#1

Music and brain science

Held at East Sussex on 9-11th of August 2010 under the theme of "Music, Pattern and Mathematics"

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Abstract :

Activities of the central nervous system in vertebrates can be analyzed in terms of their cognitive, emotional and motor aspects. Primitive stages of the functions can be identified even in fish and birds, but they attain a much richer expression in mammals, culminating in humans with the emergence of language, art and music.

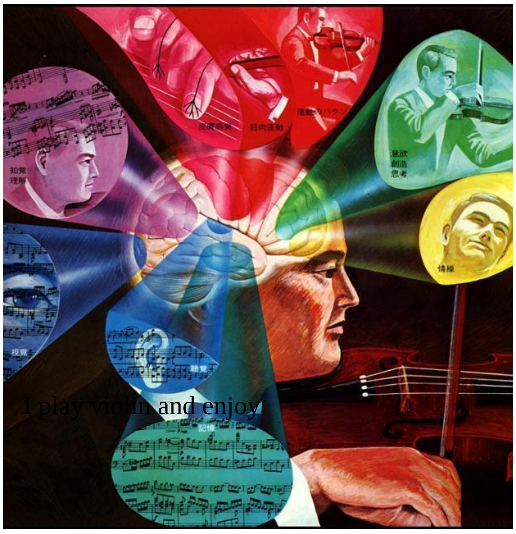
We will discuss the neural basis of acoustic cognition and emotion, that is music. The primary input for music is of course the acoustic signal. Our understanding of the auditory system is however far behind that for vision in which the neural basis of processing of shapes, colors and movements of visual objects have been studied in great details. Music is not just an acoustic experience. Like all other artistic human activities, it recruits multiple systems dealing among others with emotion, movement and possibly language. The neural manifestation of these systems is activity in limbic structures, higher motor cortical areas and neocortical association areas.

Anatomic and physiologic data of the higher function of the human brain, however, are scanty. A lot more is known from experimental animals, so it is useful for now to discuss principles of morphology and function of the human brain in terms of findings in cats and monkeys. We can use this approach to relate anatomical information from animal experiments to recent human studies of music using non-invasive techniques. We will describe the processing of the acoustic signal to the final formation of concepts like harmony and sensory recognition of a melody which puts elements together as a whole leading to the "Gestalt" formation of the human music experience.

<u># 2</u>

Music and Brain science

I play violin and enjoy music



I play violin and enjoy music　時実

Brain activities in musical performance.　(from Tokizane, 1969)

Violin player looking at the musical notes, moving hands to produce sound to which listen and adjust to create melody with emotional expressions.　In a particular region of the human brain, each function of visual, auditory, movements, emotional feelings is responsible to be activated and all of these areas are connected and then further integrated into a piece of music.

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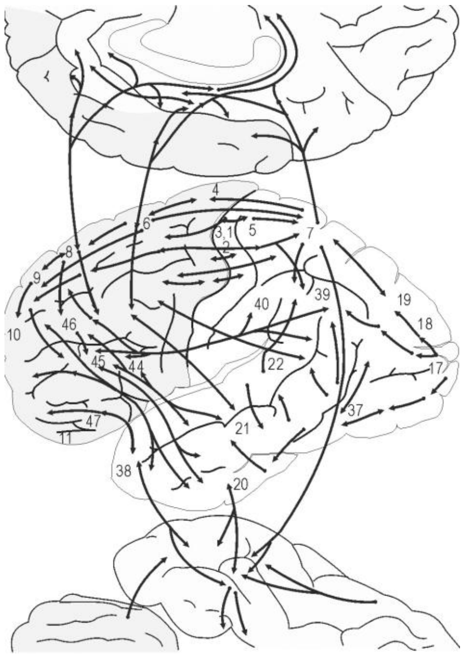


A schimatic drwing of cortico-cortical connections in the human cerebrum

Arabic numerals are referred to the nomenclature of Brodmann (1909).

(Kawamura, 1977)

<u># 4</u>

Brain Response to Music

- **Right hemisphere of the brain**
  - Activated when you ***<u>hear melodies with a variety of pitch and timbre</u>***
  - It also "lights up" when people play music by ear.
- **Left hemisphere of the brain**
  - "Lights Up" when you learn to ***<u>read music, understand key signature and notation, and follow the sequence of notes.</u>***
  - Significantly, **the brain is activated in the same area that is involved in analytical and mathematical thinking.**
- **So you can simultaneously stimulate the right and left hemispheres of the brain by playing an instrument or by singing**

<u># 5</u>

Objectives: **Develop novel computational tools** to help elucidate complex **interactions among regionally specialized neural sub-systems** responsible for the **human perception, cognition emotions and action.**

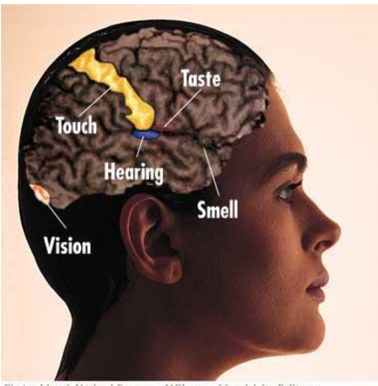
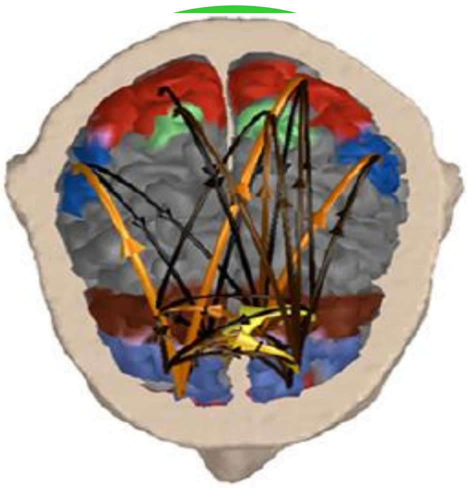


Photo of head-Michael Freeman; MRI scan of head-John Belliveau, NMR Center, Massachusetts General Hospital

