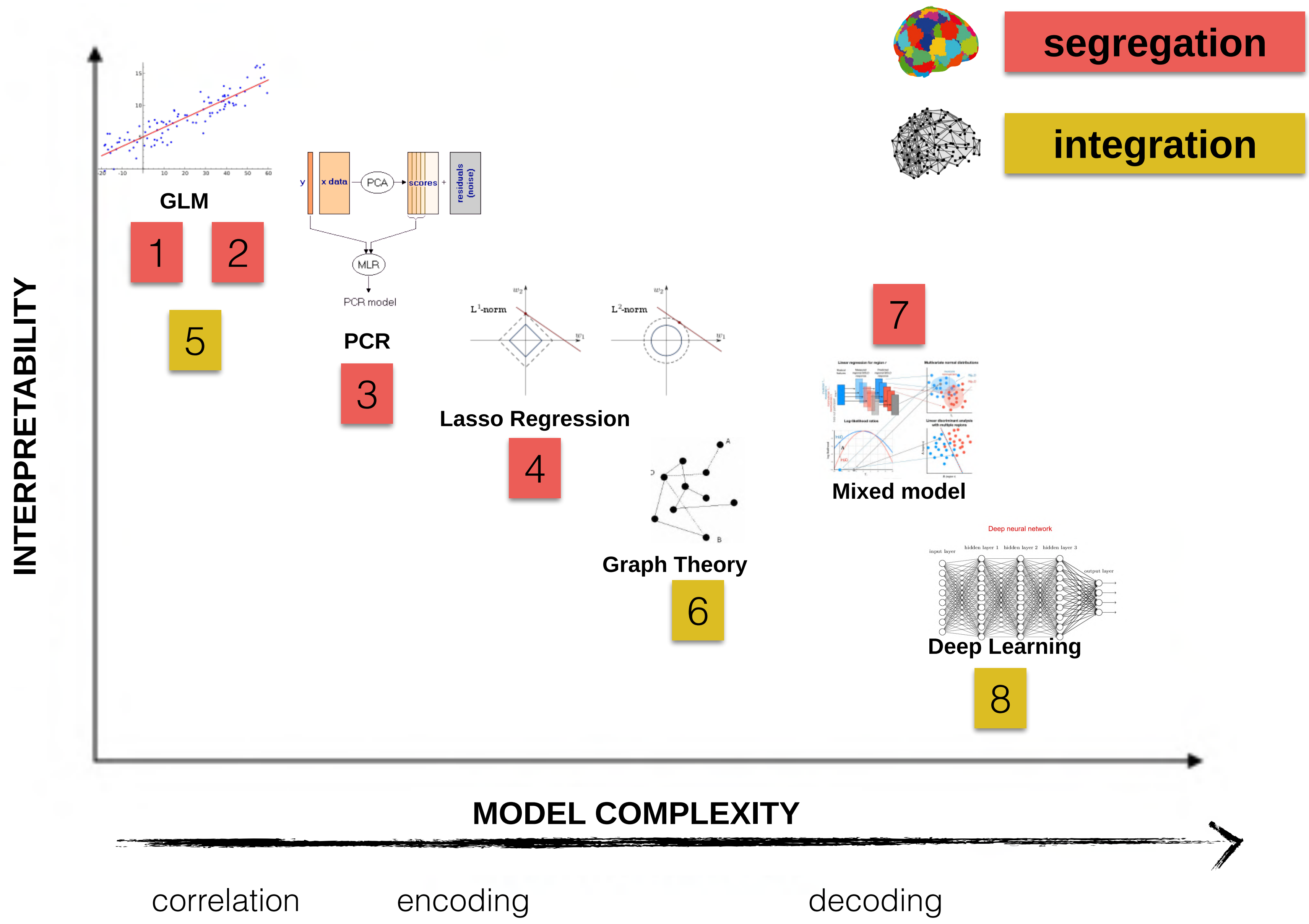


$$payoff = f(ecological\ validity, model\ interpretability)$$



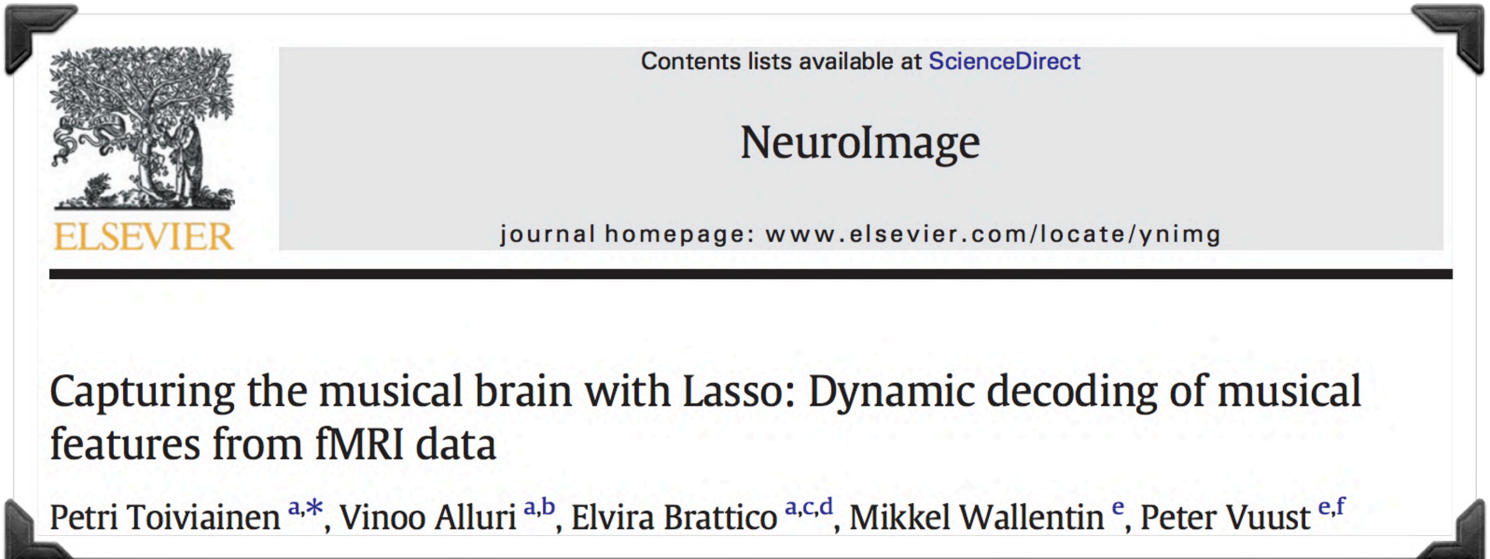


Interpretability vs Model Complexity



How accurately can musical features be decoded from fMRI data?
Which brain areas contribute to prediction?

Study 4: Reading the musical brain



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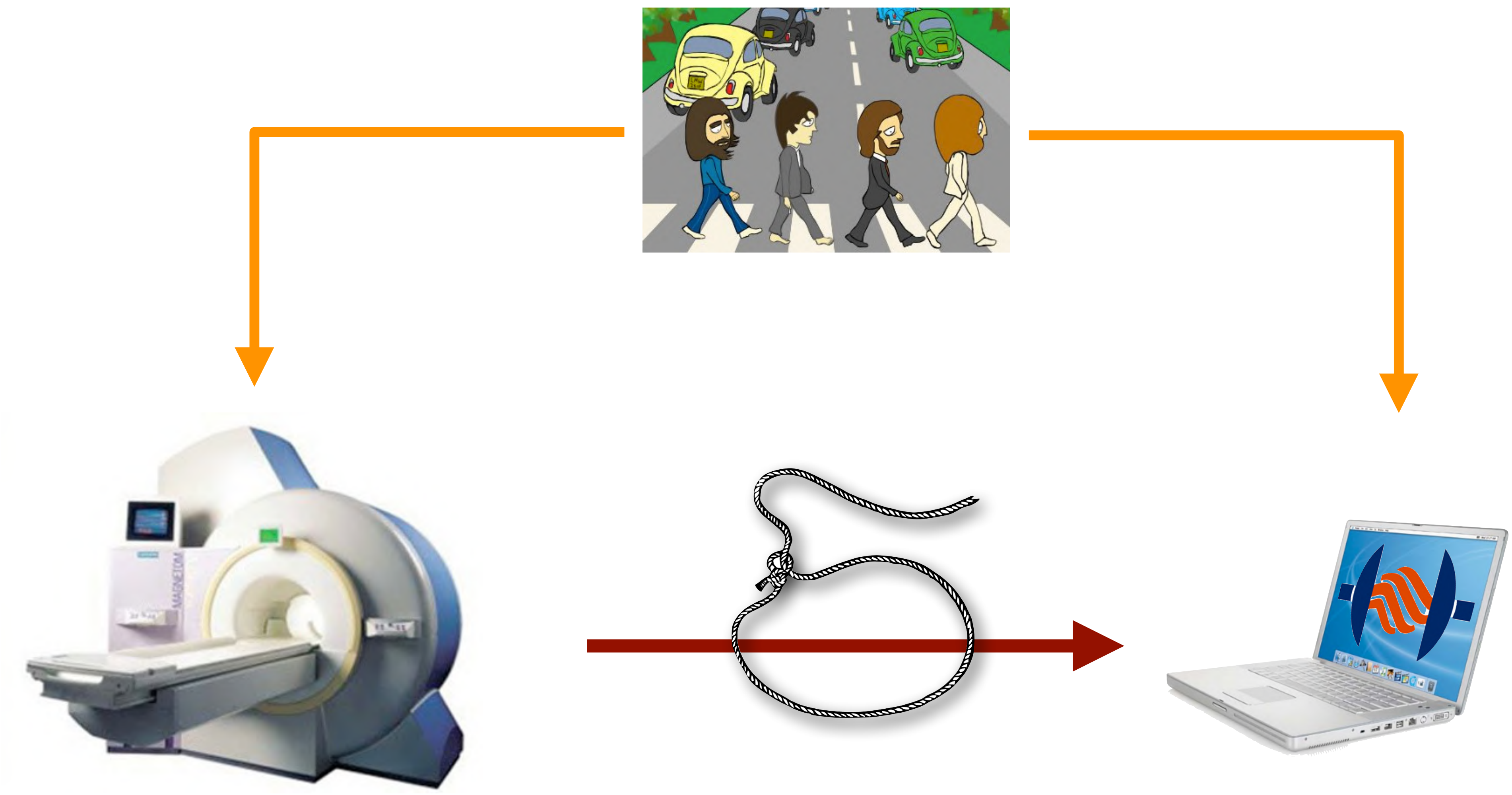
journal homepage: www.elsevier.com/locate/ynimg

Capturing the musical brain with Lasso: Dynamic decoding of musical features from fMRI data

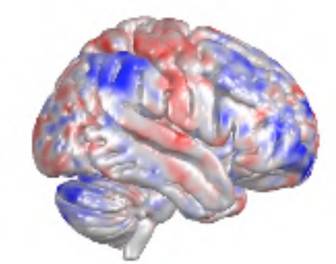
Petri Toiviainen [a,*], Vinoo Alluri [a,b], Elvira Brattico [a,c,d], Mikkel Wallentin [e], Peter Vuust [e,f]

