
Groove on the brain
Predictive processing of music
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Bassist/composer

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Music In the Brain (MIB)
The Royal Academy of Music
Aarhus/Aalborg

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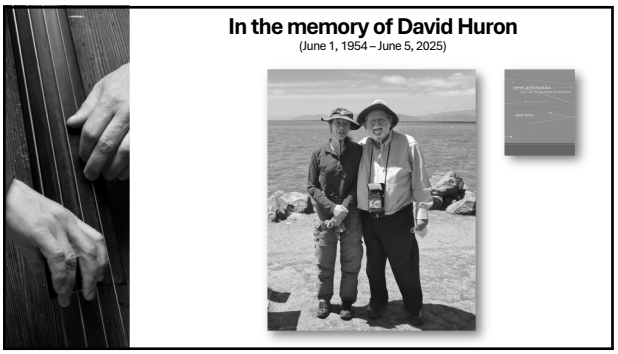
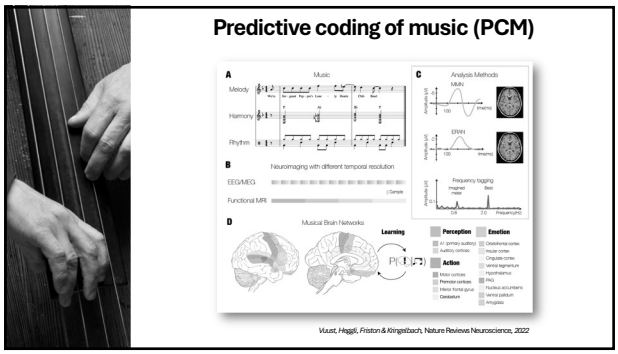

In the memory of David Huron
(June 1, 1954 – June 5, 2025)

3


Predictive coding of music (PCM)
Vuust, Heggli, Friston & Kringelbach, Nature Reviews Neuroscience, 2022

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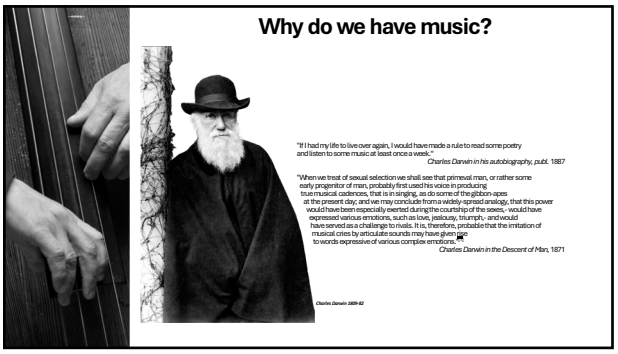
Why do we have music?
"If I had my life to live over again, I would have made a rule to read some poetry and listen to some music at least once a week."
Charles Darwin in his autobiography, publ. 1887
"When we treat of sexual selection we shall see that primeval man, or rather some early progenitor of man, probably first used his voice in producing true musical cadences, that is in singing, as do some of the gibbon-apes at the present day; and we may conclude from a widely-spread analogy, that this power would have been especially exerted during the courtship of the sexes, - would have expressed various emotions, such as love, jealousy, triumph, - and would have served as a challenge to rivals. It is, therefore, probable that the imitation of musical cries by articulate sounds may have given rise to words expressive of various complex emotions."
Charles Darwin in the Descent of Man, 1871
Charles Darwin 1809-82

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Mate Seeking
The Beatles

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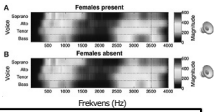
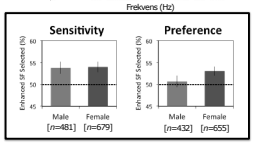
Boys sing differently in the presence of females

St Thomas Choir, Leipzig

The boys strengthen "the singer's formant", when there are girls in the audience





- Males and females are equally sensitive to the difference in sound
- Only females prefer A

Keller, König, & Novembre, 2017 & 2023

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Group coherence

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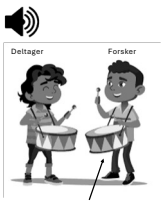
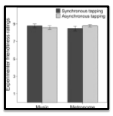
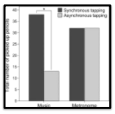
Prosocial behavior and synchronization





How much do you like the researcher?