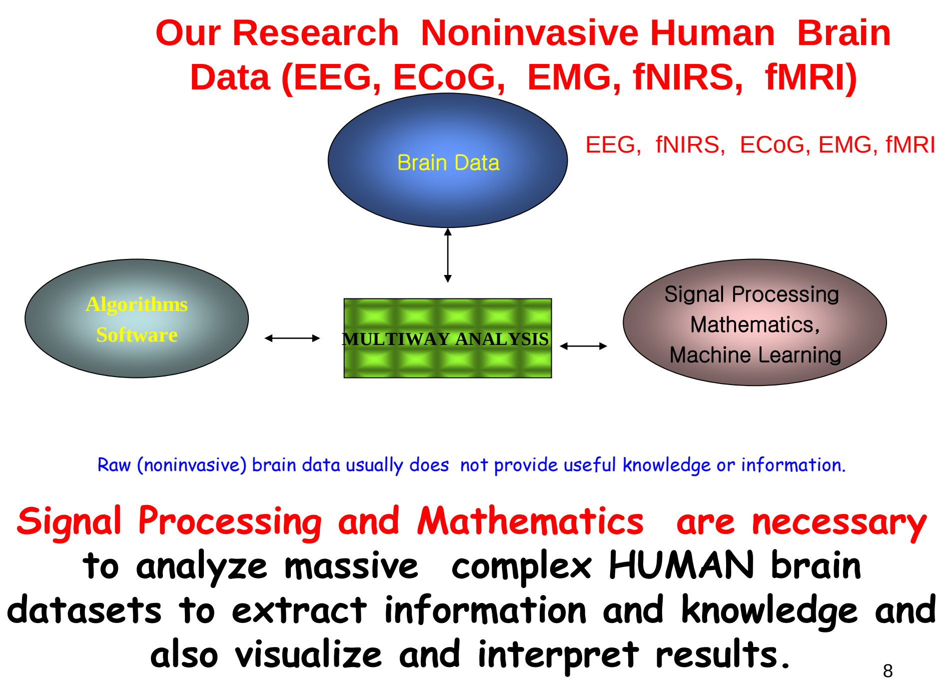
Human Perceptions



Computational Systems 6

Our research is related to **System and Computational neuroscience. We elucidate complex directional interactions in the human brain. We attempt to elucidate** interactions among regionally specialized neural sub-systems responsible for the human perceptions of music, cognition, emotions and action (dancing). ***We investigate information flows in real -time among various neural systems for example Granger causality , PDC, DTF and how find effective and functional connectivity. We try to use the insights gained to build intelligent feature extraction and classification systems.*** **Our objective to improve dramatically existing technologies especially spatial resolution and temporal resolution.** Analysis in real time multimodal EEG, EcOG, EMG , fNIRS and fMRI. ***I investigate the following problems How better and more reliably extract, detect, recognize, localize and classify brain patterns so called ERP /EP related to specific stimuli or specific mental tasks.*** I have interest that my research results will have at least potential applications and will be useful for society and humanity.

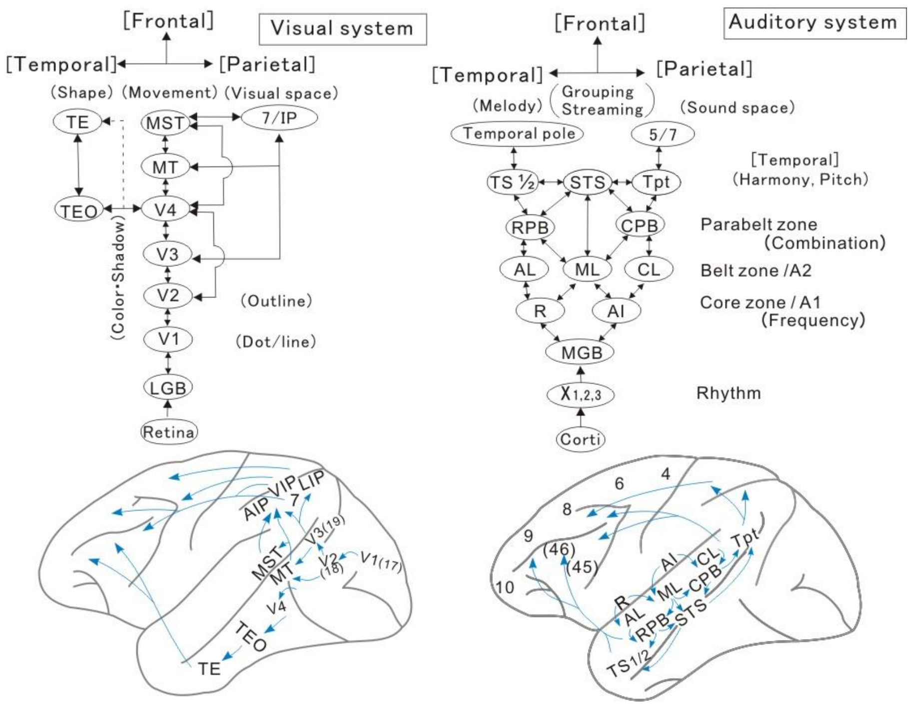
 # 6



Raw noninvasive Brain data such as EEG/MEG NIRS and fMRI usually does not provide any useful knowledge or information. Signal processing Machine Learning and

Mathematics are necessary to design and analyze massive complex brain to extract information and knowledge and also visualize and interpret results. We use advanced Approaches Methods Tools. Blind Sources Separation (ICA, NMF, SCA, MCA), Multiway analysis, Tensor (multi-mode array) decompositions. Data are represented by multiple-matrices and tensors . Brain Data in the form of tensors (multi-mode arrays) are becoming very promising in the data mining and information retrieval in the last few years. Goal Learn models for the underlying "electrophysiolgical" neural systems generating the datasets.

 # 7



A diagram to show the flow of visual (to the left) and auditory (to the right) information in the cerebral cortex. Originally the dorsal and ventral pathways were referred to the neuronal paths within the posterior association cortex. These terms are used here to extend the routes to and from the prefrontal cortex. Correlation with motor-related domains is included in the diagram.