Decoding the Brain on Beatles



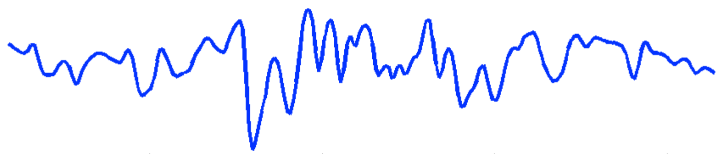
Overfitting Problem

fMRI data



machine learning

feature data



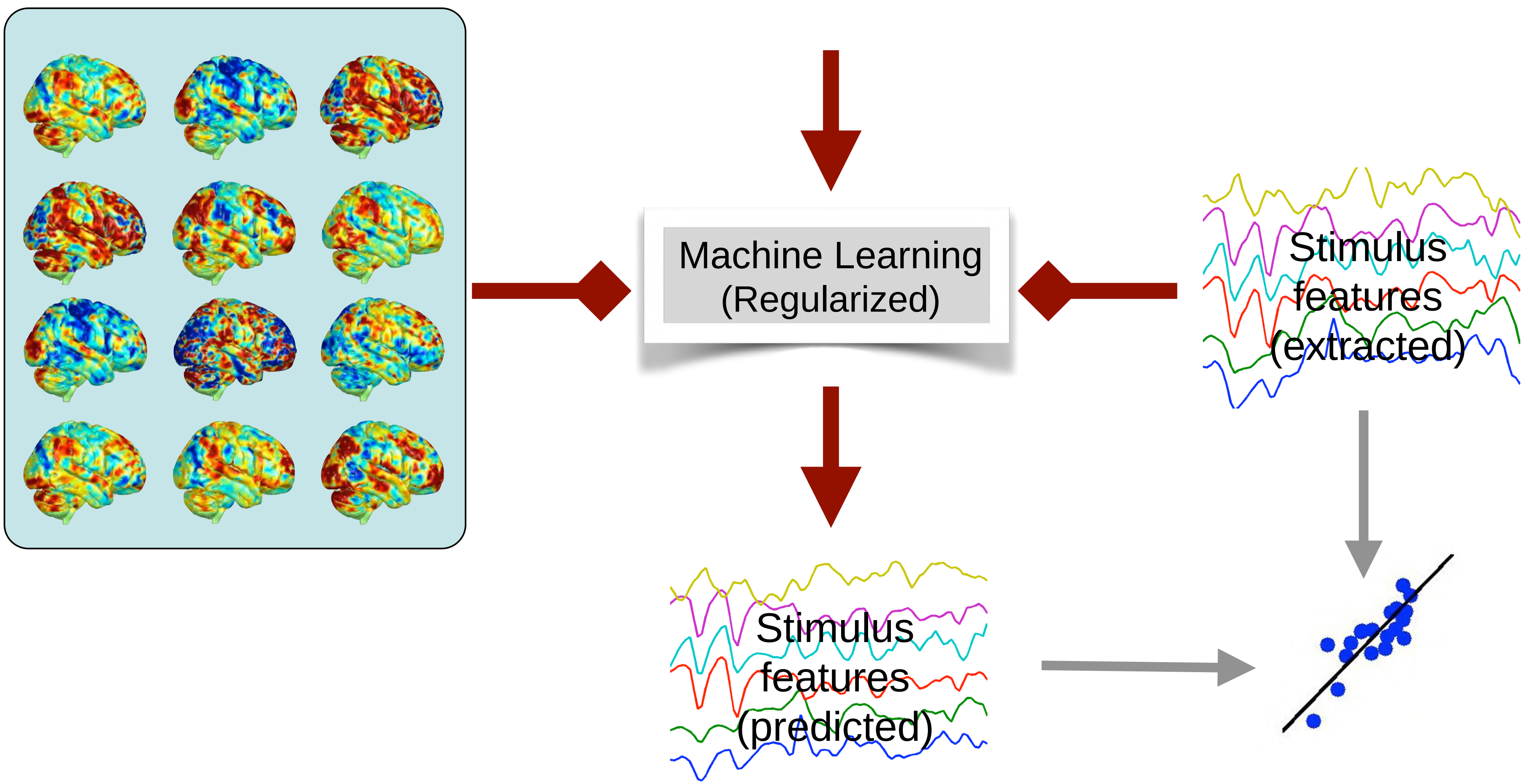
~200.000 voxels
~500 time points

Solutions:
- dimensionality reduction
- regularization
- cross-validation

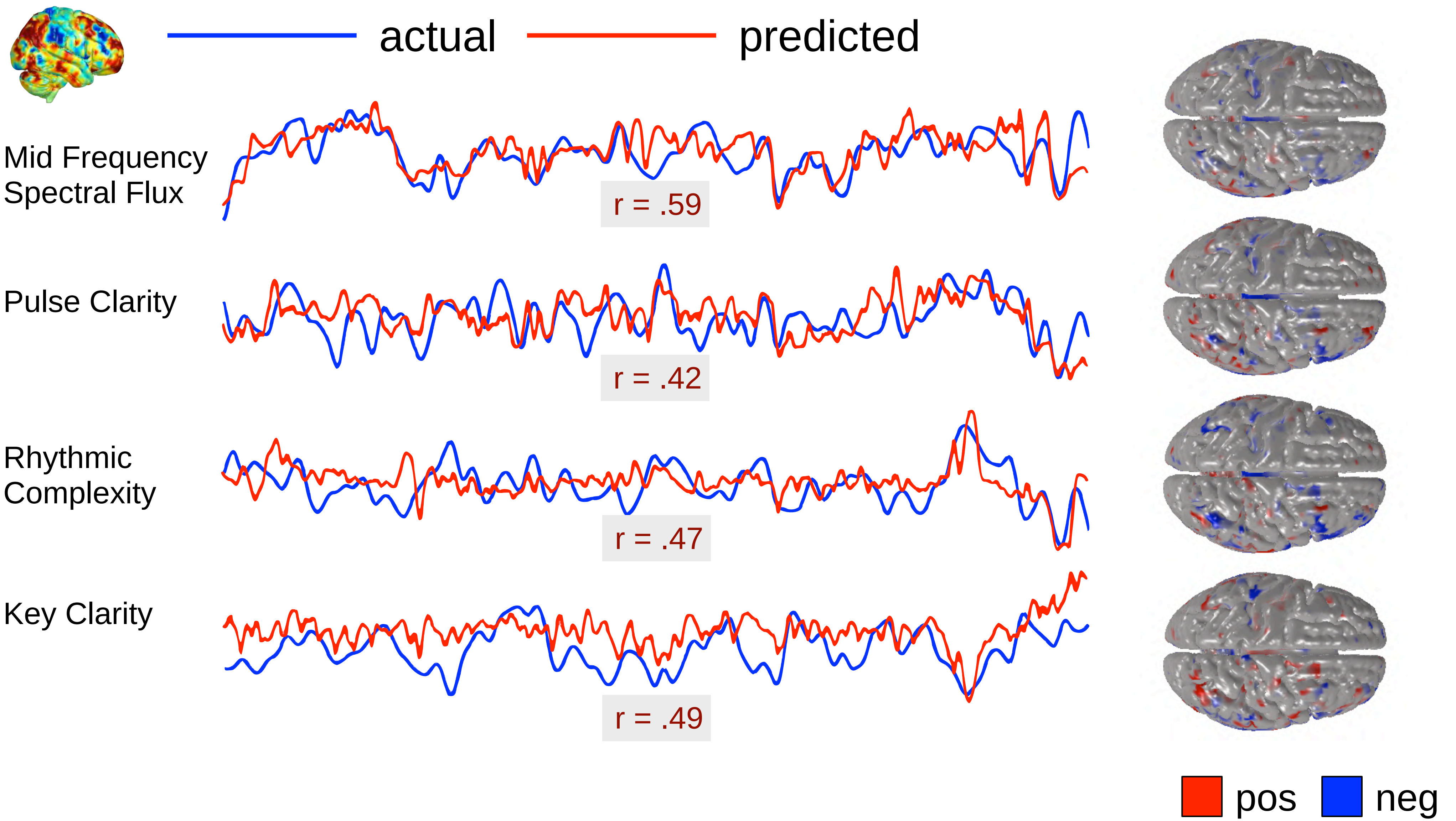
Decoding Model

	Model selection	Find optimal dimensionality reduction and regularization parameters
Cross-validation	Leave one out	
Regularization	LASSO regression	
Dimensionality reduction	PCA	
	Voxel selection	Mean inter-subject correlation thresholding

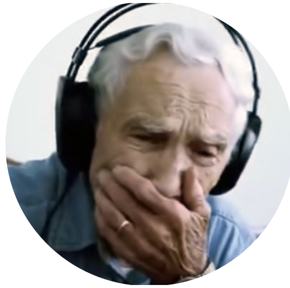
Decoding Musical Features from fMRI



Decoding Musical Features (Example)



5

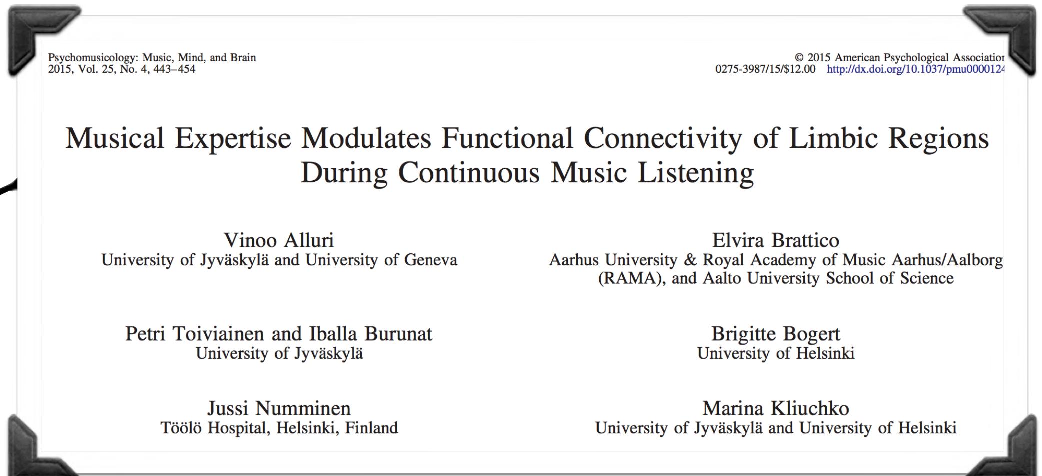


integration

variance

Which brain regions are more connected to emotional hubs?
How does musical training modulate these connections?