Kokal 2011
Stupacher et al., 2017, 2020 & 2022

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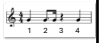
Music and group behavior

Why do we move to music?

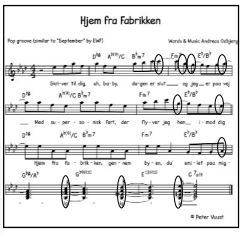
10

Why do we move to music?



Verse: NO SYNCOPATIONS

Chorus:



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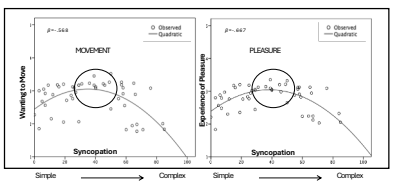
"The inverted U" of groove



There is a ***sweet spot*** for wanting to move and pleasure

Witek et al, 2014

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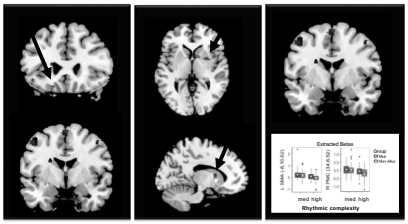
Groove in the brain



Motor, premotor og reward

Matthews et al, Neuroimage 2020

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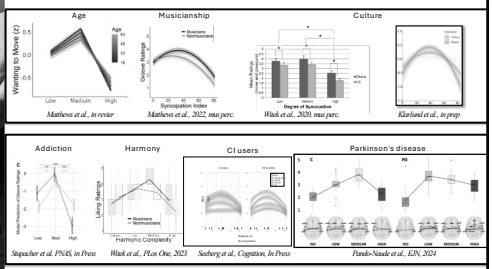
"The inverted U"



Matthews et al., in revise *Matthews et al., 2022, mus perc.* *Wlask et al., 2020, mus perc.* *Klarlund et al., in prep*

Stupacher et al. PNAS, in Press *Wlask et al., PLos One, 2023* *Sioeberg et al., Cognition, In Press* *Pando-Naude et al., EJN, 2024*

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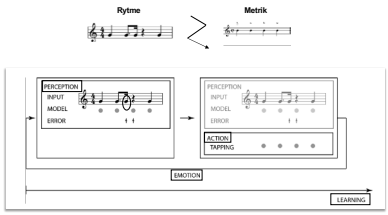
Syncopation



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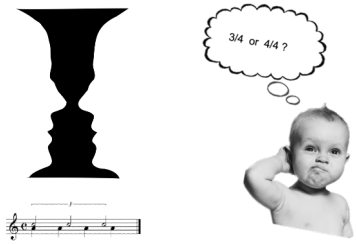
The brain's job is to predict the future



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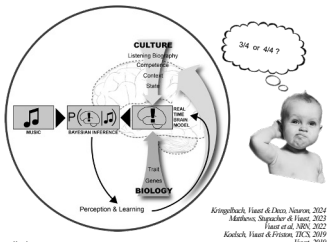
Predictive coding of music



Precision-weighted prediction error

$$\xi^{(i)} = \pi^{(i)}(\mu^{(i-1)} - g(\mu^{(i)}))$$

Kringelbach, Vuust & Doco, Neuron, 2024
Matthews, Stupacher & Vuust, 2023
Vuust et al., NRN, 2022
Koelsch, Vuust & Friston, TICS, 2019
Vuust, 2019
Vuust, 2018
Vuust & Wlask 2014
Gebauer, Kringelbach & Vuust , 2013
Vuust et al., 2009
Vuust & Frith, 2008

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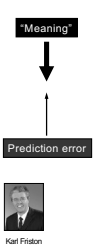
Predictive coding



$$\xi^{(i)} = \pi^{(i)}(\mu^{(i-1)} - g(\mu^{(i)}))$$

Koelsch, Vuust, & Friston, 2019

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Predictive coding in art

Ole Folmer Hansen 1964

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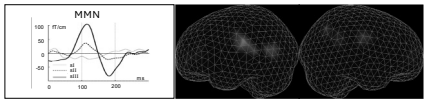
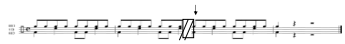
Brain processing of syncopation