Electric signals are degraded into each element in different parts of the brain in which different neuronal groups are composed and there, each information is analyzed and treated with in parallel ways, and as a result, cognitive features are integrated as a form or Gestalt.

Flows of information are certainly direct from the sensory organ (retina, corti) to the cerebral cortex. However, since there are feedbacks in these paths, arrows with bilateral directions are indicated in the diagrams.

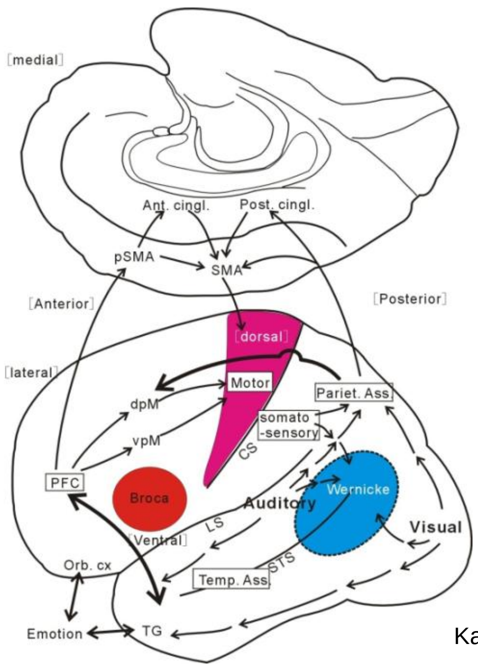
Another point to be mentioned is that in the visual system V2-V3-V4 regions are located in the bifurcation point of shape, movement and space which is taking a role of proper segregation and distribution of comming infomations, so called switch-board roles.

Similar type of mechanical organization appears to exist in the auditory system in the belt (AL, ML, CL) zone and the parabelt (RPB, CPB) zone.

<u># 8</u>

It is of highly interest and of importance in the human brain that possesses the linguistic regions where digital informations from the thalamus are converted to analogue info in the visual and auditory cortices. Cf. maybe divided into "musical" elements and "linguistic" elements.

(Revised from Kawamura, 2008)

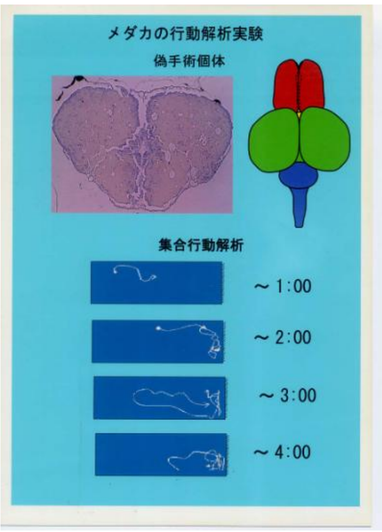


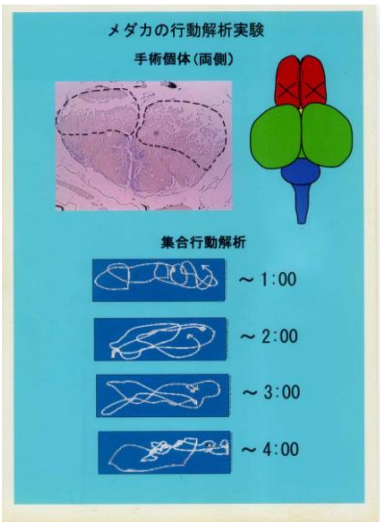
Kawamura, 2002

Grossly speaking, there are two main pathways in the visual and auditory systems. The one is the spatial cognition（where/how）in the dorsal pathway, the other is the object cognition (what) and emotion in the ventral pathway.
In addition, the visuo-spacial and sound-spacial or grouping function are included in the dorsal path, while the emotional function are included in the ventral path (Kawamura, 2002).
In the process of active behavior, "higher motor cortical areas or higher order cortical motor association areas" are concerned to plan, order, fulfill active actions. These regions are known to comprise the premotor (area 6,in the lateral surface of the hemisphere), the supplementary motor area (area6 in the medial furface) and the motor cingular cortical area (Tanji, 1999).

#9

Mirror approaching behavior in the fish, medaka (Oryzias latipes) after lesion in the amygdala





Fish (Oryzias latipes) behavioral study, a fish is placed in the water pool.
Swimming pool with a mirror on one side (in this experiment , right side)
Detroyed the fish amygdale bilaterally, and observed and analyzed the behavior of the animal. (Tsubokawa, 2002, 2009) . Used immunohistochemistry of GAD,CGRP in

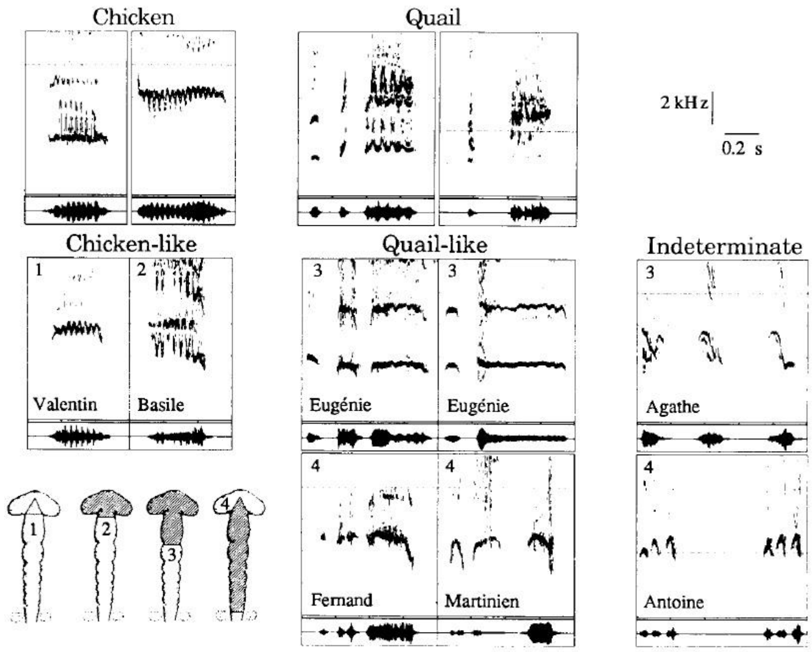
Medaka (**Oryzias latipes**)　and mouse for comparison.