Study 5: Effect of musical expertise on limbic region connectivity



Psychomusicology: Music, Mind, and Brain
2015, Vol. 25, No. 4, 443–454

0275-3987/15/$12.00 http://dx.doi.org/10.1037/pmu000012

Musical Expertise Modulates Functional Connectivity of Limbic Regions During Continuous Music Listening

Vinoo Alluri
University of Jyväskylä and University of Geneva

Elvira Brattico
Aarhus University & Royal Academy of Music Aarhus/Aalborg (RAMA), and Aalto University School of Science

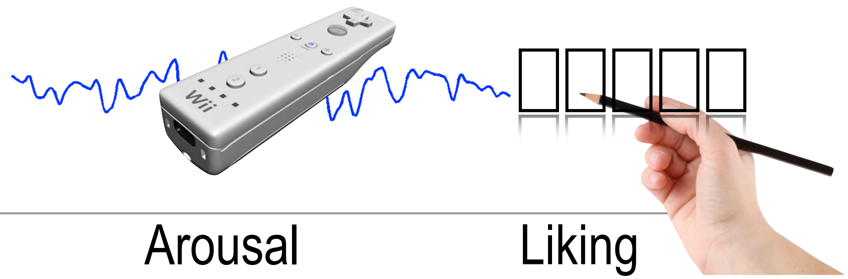
Petri Toiviainen and Iballa Burunat
University of Jyväskylä

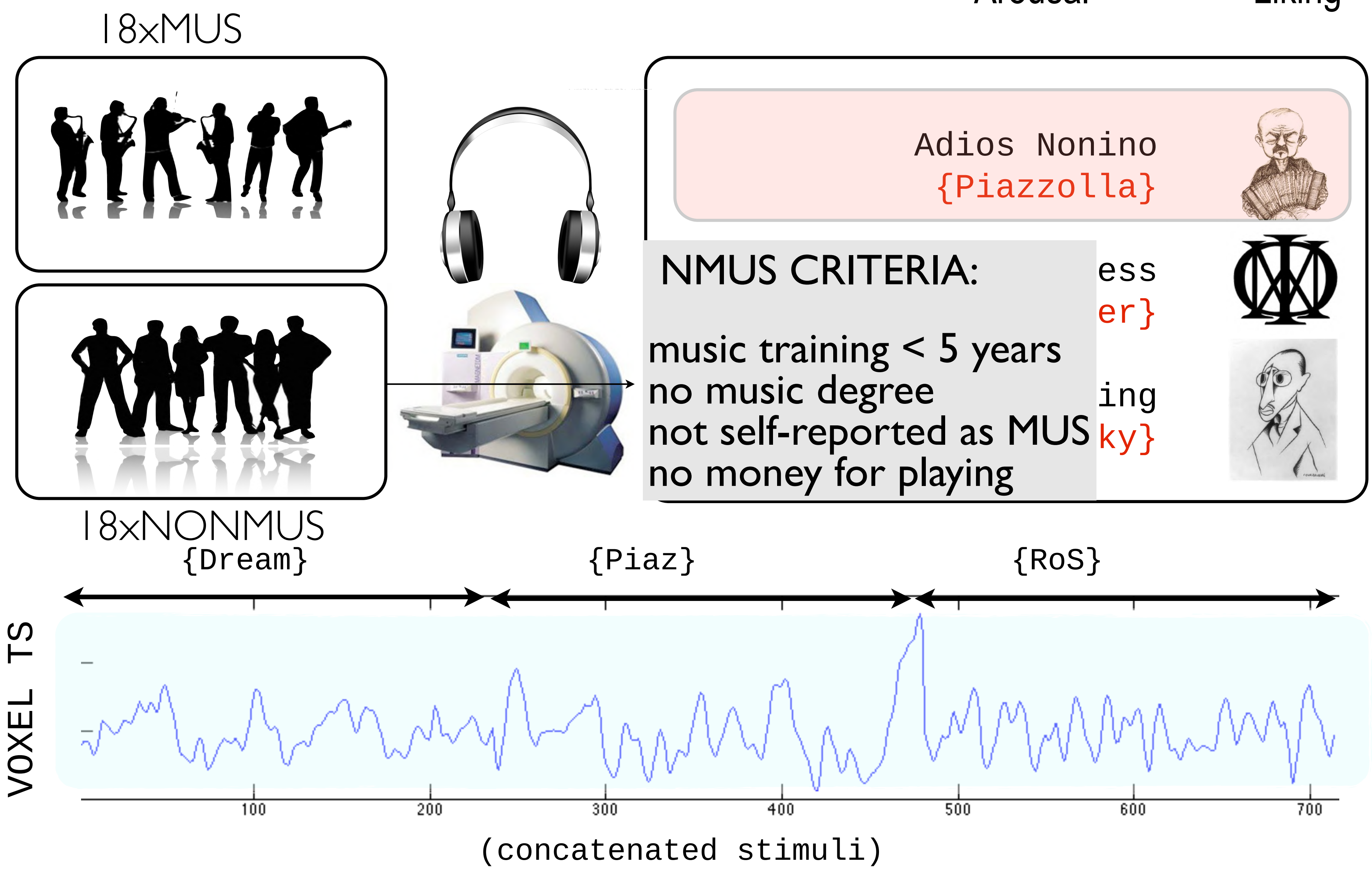
Brigitte Bogert
University of Helsinki

Jussi Numminen
Töölö Hospital, Helsinki, Finland

Marina Kliuchko
University of Jyväskylä and University of Helsinki

Experimental Setting





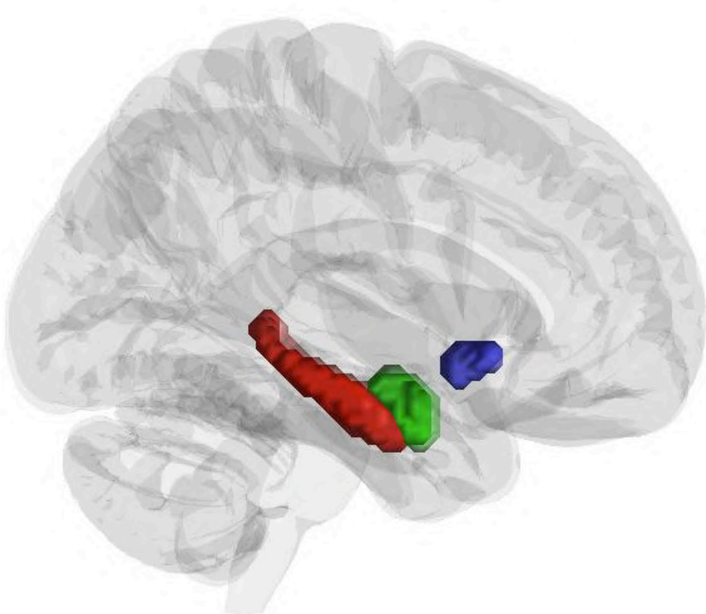
Meta-Analysis

Koelsch, S. (2014) *Nat.Rev.Neu*

Nucleus accumbens

Amygdala

Hippocampus



Seed-based Connectivity

- functional connectivity between seed region and other regions

Results

- greater & wider connectivity in musicians

- increased coupling between areas that process musical emotions with areas that process motor commands

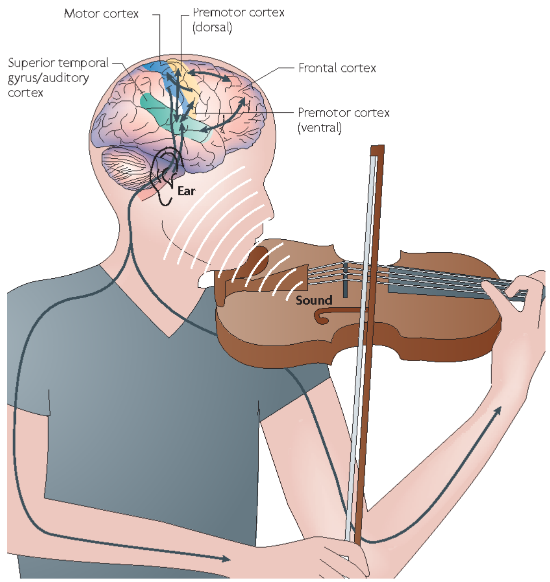


Figure 1 | **Auditory–motor interactions during musical performance.** This

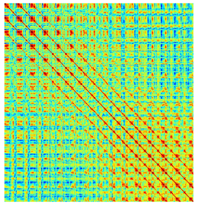
6

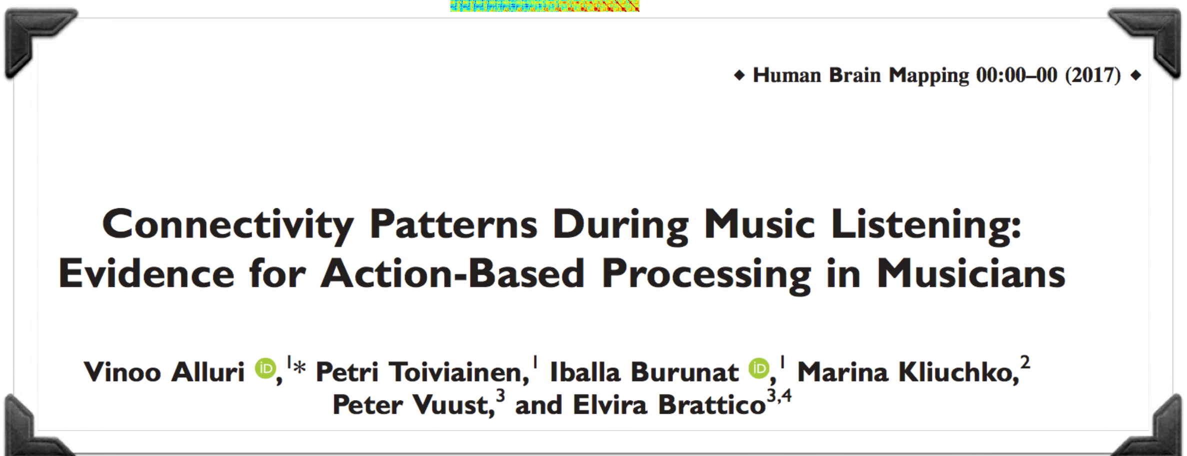
integration

Where do “hubs” emerge in the brain while listening to music?

How do musicians and non-musicians differ in their functional connectivity patterns during continuous music listening?