Vuust et al., NeuroImage 2005



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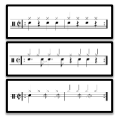
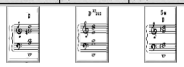
Groove paradigm with rhythm and harmony

HARMONY / RHYTHM	LOW Major triads	MED 7th chords with tensions	HIGH including b9-intervals
LOW *(Clave minus syncopation)*			
MED *Clave*			
HIGH *Wrong Clave*			

6 versions of each of the 9 categories (54 stimuli in total)





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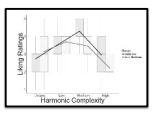
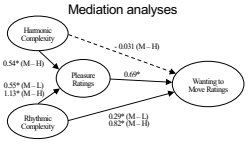
What is the contribution of harmony

Harmonies alone



Mediation analyses



Matthews, Witek, Penhune & Vuust, PloS one 2019

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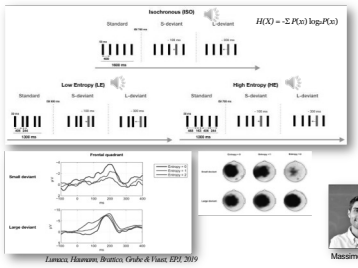
"Prediction error" is weighted by precision



Massimo Lumaca

Lumaca, Haumann, Brattico, Grube & Vuust, EPL 2019

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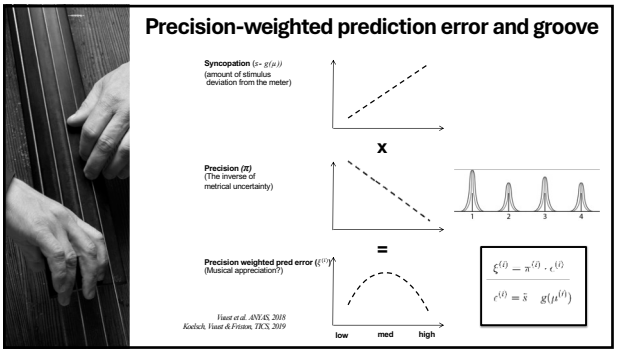

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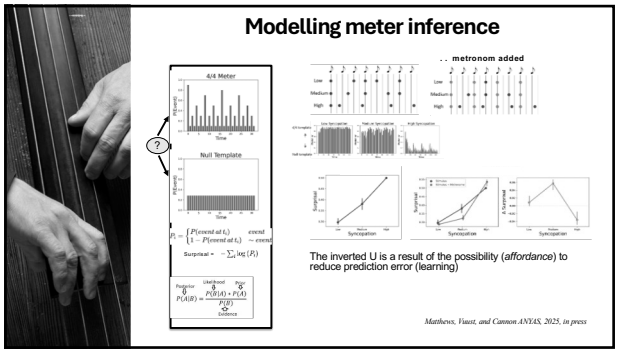

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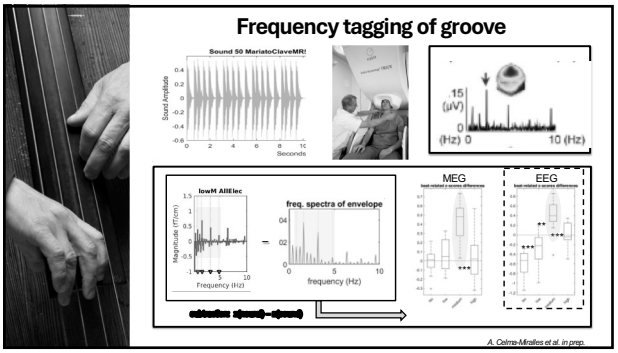