Healthy medaka (with non-destroyed amygdala): swimming pattern is traced in the left diagram.　He is approaching to the mirror where his figure is reflected.

Medaka with lesioned amygdale: swimming pattern in the right diagram. Totally indifferent to his own figure reflected in the mirror.

Numericals indicate minitutes after the fish was put in the pool.

 # 10



Embryonic quail tissue (E7-E10) graft to chick CNS tissue

(Takeuchi-Tan and LeDouarin, 1991)（Balaban et al., 1988)

Creating chimera animal between chick and quail, by mean of transplantation experiments : exchange tissues (graft tissues are shaded) from a portion of the neural tube of quail to chick. Develop to young adults and observe the changes of the song patterns.

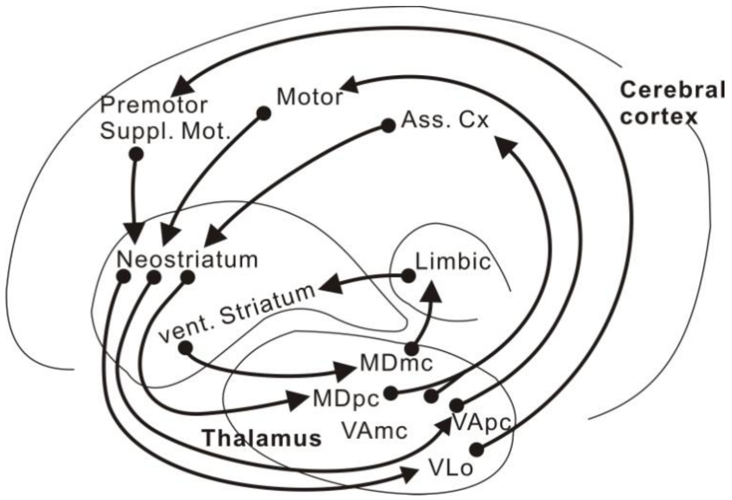
Numbers of sonographs correspond to the numbers of the grafts indicated by shaded areas in the left-lower drawings (No. 1,2,3 and 4). Brain sections were examined microscopically.

No.1 : sham experiment , i.e., no grafting

No.2：the cerebrum
No.3：No.2 plus anterior part of the brainstem
No.4：brain tissue without the cerebral region
In experiments No. 3 and 4, the amygdale is included, ; the chick sound (chi-) is converted to the quail sound (chi-chi-) as shown in the sonographs.

 # 11

Parallel circuit, spiral circuit, a model of the brain



Parallel circuitry systems occurring in the brain composed of cerebral cortex, striatum and thalamus.

There are largely three systems, at least , having their own features;

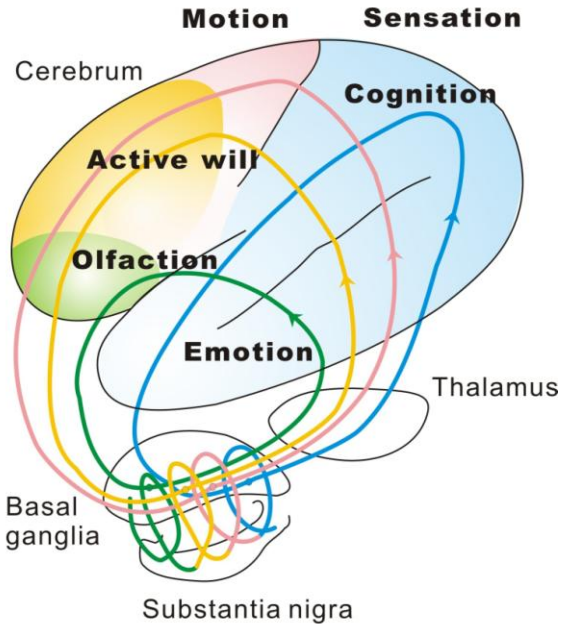
1) Motor system：planning and fulfillment of the movement,
   a) Motor loop
   b) Eye movement loop
   c) Dorsolateral-prefrontal loop
   d) Anterior cingulate loop
2) Association system：cognitive function,

3) Limbic system : emotion and motivation
(for ref. see Kawamura, 2007 revised ; Alexander et al., 1986)

Each loop has its independent domain, functionally and simultaneously reacts each other and transmit information in a parallel way. And they are integrated as a whole.
The authors propose here as a system of "spiral processing", so-called "aufheben" in German terms the following two processes 1) the parallel processing and 2) information funneling, which have been discussed in 1990s.
cf. Haber et al.,2000.

 # 12

Tekin and Cummings (2002) have proposed an idea of correlating functions of active loops with psychiatric functions on the basis of classifications of the human frontal cortex. Namely, they parceled the frontal cortex into five parts as considering the origins of the Frontal-BG-Thalamus loops; 1) supplementary motor area, 2) frontal eye field, 3) dorsolateral PFC, 4) lateral part of the frontal orbital surface, and 5) anterior part of the posterior cingulate cortex. They have considered the motor function, cognition, motivation, behavioral cognition and so forth. And they dared to conjecture the disturbances of higher nervous activities that produce psychic symptoms ; disturbances of execution, character changes, apathy etc. Deliberate consideration/discussion should be further taken for the development of such kind of academic trials.



Neural impulses (excitation) of the nigrostriatal system process in parallel ways as well as in spiral ways. Morphological bases of this system was shown by Haber et al. (2000) using axonal flow methods. Upper: cerebral cortex; Middle: basal ganglia; Lower: substantia nigra/ventral tegmental area. Activities of the brain as a whole temporally and dynamically change, proceed simultaneously and mutually in parallel ways.

That is, spiral processing of dynamical information ; emotion → cognition → movemen/motor . These lead to the operation of the active behavior.