Study 6. Effect of musical training on full-brain connectivity: a graph-theoretical approach



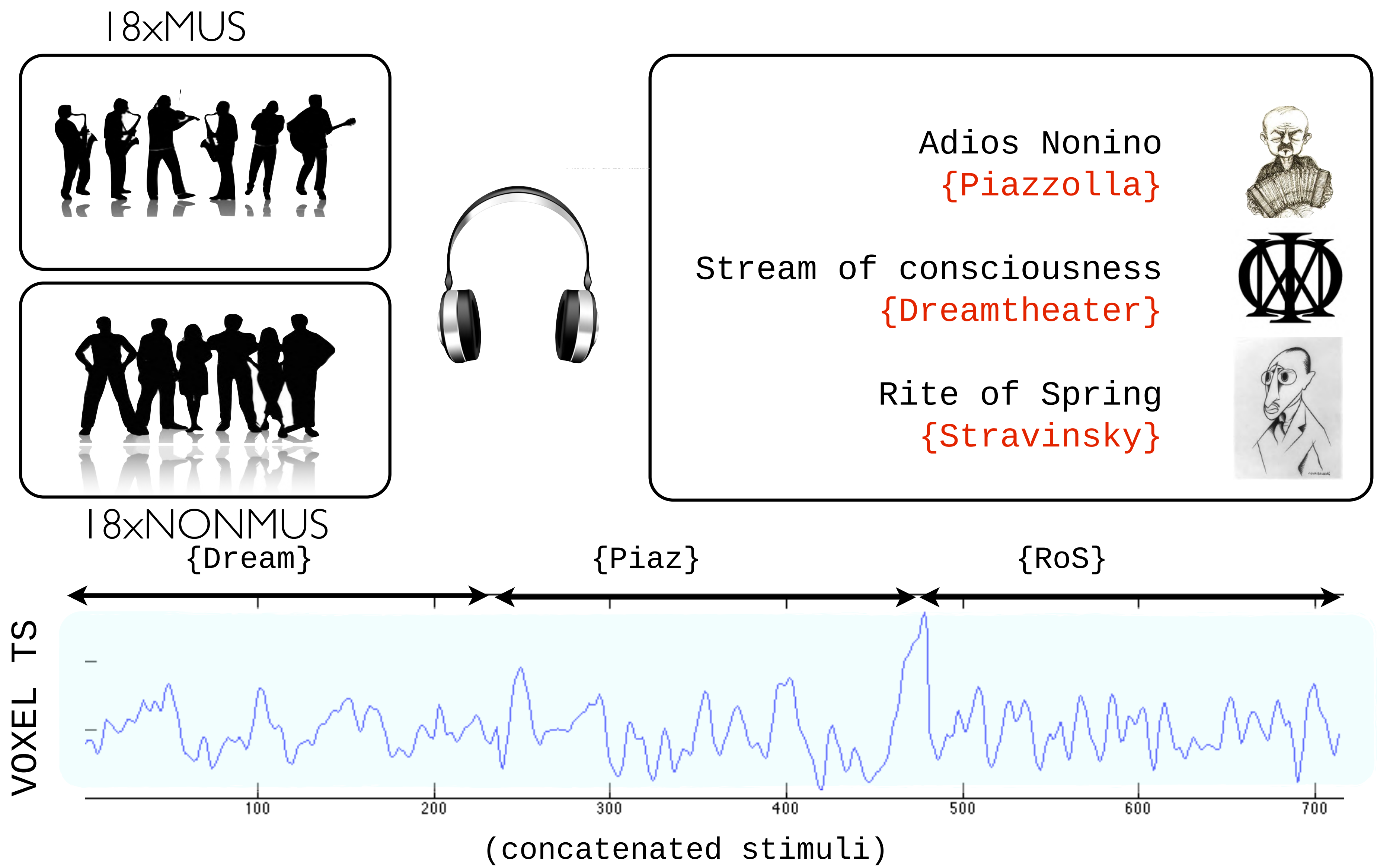


◆ Human Brain Mapping 00:00–00 (2017) ◆

Connectivity Patterns During Music Listening: Evidence for Action-Based Processing in Musicians

Vinoo Alluri,[1,*] Petri Toiviainen,[1] Iballa Burunat,[1] Marina Kliuchko,[2] Peter Vuust,[3] and Elvira Brattico[3,4]

Experimental Setting



Graph-theoretical analysis

- voxel-by-voxel correlation matrix
- thresholding -> adjacency matrix
- “hubness”/integration measure - *node degree*

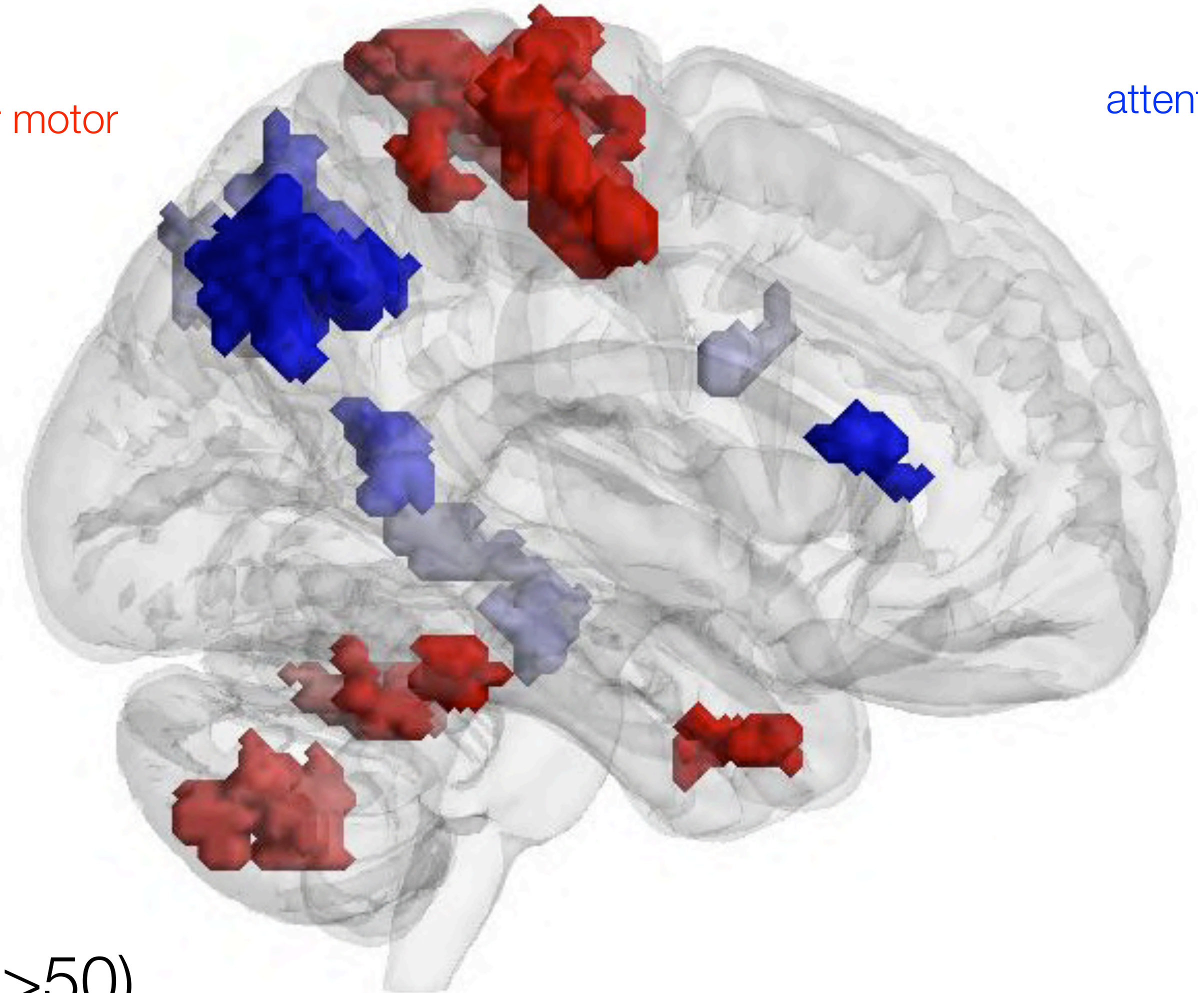
Results | node degree

mus > nonmus

cerebrocerebellar motor regions

nonmus > mus

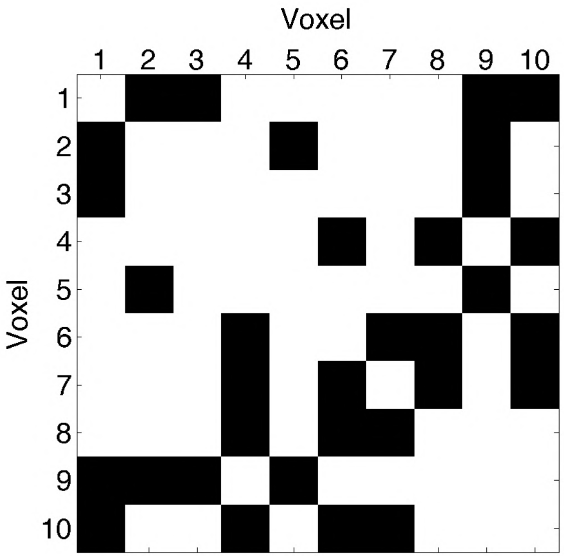
attention networks, sensory processing

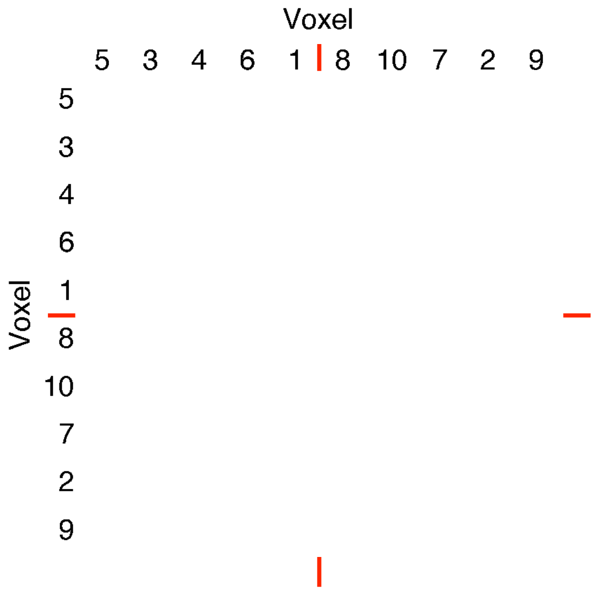


(p<.01, CS>50)

community analysis – spectral graph partitioning (Q-Cut)

- identification of groups of nodes that are more connected to each other than to other groups



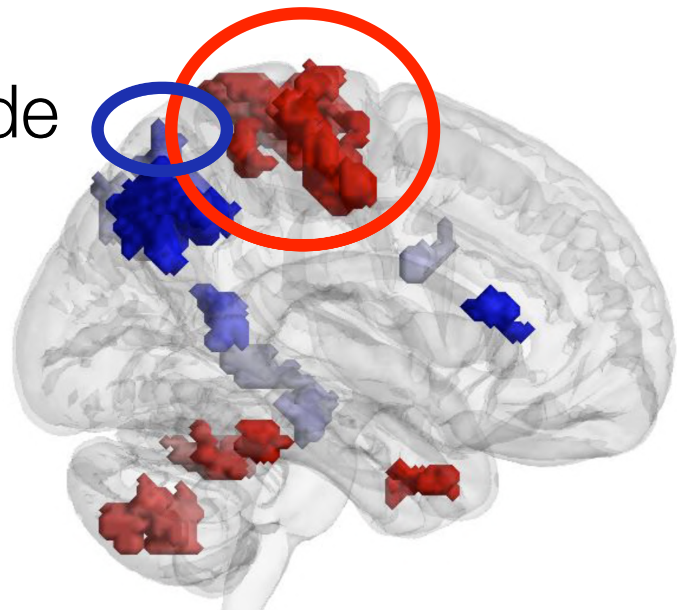


Community analysis – group-level consistency

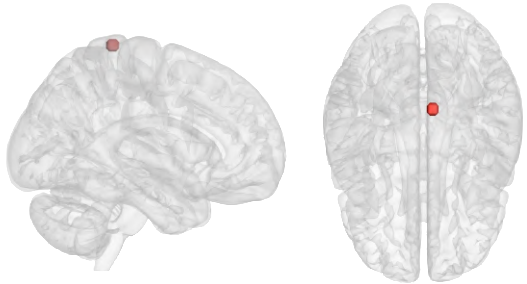
- identification of groups of nodes that are more connected to each other than to other groups
  - *Q-cut*: a combination of spectral graph partitioning and local search to optimize the modularity measure
- group-level probability of belonging to the same community with a given seed