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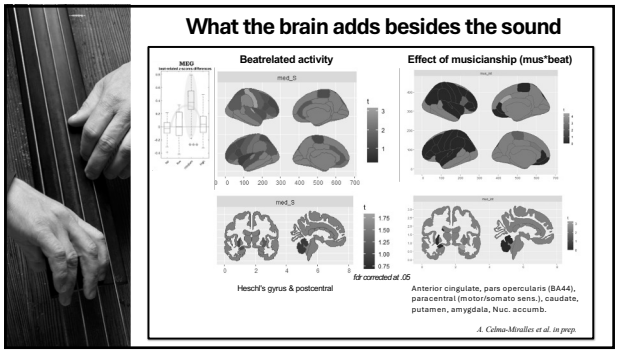

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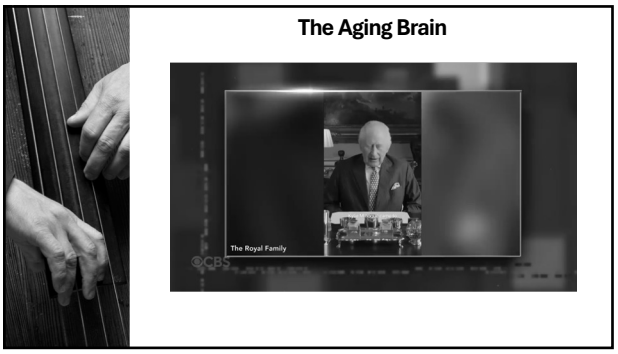

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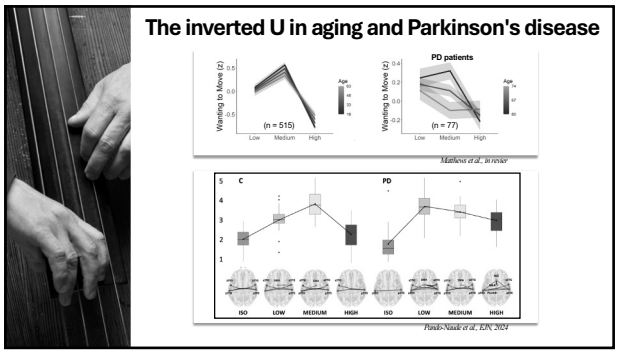

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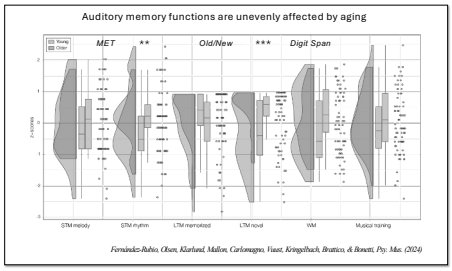
Auditory memory in healthy aging

Auditory memory functions are unevenly affected by aging



Fernández-Rubio, Olsen, Klarlund, Mallon, Carlomagno, Vuust, Kringelbach, Brattico, & Bonetti, Psy. Mus. (2024)

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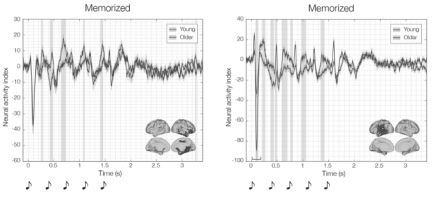
Auditory Memory in healthy aging

Older adults have reduced neural activity in memory-related regions **but** stronger activity in auditory regions display



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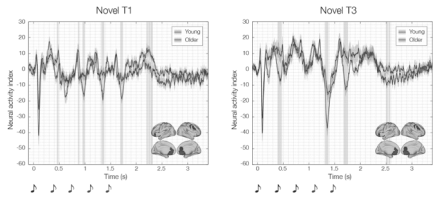
Auditory Memory in healthy aging

Older adults have **reduced** activity at brain regions related to decision-making processes during identification of novel sequences



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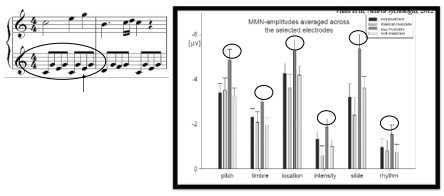
The Multifeature MMN paradigm