Plural neuronal circuitries are linked/coupled / connected (each other)

Mental phenomena, total activities or ensemble of the higher nervous activities, are not neither single-loaded nor local-occurring, constantly changing dynamically. The present author thinks the key (machanism) to activate this cycle lies in the spiral rolling loop in the nigra-striatal link.

In the basal ganglia, ventromedial part of the accumbens (called "shell", ample inputs of dopamine fibers)is related with the emotion and autonomic system, while its dorsolateral part (called "core") is related with the motor function. Further proceed to the central →dorsolateral parts of the neostriatum.

13

Why Blind Source Separation (ICA, SCA, NMF MCA) ?

Signal Mixtures are Everywhere

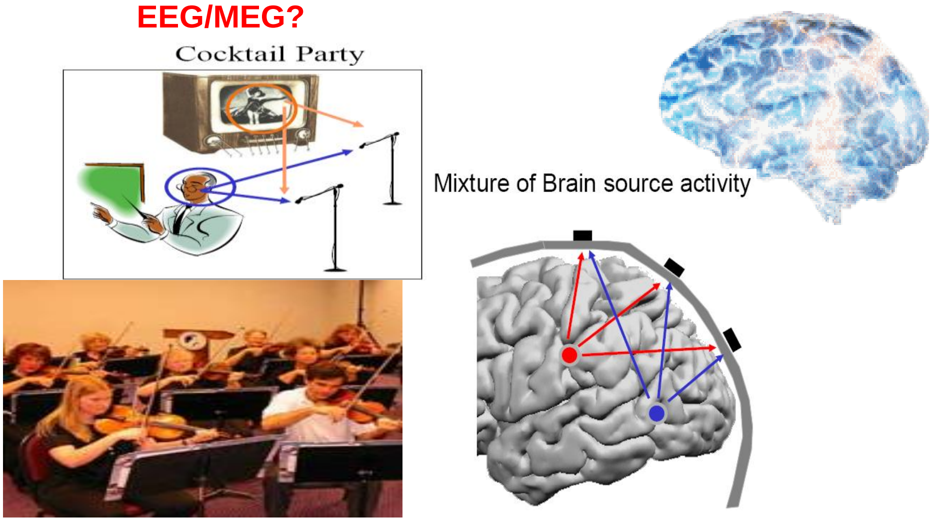
- EEG/MEG , EMG,
- fMRI, PET
- **Music Analysis**

How do we make sense of it all?

Signal mixtures are everywhere in EEG, MEG, fMRI, PET but also in microarray gene. BSS methods have found already applications not only in EEG and MEG but also in fMRI, PET also in bioinformatics gene microarray clustering and clasifcation.
Our research has been devoted to BSS not only ICA but also so called SCA, NMF, Morphological Component Analysis,

 # 13a

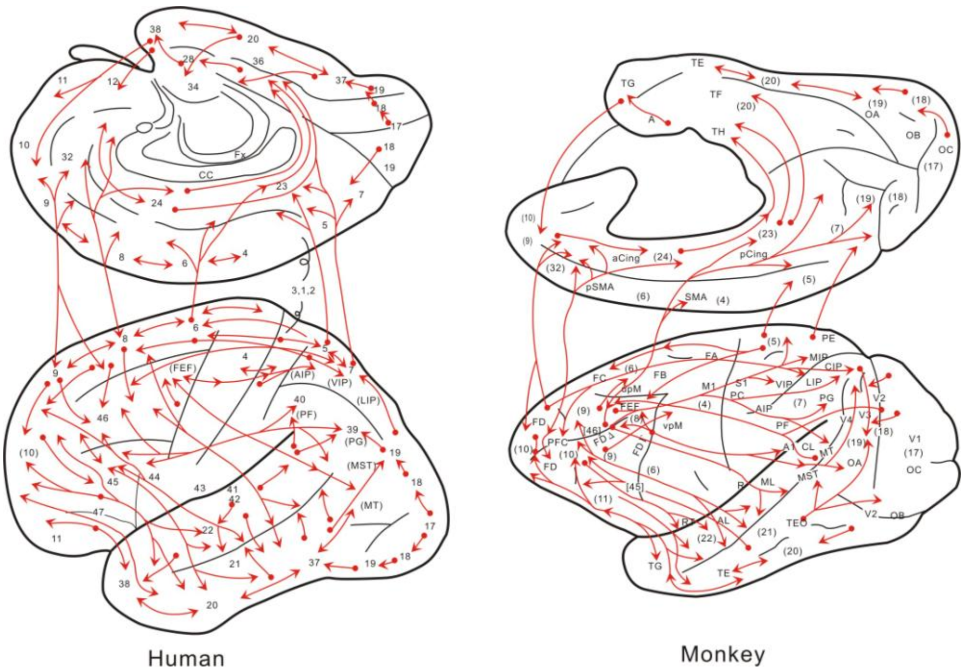
What is Blind Source Separation and Why Blind Source Separation and ICA are important for EEG/MEG?



Scalp EEG signals are produced by partial synchronization of cortical field activity. They can be considered as mixture of locally synchronous electrical activities of many cortical areas [Scott Makeig Terry Sejnowski 2004] 29

Some our research is devoted to blind source separation. We would like to illustrate these complex signal processing tools via several intuitive examples. **Why Multiway Blind Source Separation is important and useful for EEG or MEG analysis ?** The EEG or MEG data are superimposed, overlapped corrupted by additive noise. Scalp EEG signals are produced by partial synchronization of cortical field activity. They can be considered as mixture of locally synchronous electrical activities of many cortical areas [S. Makeig 2004]. **There is some analogy between EEG and coctail party problem. May be better analogy to EEG is a big orchestra.** There is some rough analogy between EEG signals pick up via tiny electrodes and huge orchestra via array of microphones, electrodes similar to microphone pick up al signals and we need to extract some instruments or sources and localize them in space.

 # 14



Schematic diagram to show the comparison of associations (cortico-cortical) fibers between the human and the monkey

Arabic numerals are indicated after Brodmann (1909), Roman letters, Bonin と Bailey (1941). Map on a reduced scale is different; the human brain is about three times larger than the monkey brain.　Upper：inner surface,　Lower; outer surface.