➡ seeds selected based on maximal node degree differences between groups

- **sensorimotor seed (MUS)**
- **precuneus seed (NMUS)**



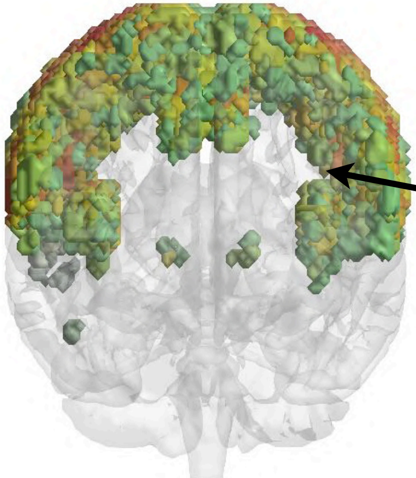
Results | sensorimotor seed



MUS

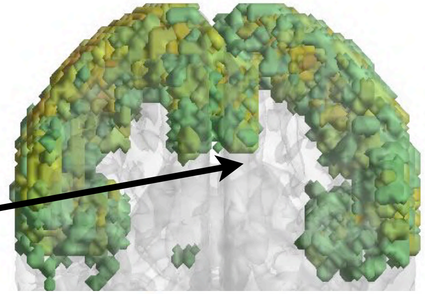
inclusivity per group

NONMUS



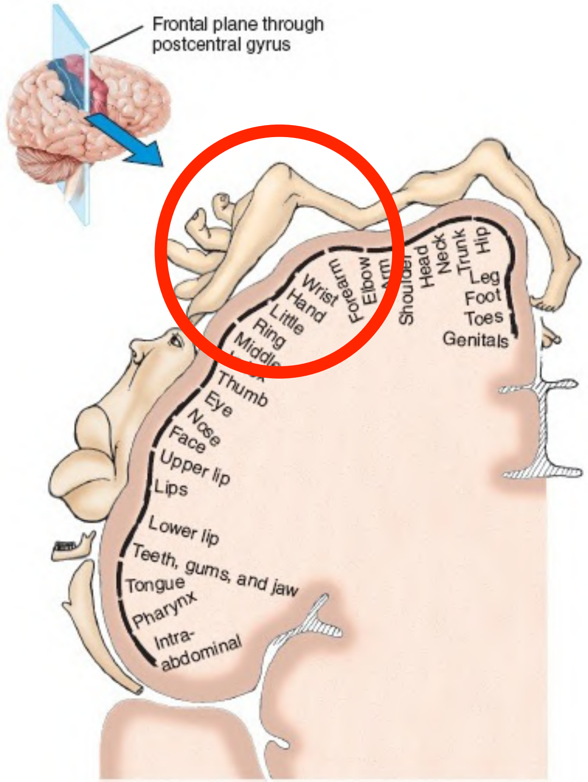
1

PMC, SMA
somatosensory

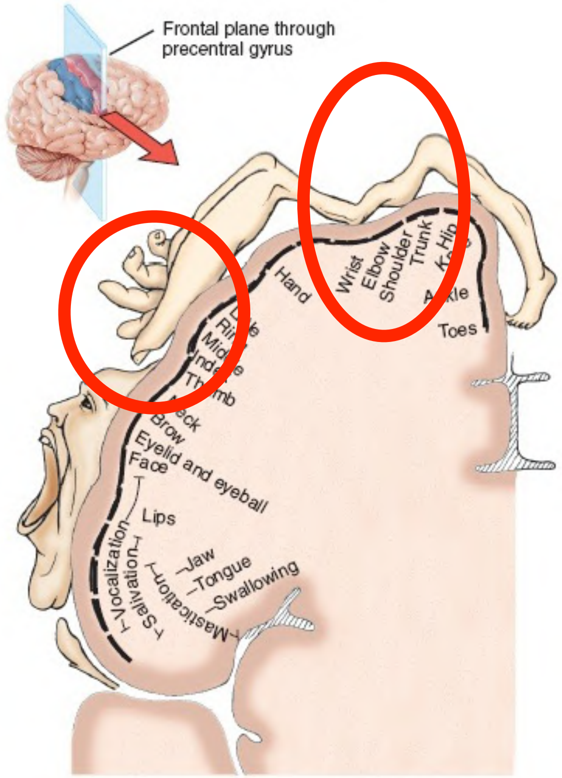


MUS>NONMUS

in

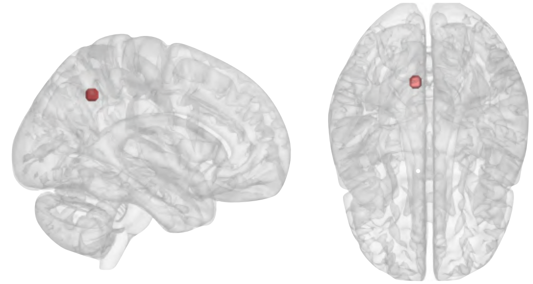


(a) Frontal section of primary somatosensory area in right cerebral hemisphere

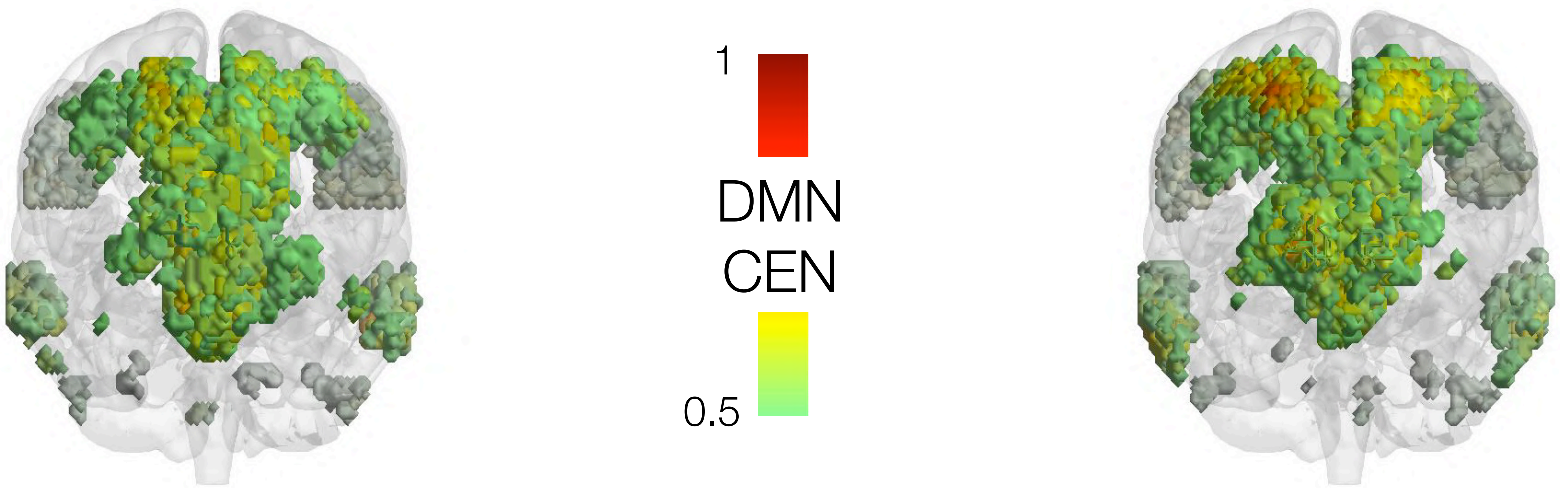


(b) Frontal section of primary motor area in right cerebral hemisphere

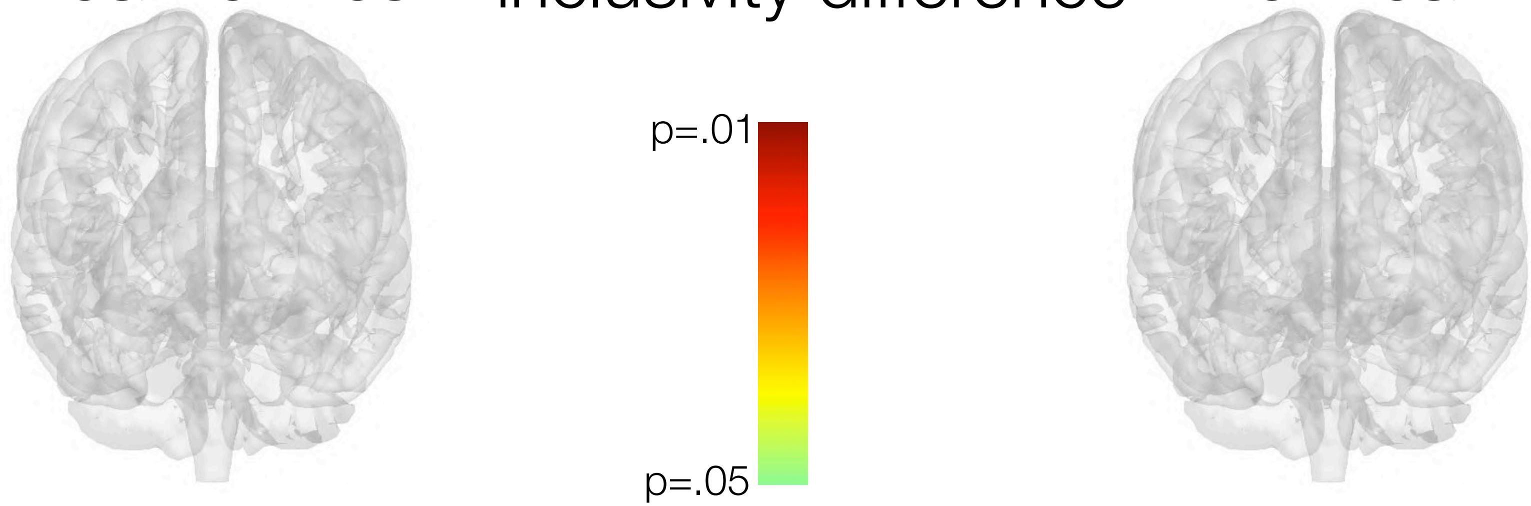
Results | precuneus seed



inclusivity per group

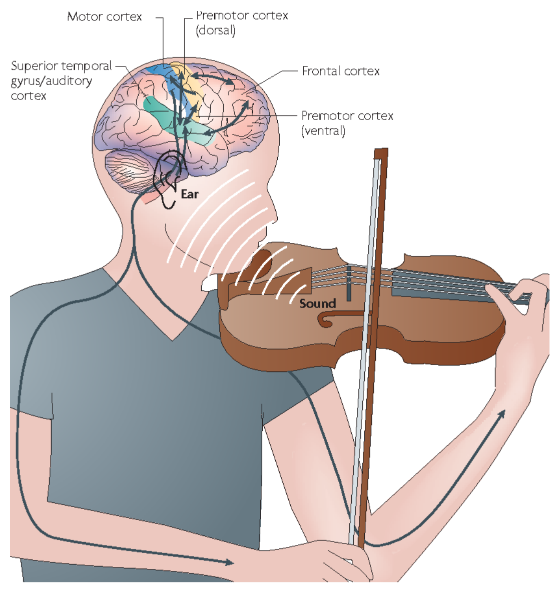


inclusivity difference



Results

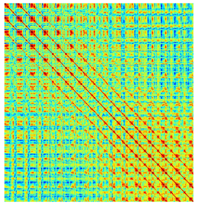
- action hubs (mus) vs attention-oriented hubs (nmus)