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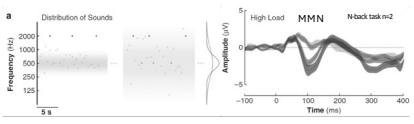
Melody: Precision weighted prediction error



(Garrido et al. npj Science of Learning 2016)

MMNs to outliers, in a narrow (blue) and broad (red) distribution of frequencies.

$$\xi^{(i)} = \pi^{(i)} \cdot \epsilon^{(i)}$$
$$\epsilon^{(i)} = \tilde{s} \quad g(\mu^{(i)})$$

Vuust et al. Annals NYAS, 2018

During perception, we estimate the uncertainty of the signal. Then a precision-weighting mechanism adjusts prediction error.

(Feldman & Friston, 2005; Hsu et al. 2016; Vuust et al. 2018; Clark, 2015)

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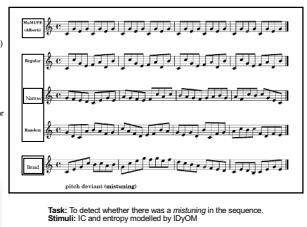
The effect of melodic uncertainty (behavior)

Stimulus:
Only one key
Same range (8 tones) (except Alberti)
Major versions only

Pitch deviant – 25 cents

10 standard and 10 deviant sequences for each condition

Analyses: one-way ANOVA on the two outcome variables with musical context as a factor.



	I.C.	Entropy
Alberti	1.01	1.46
Regular	1.75	1.73
Narrow	3.14	2.74
Random	3.22	2.76
Broad	3.66	3.62

David Quiroga

Task: To detect whether there was a *mistuning* in the sequence.
Stimuli: IC and entropy modelled by IDyOM

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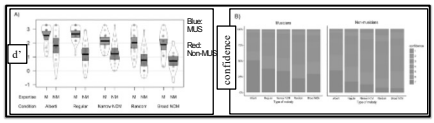
The effect of melodic uncertainty

Detection of mistuning in 5 melodies



A linear relation between melodic uncertainty and d'/confidence scores

Melodic uncertainty

Condition	Alberti bass	Regular (8 notes)	Narrow	Random	Broad
I-C	1.01	1.75	3.14	3.22	3.66
Entropy	1.46	1.73	2.74	2.76	3.62

Quiroga, Hoglund, Hansen, Pearce, Brattico, Vuust, Cortex 2019

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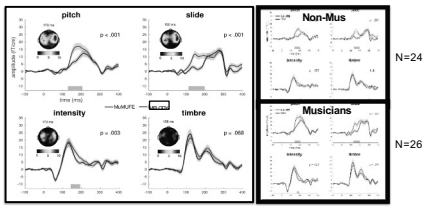
Melodic uncertainty influences the MMN

Difference between Alberti bas and Melody



Difference waves (musicians and non-musicians). The ERFs correspond to an average of the nine right temporal gradiometers with the strongest MMNm amplitudes. Shaded areas depict standard error. Topographic maps correspond to an average of 50 ms around the peak difference. The most prominent cluster with a Montecarlo estimate smaller than .05 is marked with green lines and the "x" symbol.

Quiroga, Hoglund, Hansen, Pearce, Brattico, Vuust, Cortex 2019

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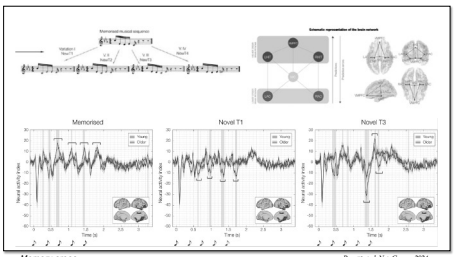
Predictive coding and memory of melodies



Memory areas

Bonetti et al, Nat. Comm., 2024

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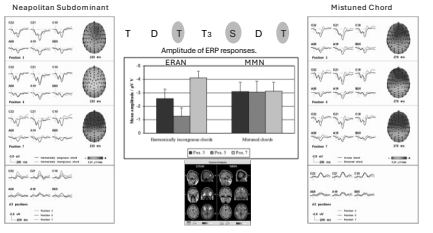
Predictive coding of harmony



Leino et al. 2007 Brain Research, Garza et al. 2011, Brain research
Paradigm adapted from Koelsch et al..