Drawing of the cortical connections human brain is in a sense hypothetical, because experimental data are as a matter of course unobtainable. It is basically based upon the macroscopical dissection, chimpanzee's findings which Kawamura carefully constructed before （see Ref. Kawamura, 1977, Progress in Nerv. Res., 21/6, Fig.7）. Remarkable features of the association fibers in the human brain are enormous and complex development as shown in the figure.

Monkeys and chimpanzee：strychinine ? methods by Baileyet al., 1943）

＊）For references of association fibers in animals higher than monkeys, see the following papers below.

Bailey, P. et al.：Functional organization of temporal lobe of monkey (Macaca

mulatta) and chimpanzee (Pan satyrus). & Long association fibers in cerebral hemispheres of monkey and chimpanzee, J. Neurophysiol., 6 (1943) 121-134.
Creutzfeldt, O.D. : Cortex Cerebri, Oxford University Press, 1995.
Paxinos, G., and Mai, J.K.. (eds.) : The Human Nervous System, 2 ed, Elsevier Academic Press, 2004.
Rilling, J.K. et al. : The evolution of the arcuate fasciculus revealed with comparative DTI, Nature Neurosci. 11 (2008) 426-428.
Schmahmann, J.D., and Pandya, D.N. : Fiber Pathways of the Brain, Oxford University Press, 2006.

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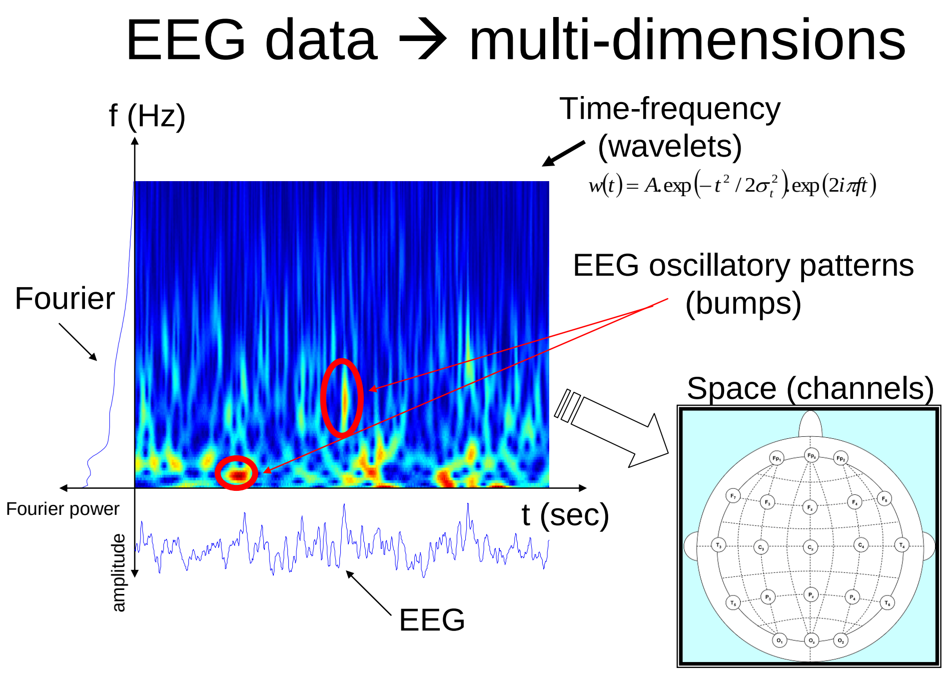
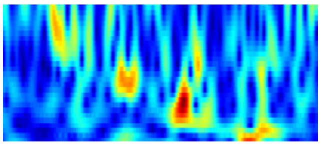


15a

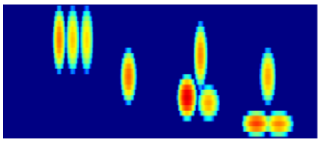
EEG time-frequency patterns

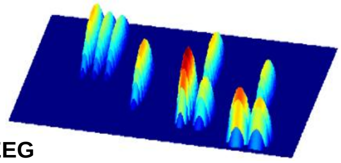
Sparse modeling of local synchrony patterns



Bumps

Sparse representation





Assumptions:

1. **time-frequency information is relevant for EEG**
2. **oscillatory bursts convey a key information about local synchrony**
3. **Statistical wavelet thresholding (SWT or z-score) allows identification of significant patterns** $\leftrightarrow \forall t, z_{ft} = \frac{c_{ft} - M_f}{\Sigma t}$

Vialatte, et al., 2007 Neural Network - about SWT, see Browne & Cutmore 2002

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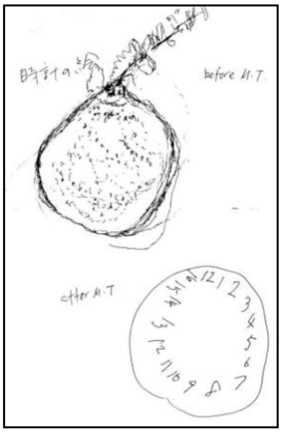
Music Therapy in Dementia – CDT Benchmark

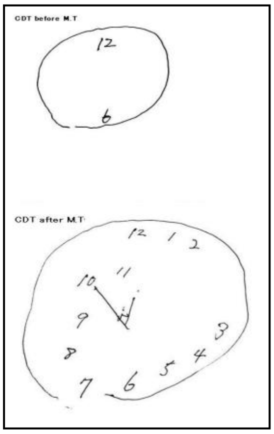
Our preliminary results

Benchmark Clock Drawing Test (CDT) before and after music therapy



Before therapy

After therapy



Subject 1, female **Subject 2, male**

Dramatic improvement of cognitive functions and memory after music therapy

We have already performed some preliminary experiments. We recorded EEG or elderly patients with MCI/AD before and after music therapy. This slide show improvement of cognitive functions after music therapy so called Clock Drawing Test (CDT)