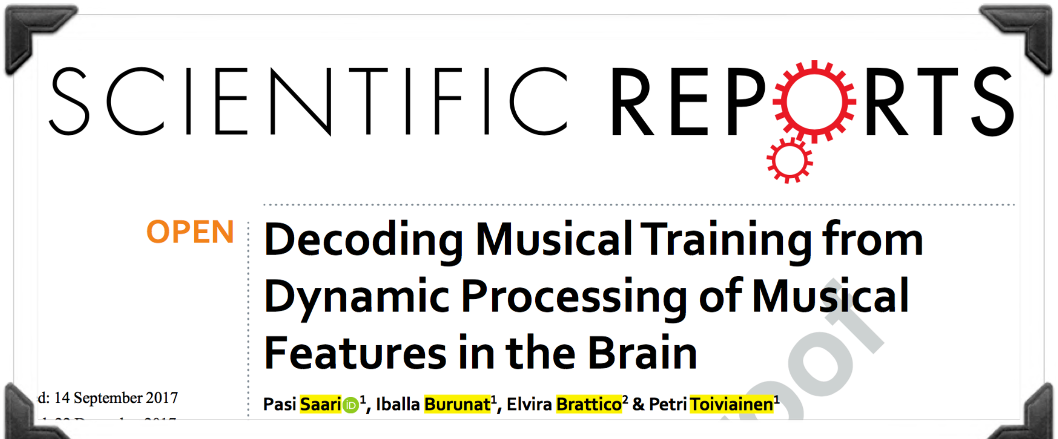


- more consistent community structure in movement- and touch-related regions in musicians

Can musicianship being listened to be predicted from fMRI data?
Which brain regions provide the highest classification rate?

Study 7. To be a musician or not to be





SCIENTIFIC REPORTS

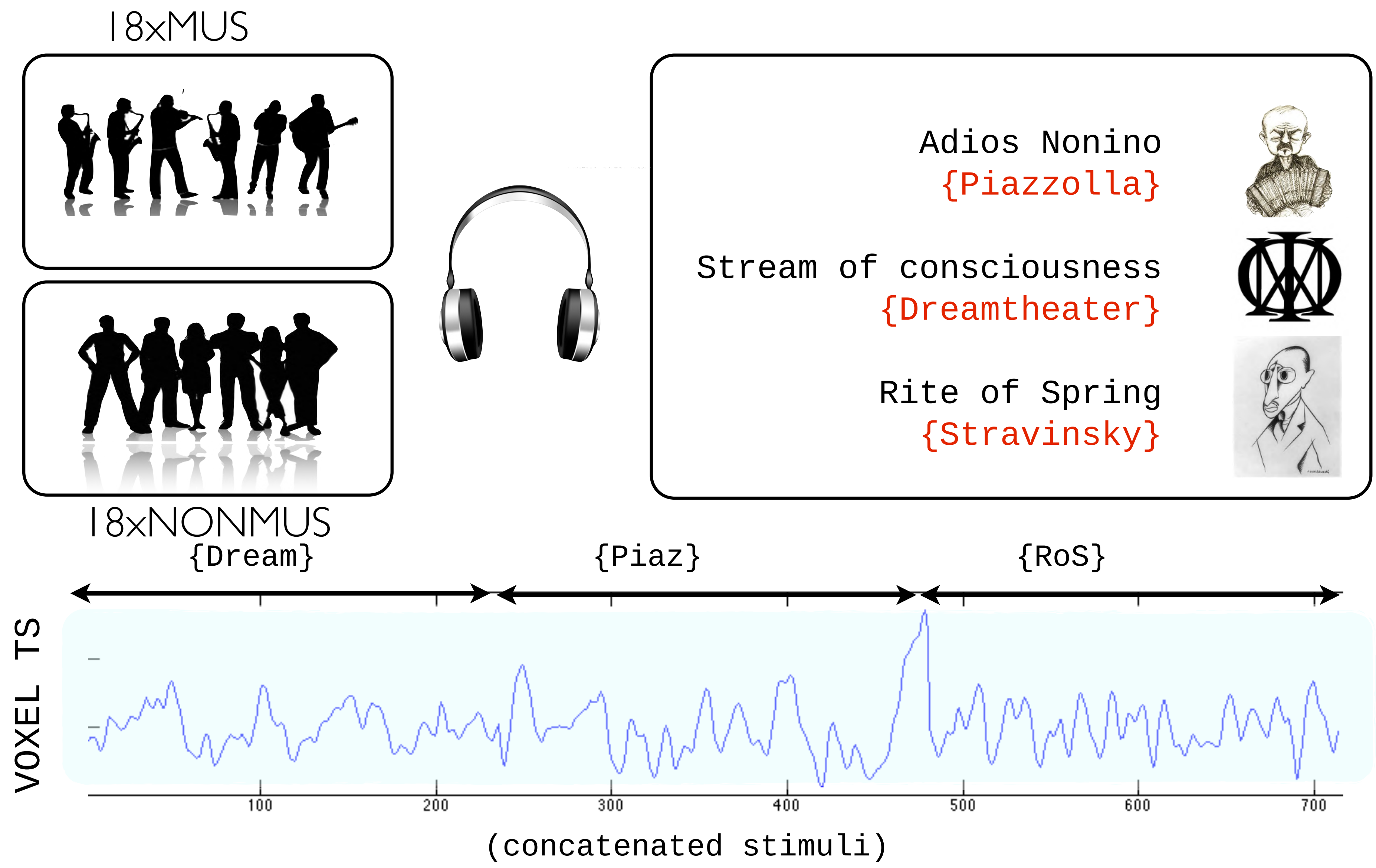
OPEN

Decoding Musical Training from Dynamic Processing of Musical Features in the Brain

d: 14 September 2017

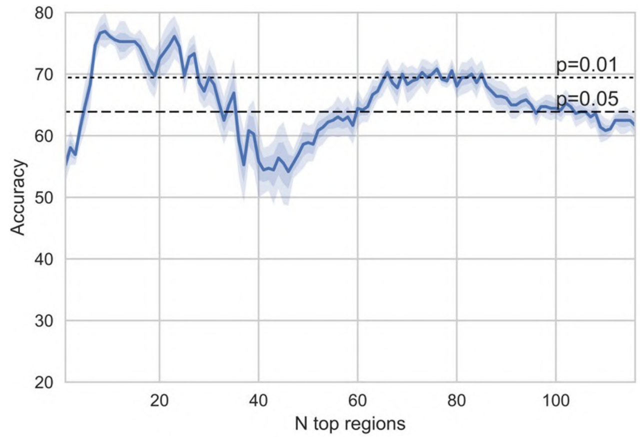
Pasi Saari[1], Iballa Burunat[1], Elvira Brattico[2] & Petri Toiviainen[1]

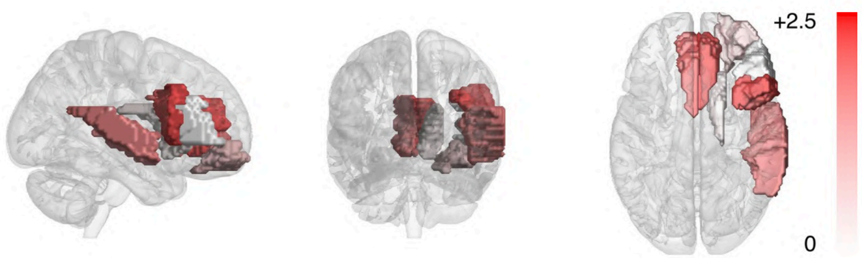
Experimental Setting



Results

- max. classification accuracy of 77% with a combination of 9 regions
- right lateralization
- **cons**:
  - oversimplification
    - neglects within-region functionality
    - neglects across-region functionality
  - musical training but not musicianship

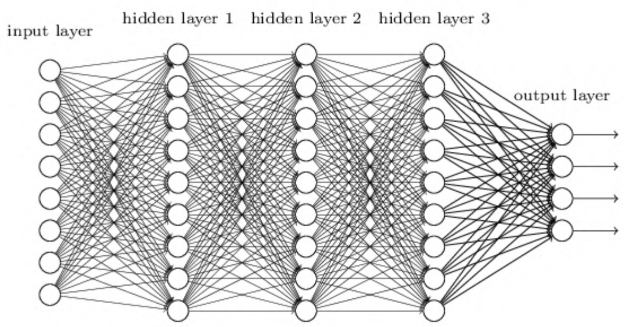




Can musicianship being listened to be predicted from fMRI data? Which brain regions provide the highest classification rate?