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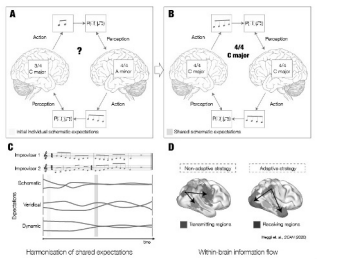
Predictive coding in musical interaction



Vuust, et al, NRN 2022

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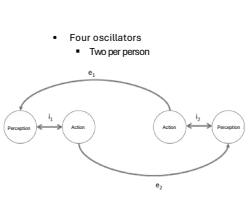
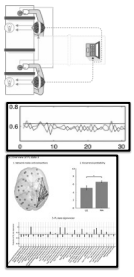
Modelling synchronization relationships

- Four oscillators
  - Two per person



$$\frac{d\theta_n(t)}{dt} = \omega_n(t) + \sum_{p=1}^{n} K_{np} \sin\left(\theta_p(t) - \theta_n(t)\right) + \xi_p(t), \qquad n = 1, \ldots, k(1)$$



Hoggli et al. Plos Computational Biology, 2020

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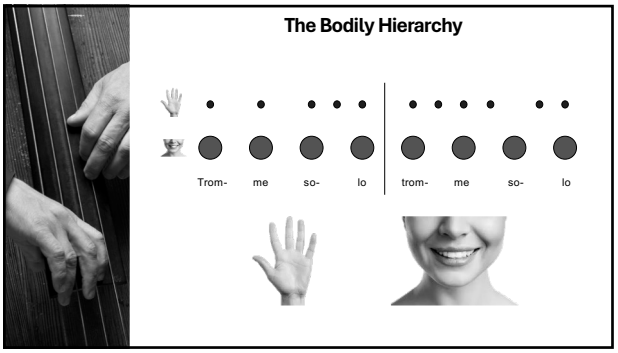

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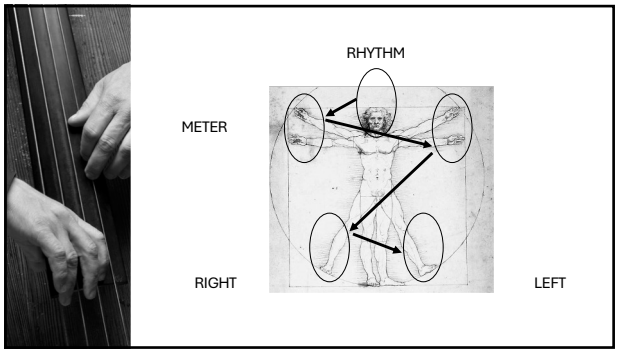

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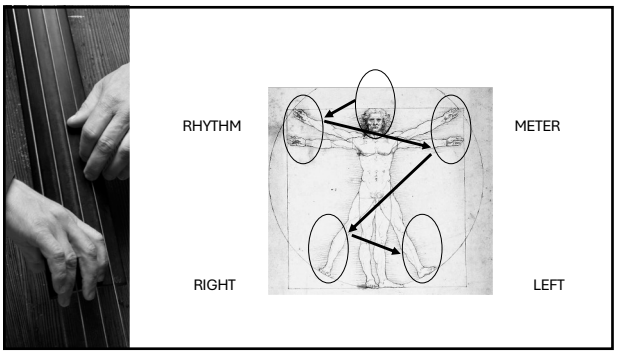

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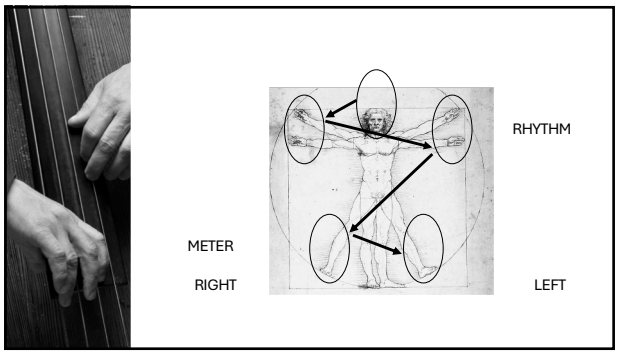