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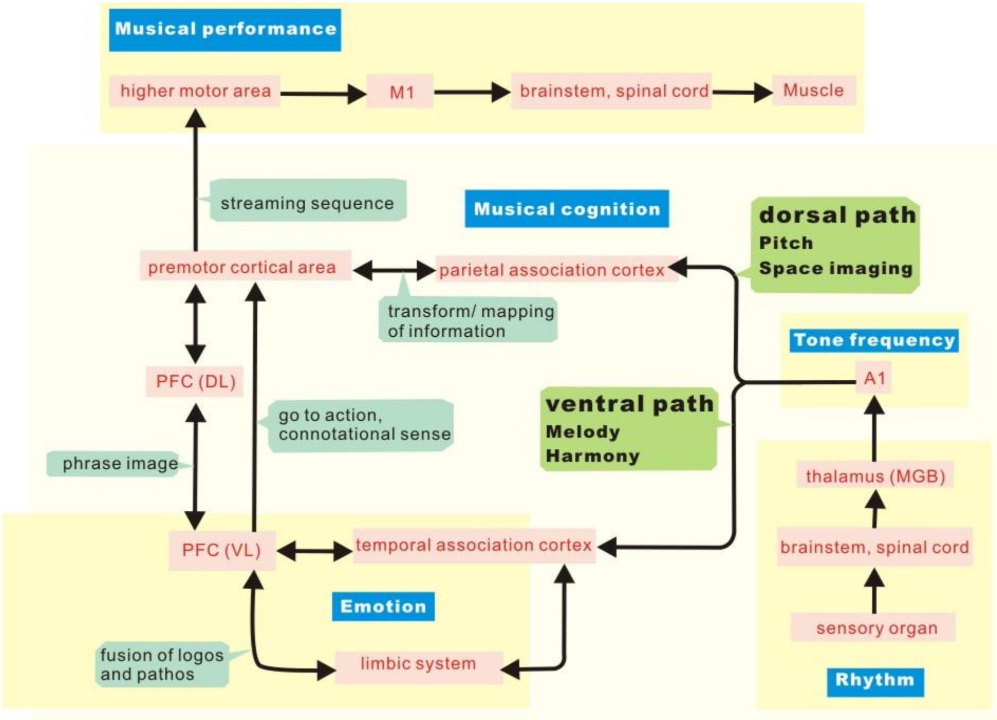


Cognition, emotion, and intention in the music

How musical performance is carried on in the human brain?

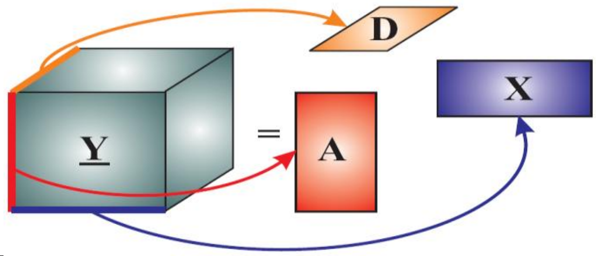
Flows of acoustic sensori-motor information is schematically illustrated in relation to the music. Fields of recognition, emotion and intension is also indicated.

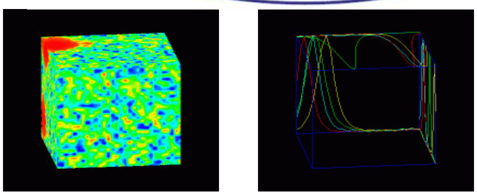
Among several motor candidates prepared by means of activities in the parieto-premotor system, one will be chosen by encountering the functions of the temporo-prefrontal system, in accordance with suitable connotation. （CHOPIN Kawamura、2007a, revised ）DL : dorsolateral part , VL : ventrolateral part of the PFC.

18

3D Tensor Factorization
PARAFAC (CANDECOMP), NTF

Searching for common factors, hidden components, sparse representation, dimensionality reduction, canonical decomposition, multi-way clustering





$$\mathbf{Y}_i = \mathbf{A}\,\mathbf{D}_i\,\mathbf{X} + \mathbf{E}_i \qquad i = 1, 2, \ldots, K$$

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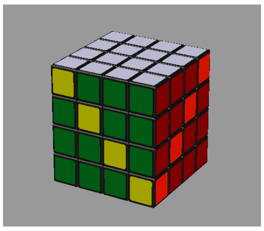
What is tensor factorization ? It is generalization of matrix factorization or BSS/ICA This is not trivial neither straightforward generalization. Depending on constrains this can be considered as generalization of ICA or NMF or SCA. However, tensors decompositions and factorization is going far beyond Blind Sources separation. It is used for feature extraction and selection, multi-way clustering and powerful classification. In the simplest case scenario we represent 3D data tensor into 3 component matrices in PARAFAC model or by core tensor and 3 factors in the Tucker model, for example factors can be represented simultaneously in the time space and frequency domain. We perform such factorization in order to extract **common factors, discover underlying hidden components, or perform sparse representation, dimensionality reduction, canonical decomposition, multi-way clustering .**

<u># 19</u>

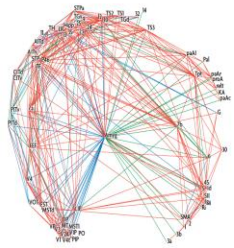
Current and Future Problems in Modeling and Analysis of Human Brain Data

- How to extract hidden brain patterns? How does the brain patterns look like?



- **What is 'normal'/'abnormal' components? Which patterns/laws hold ?**

- How interact different components Sub-networks How do they evolve? Functional and effective connectivity



- How to extract and select features and classify them depending on mental tasks

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By using multi-way analysis and tensor decompositions and factorizations we can address efficiently the following key problems: **How to extract hidden brain patterns and classify them? How does the brain patterns look like?** What is 'normal'/'abnormal' components? Which patterns/laws hold? How interact different components? How do they evolve in time ? How to identify find artifacts, outliers and remove them?

<u>End of the presentation at the meeting, held on 9-11th of August 2010</u>

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<u># 20</u>

<u>Supplement</u>

Below is the description by Andrzej S. Cichocki, maybe used afterward in the text or explanation of figures

We use advanced mathematical tools for analysis of brain patterns related to music perception and music performance.
We use Blind Sources separation , multi-way analysis and tensor factorization for extracting Event Related potentials and brain patterns form noisy EEG data.