Study 8. To be a musician or not to be

Deep neural network



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Experimental Setting

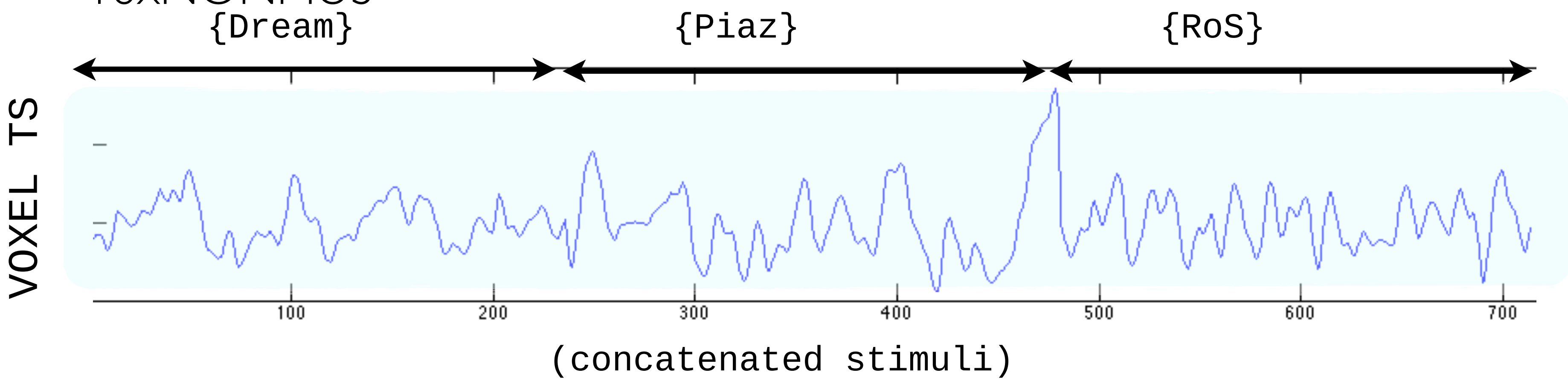
18xMUS

18xNONMUS

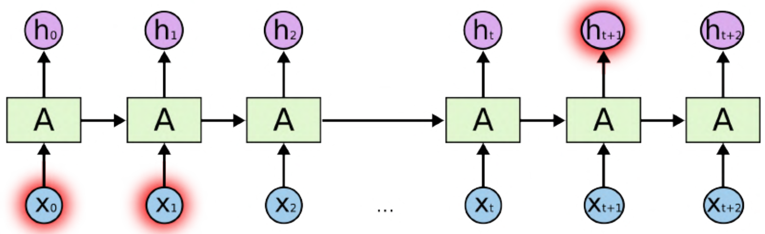
Adios Nonino
{Piazzolla}

Stream of consciousness
{Dreamtheater}

Rite of Spring
{Stravinsky}



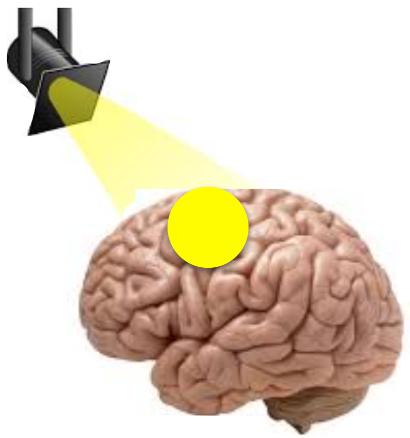
Method



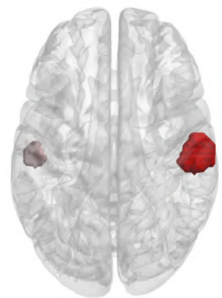
leave-one out
n-fold
crossvalidation

LSTM netork

Voxel selection

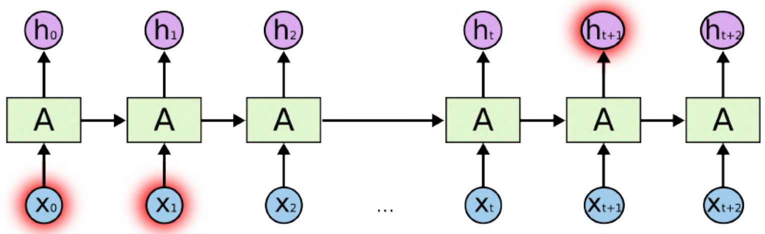


Searchlight



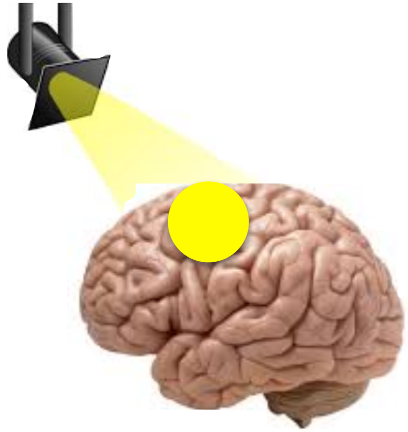
Mean inter-subject
correlation thresholding

Preliminary Results



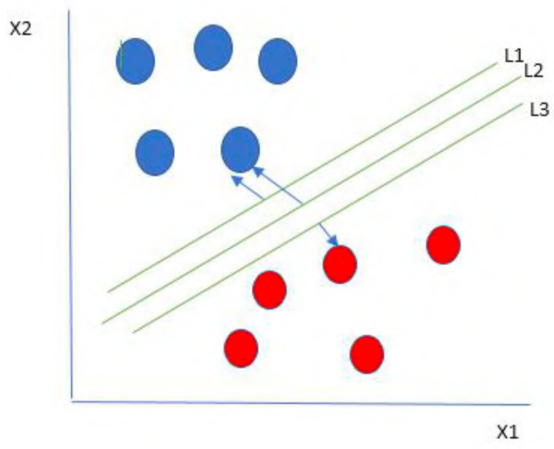
- mean ISC
  - cross-validation accuracy of 59%
  - 2% increase from “mixed model” with fewer number of voxels

- searchlight
  - in progress (NOT)



Can the individual be predicted from fMRI data?
Which brain regions provide significantly to the prediction?

Study 9. Decoding individuals



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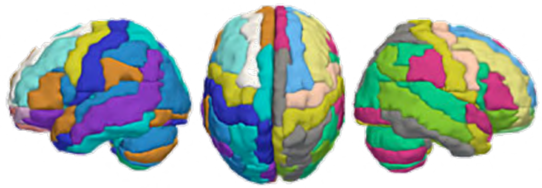
Decoding individuals



- AAL parcellation (116 ROIs)
- HCP dataset:
  - First scanning session for training and second for testing.
- Musical dataset:
  - 50% time points for training and other 50% for testing.
- Leave-one-stimulus-out cross validation

Classification Results

- LDA

	Classification Accuracy					
			Dynamic Analyses			
			Individual Accuracy		Majority Voting	
Data set	Chance	Static Functional Connectivity	CSW	IPS	CSW	IPS
Musical	0.0278	**0.4814**	0.2541	0.3437	0.7129	**0.8148**
HCP 40	0.025	**0.1625**	0.386	0.273	**0.775**	0.45

- MLP

	Classification Accuracy					
			Dynamic Analyses			
			Individual Accuracy		Majority Voting	
Data set	Chance	Static Functional Connectivity	CSW	IPS	CSW	IPS
Musical	0.0278	**0.5**	0.3324	0.5273	0.7778	**1.0**
HCP 40	0.025	**0.3225**	0.4014	0.025	**0.8**	0.025

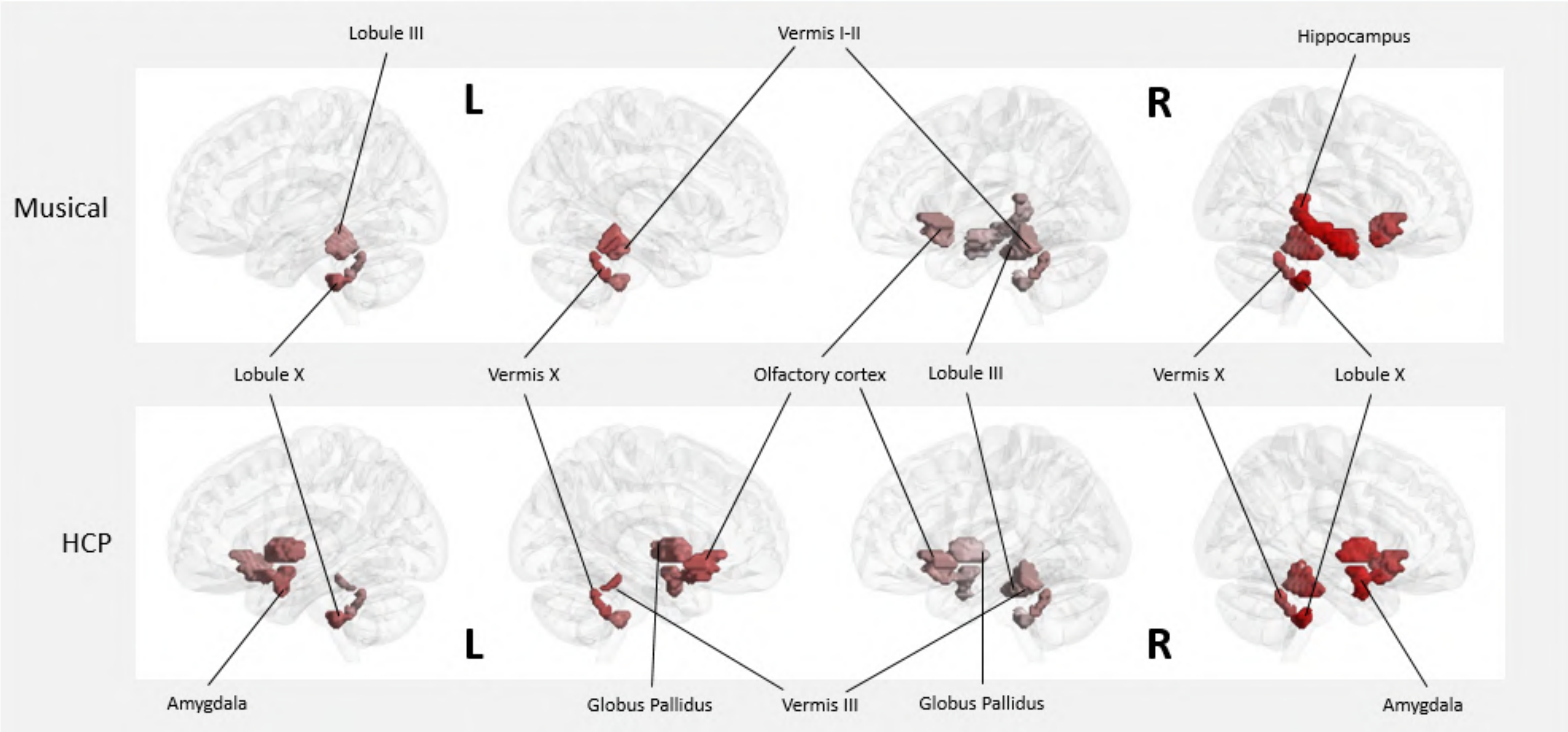
Observations

- Individuals can be identified using their unique brain signatures.
- Dynamic analyses work better than static analyses.
- Perfect accuracy with IPS in Musical dataset.
- Failure of IPS for HCP dataset.
- Reducing feature set works well.
- Importance of homotopic pairs.
- Regions in Cerebellum, Olfactory cortex, and limbic regions are important.

Observations

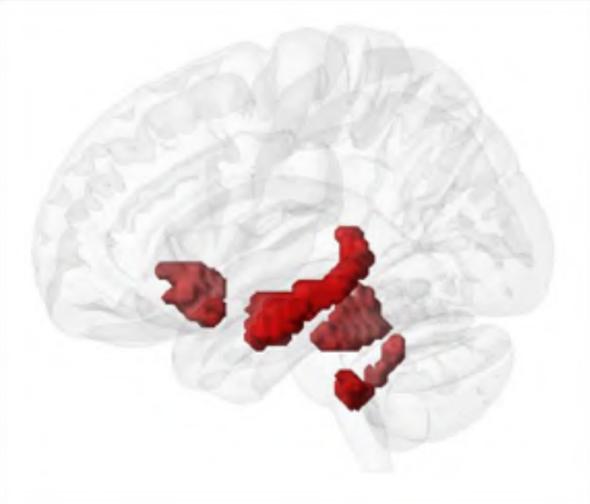
- Best results in naturalistic music-listening paradigm.
- Instantaneous Phase Synchrony analysis works best.
- Linear Support Vector Machine for classification.
- Bandpass filtering is an important preprocessing step.
- Increasing sample size works well.

Region Importance



Region Importance

- Importance of homotopic pairs
- Important regions for identification:
  - Cerebellum
  - Limbic system
  - Olfactory cortex



Can we reconstruct the song from brain responses?