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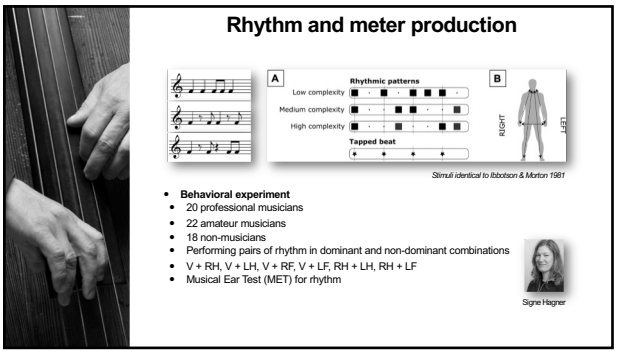

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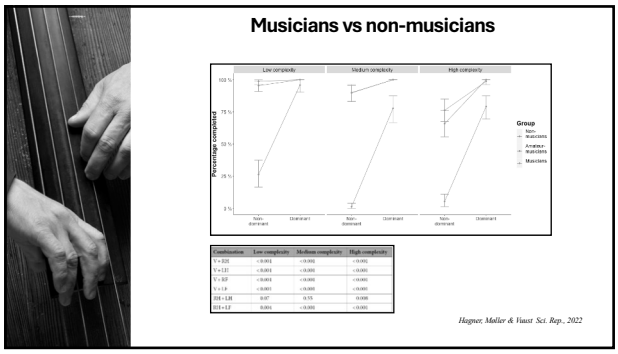

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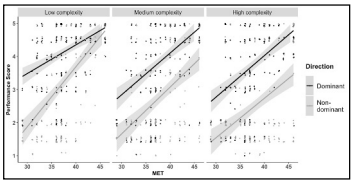
Production correlates with rhythm perception



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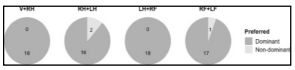
Control Experiments

- **Control experiment 1 (improvise):**
  - 18 right-handed musicians
  - "Keep the rhythm with one effector and improvise with the other"
  - Which combination is the more difficult one?



- **Control experiment 2 (dexterity):**
  - 19 right-handed musicians performing a "slow rhythm"
  - "Rate how difficult the task is (0-100)"
  - In Clap + RF, V + Clap participants still preffered the dominant combination (p < .005)
  - RH + LH was non-significant

"slow rhythm"

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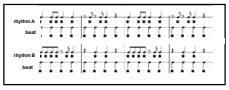
fMRI setup

- **fMRI**
  - 41 right-handed musicians
  - With and against the hierarchy
  - Baseline (the beat in both effectors)



AGAINST	*BEAT*	*RHYTHM*	*RHYTHM*	*BEAT*	*BEAT*	*RHYTHM*
WITH	*RHYTHM*	*BEAT*	*BEAT*	*RHYTHM*	*RHYTHM*	*BEAT*
BASELINE	*BEAT*	*BEAT*	*BEAT*	*BEAT*	*BEAT*	*BEAT*

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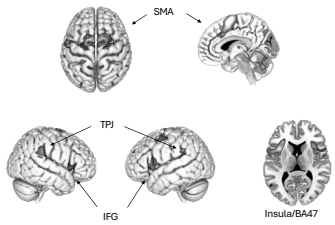
Going against the hierarchy (all conditions)



Hagner, Møller & Vuust Cortex, 2024

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Results

Cognitively meter and rhythm can be described as a figure/ground relationship, where meter is the background, anchoring the rhythm which is in the foreground (Greimas 1987, London, 2012, Vuust et al. 2011)