Study 10. Reconstructing the song

PLOS BIOLOGY

OPEN ACCESS PEER-REVIEWED

RESEARCH ARTICLE

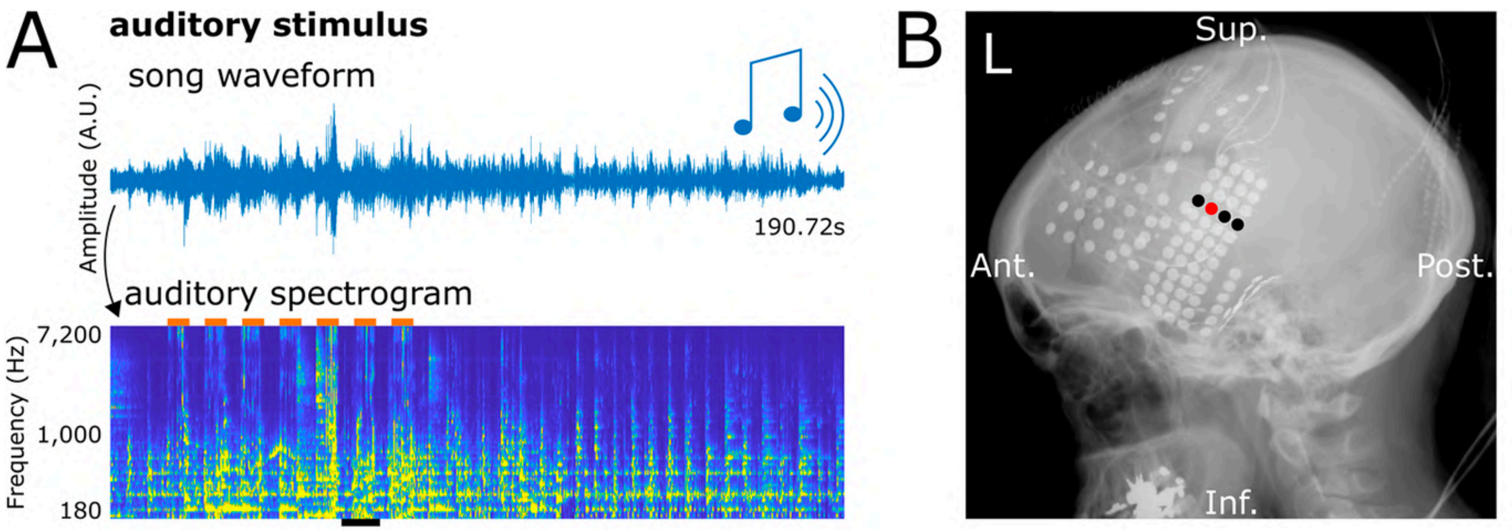
Music can be reconstructed from human auditory cortex activity using nonlinear decoding models

Ludovic Bellier, Anaïs Llorens, Déborah Marciano, Aysegul Gunduz, Gerwin Schalk, Peter Brunner, Robert T. Knight

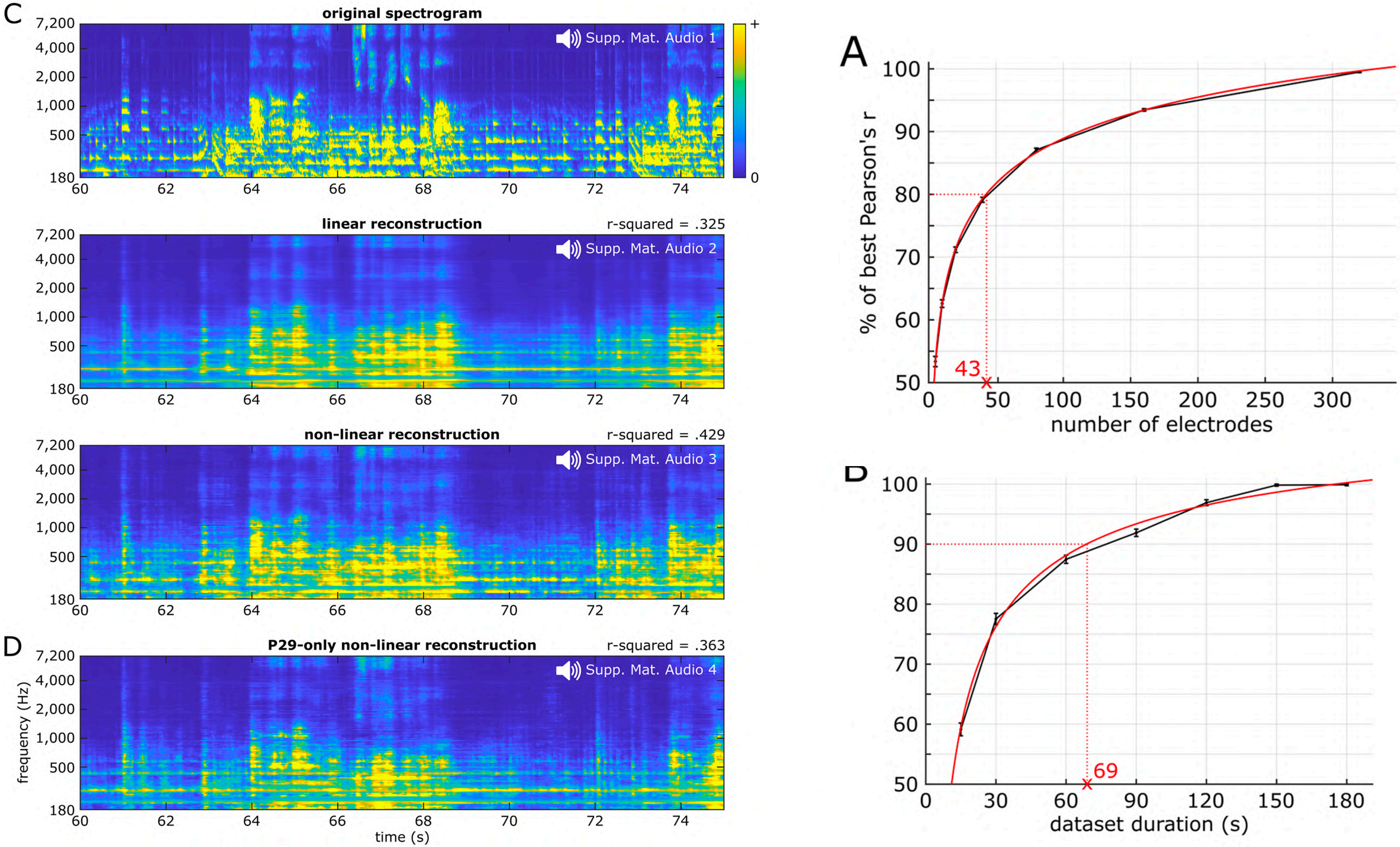
Published: August 15, 2023 • https://doi.org/10.1371/journal.pbio.3002176

Method

- 29 neurosurgical patients
- ~2000 electrodes (ECoG)
- passive listening



Results



C
original spectrogram
Supp. Mat. Audio 1
linear reconstruction
r-squared = .325
Supp. Mat. Audio 2
non-linear reconstruction
r-squared = .429
Supp. Mat. Audio 3
D
P29-only non-linear reconstruction
r-squared = .363
Supp. Mat. Audio 4
frequency (Hz)
time (s)
A
% of best Pearson's r
number of electrodes
43
dataset duration (s)
69

Results

- model type (linear vs non-linear)
  - **non-linear models** provide highest
    - decoding accuracy
    - more detailed decoded spectrogram
    - recognizable song
- electrode density (the number of electrodes used as inputs in decoding models)
  - adding electrodes beyond a certain amount had diminishing returns
- dataset duration
  - 80% of max observed decoding accuracy was achieved in 37 seconds, supporting the feasibility of using predictive modeling approaches in relatively small datasets.

Limitations

- Limitations and future studies
  - extend to other regions
  - include PAC (A1)
  - interindividual variability

SUMMARY

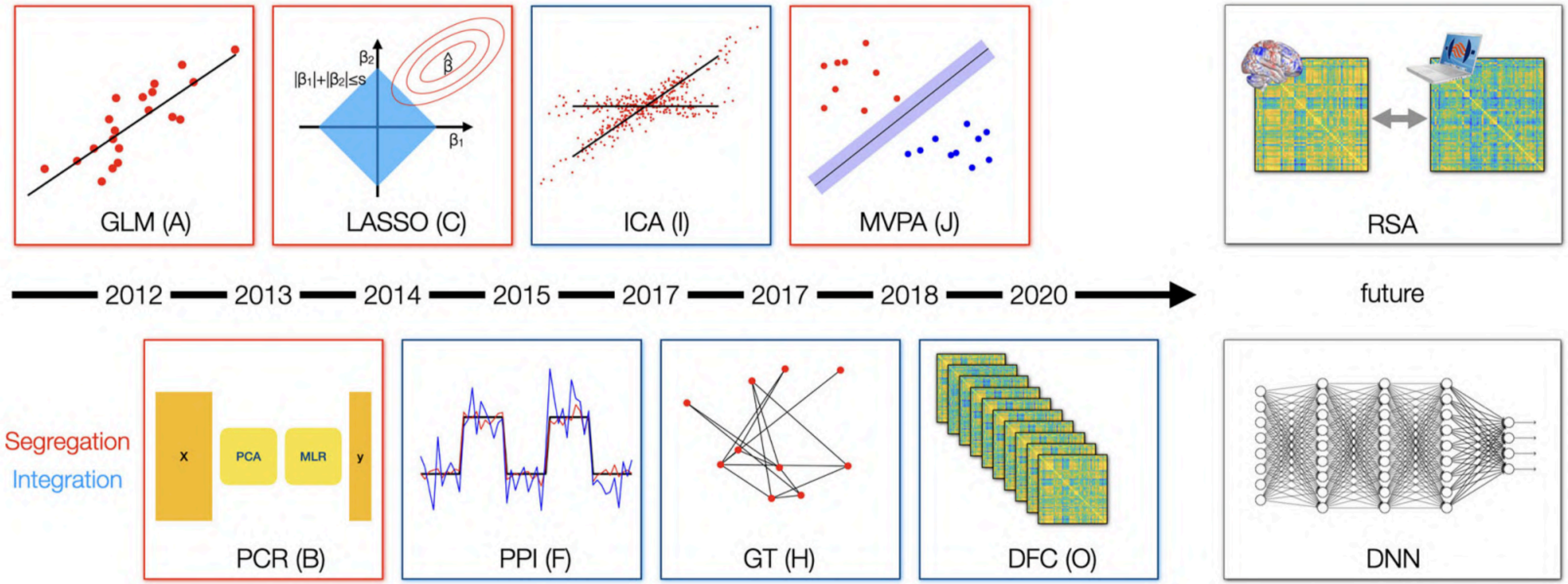
- choice of method based upon approach to brain functioning, interpretability, question at hand
- always a trade-off between complexity, interpretability, generalizability
- growing evidence of the effectiveness of the integration approach to brain functioning
- possible right-hemispheric dominance

SUMMARY

- neuroscience fraught with reliability and replicability issues

- look for converging evidence by using multiple methods

SUMMARY



ANNALS OF THE NEW YORK ACADEMY OF SCIENCES

PERSPECTIVE

The naturalistic paradigm: An approach to studying individual variability in neural underpinnings of music perception

Vinoo Alluri, Petri Toiviainen

First published: 17 October 2023 | https://doi.org/10.1111/nyas.15075 |