- There is a body hierarchy which guides simultaneous performance of rhythm and meter
  - Dominant combinations [Rhythm, Meter]: V — RH — LH — RF — LF
- There is no interaction between musical expertise and the body hierarchy
- The body hierarchy seems to be strongest in the vertical direction, behaviorally and brain-wise
- Going against the bodily hierarchy involves additional frontal areas of the brain (the IFG) as well as SMA/PMC - as does perception and production of increasing metric complexity (Vuust et al. 2006, Matthews et al 2019)
- There is increased functional connectivity between primary motor effector areas and somatosensory cortex when going against the hierarchy

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Discussion

- **WHY do we have the body hierarchy?**
- Dexterity?
  - The bodily hierarchy coincides with increasing dexterity of the limbs
  - The bodily hierarchy (in particular in the vertical direction) is maintained even if the rhythm parts are motorically easier to perform than the meter.
- Is it innate or learned?
- The body hierarchy is still present after musical training
- Theory: Division of labour is benificial to many motor tasks. Cognitively, we perceive music in figure/ground relationships, which is benificial to musical memory and discrimination. **Dexterity assigns, from early childhood, the role of the anchoring (the meter/beat) to the lesser dexterous effector, a relationship which over time turns into a cognitive dichotomy.**
- Implications for the neuroscience of music and music pedagogy

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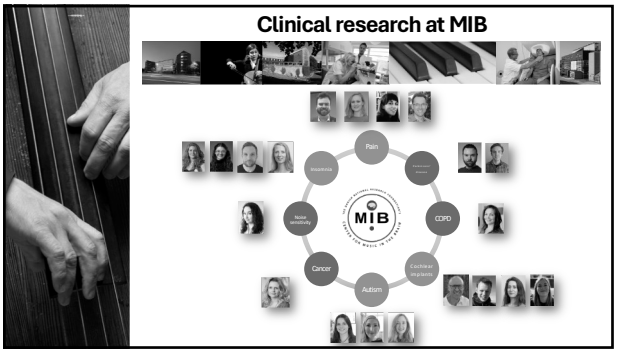
Clinical research at MIB
Pain
COPD
Cochlear implants
Autism
Cancer
Noise sensitivity
Headache
MIB

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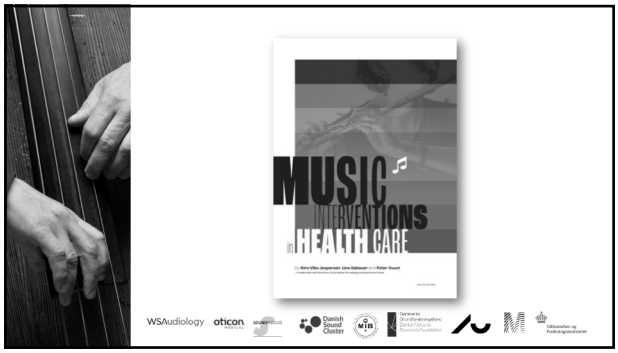
MUSIC
INTERVENTIONS
in HEALTH CARE
WSAudiology
oticon
Danish Sound Cluster
MIB

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Center for Music in the Brain
MIB

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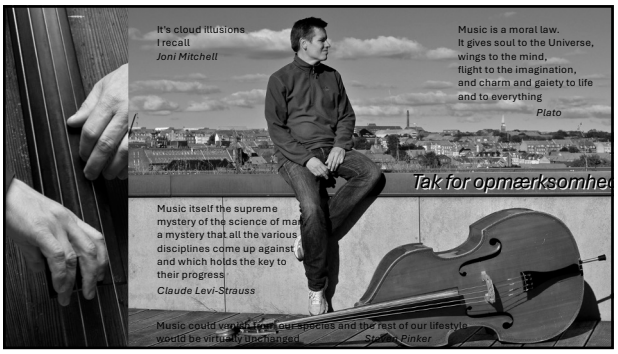
It's cloud illusions I recall
Joni Mitchell
Music is a moral law. It gives soul to the Universe, wings to the mind, flight to the imagination, and charm and gaiety to life and to everything
Plato
Tak for opmærksomhe
Music itself the supreme mystery of the science of man a mystery that all the various disciplines come up against and which holds the key to their progress
Claude Levi-Strauss
Music could vanish from our species and the rest of our lifestyle would be virtually unchanged
Steven Pinker

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