Our research is on the **System and Computational neuroscience our interest and objective is to develop methods and tools or technology to investigate complex directional interactions in the human brain. We attempt to elucidate connectivity and** interactions among regionally specialized neural sub-systems responsible for the human perceptions, cognition, emotions and action. ***We investigate information flows in real -time among various neural systems for example Granger causality , PDC, DTF and how find effective and functional connectivity.*** **Our objective to improve dramatically existing technologies especially spatial resolution and temporal resolution.** Analysis in real time multimodal EEG, EcOG, EMG , fNIRS and fMRI. ***We investigate the following problems How better and more reliably extract, detect, recognize, localize and classify brain patterns so called ERP /EP related to specific stimuli or specific mental tasks.***

We would like to emphasize that we make not only theoretical works but we also perform extensive experiments using high density array EEG and NIRS and also EMG. We organized and designed our EEG experimental rooms with EEG, EMG and fNIRS. We have actually one the best and modern in the world EEG facilities.

This slide shows typical raw EEG and simulatenous ECOG data The signals are corupted by heavy noise and artifacts
It is difficult interpret such raw data it is necessary to apply sopisticated and novel signal processing amd data mining tools to extract useful information. In fact during my talk I would like to convinece that signal processing and machine learning tools are necessary to extract in noivasive information form the human brain and understn higher functions of the brain on system level when hundered thuosands or eevn milion neurons are simualtenosly synchorinzed Raw Brain data usually does not provide any useful knowledge or information. Signal processing Machine Learning and Mathematics are necessary to design and analyze massive complex brain extract information and knowledge and also visualize and interpret results.
Approaches Methods Tools Blind Sources Separation (ICA, NMF, SCA, MCA), Multiway analysis, Tensor (multi-mode array) decompositions. **Data are represented**

by multiple-matrices and tensors . Brain Data in the form of tensors (multi-mode arrays) are becoming very promising in the data mining and information retrieval in the last few years. Goal Learn models for the underlying "electrophysical" neural systems generating the datasets.

Our method allows to extract extremely weak image or signal corrupted by superimposed with noise and other signals or convoluted with noise and interference.

We have applied BSS/ICA to analysis of EEG and MEG. First of all, ICA allows to extract and remove artifacts and extract time pattern components corresponding to specific stimuli and localize them in the brain and find their spectral characteristics.

We have applied ICA and BSS to human brain data. This method allows us estimate and remove physiological artifacts and also estimate hidden brain sources corresponding to specific stimuli or mental tasks

For example Using BSS algorithm we can reliably localized brain sources and determined temporal and spectral characteristics for simultaneous visual and auditory stimuli

Our goals is to develop efficient Unsupervised Learning methods and software to find the hidden causes and underlying structure in the modern massive datasets not only for brain science but also for bioinformatics and social networks.

Why Tensor Factorizations (Multi-way Analysis) are important and promising for Neuroscience Datasets?

Recorded data (EEG, MEG, EMG, fMRI, etc) provide datasets with **multi-way structure**. Each dimension (or mode) has a particular **physical meaning** such as: time, frequency, space, subject,

trial, conditions, classes etc. Often it is necessary to understand the complex **relationships among modes**

(we should avoid working on one vectorized version of data). This is simailar spirit to Group ICA developed by Professor Adali and her colleagues

Moreover, tensor decomposition allows often to extract components with physical or physiological meaning and interpretation. Several tasks can performed simultaneously (e.g . future extraction , selections, classification).

The more important that multi-way analysis tensor factorizations allows us to make fusion or
integration of datasets form different laboratories or hospitals or integration of data for different modalities.

Why tensor factorizations is important in EEG/MEG or fMRI? It is natural to represent brain data simultaneously in space, time and frequency. Moreover , for human brain signals and neuroimages we can add additional modalities for example trials, subjects, conditions. **Why Tensor Factorizations (Multi-way Analysis) are important and promising for Neuroscience Datasets?**
Recorded data (EEG, MEG, EMG, fMRI, etc) provide datasets with multi-way structure. Each dimension (or mode) has a particular physical meaning such as: time, frequency, space, subject, trial, conditions, classes etc. Often it is necessary to understand the complex relationships among modes . Moreover, tensor decompositions allows often to extract components with physical or physiological meaning and interpretation. Several tasks can performed simultaneously (e.g . future extraction , selections, classification). The more important that multi-way analysis tensor factorizations allows us to make fusion or integration of datasets form different laboratories or hospitals or integration of data for different modalities (EEG, fNIRS, fMRI, PET)

What is new in our approach to multiway analysis and tensor factorizations? Tensor decompositions is not completely new concept. It was developed in Chemometric sand Spectroscopy.
New models, new robust cost functions, new optimization criteria, new generation of very fast algorithms suitable for very large scale problems and real-time applications like for example BCI

Multiway BSS or tensor factorization technology allows us to analyze human brain dynamics in space time and frequency domain. We can estimate brain activation in sub millisecond resolution and simultaneously extract spatial and spectral information.

Multiway BSS technology allows us to analyze human brain dynamics in space, time and frequency domain This demo shows brain activation during movement of limbs. We can estimate brain activation in sub millisecond resolution and simultaneously extract spatial and spectral information. (Cortical activation as a result of sensory touch stimulus of the right thumb

Our research is also focused to real-time Neuro-feedback . We attempt to answer the following questions, How better and more reliably extract, detect, recognize, brain patterns so called ERP /EP related to specific stimuli or specific mental tasks how find effective functional connectivity, information flows and Granger causality and classify brain signals and to use the insights gained to build intelligent feature and classification extraction systems. **We believe that accurate estimation of the timing of neural activity is important to fully model the information flow among functionally specialized regions or sub-networks whose joint activity underlies, music perception, cognition and action (somatosensory and motoric systems) .**

We developed and tested new approach so called **Multi-way Morphological Component Analysis in which we use simultaneously several dictionaries to sparsify data. We represented EEG experimental data in the form of 4-D tensors Frequency x time x channel x dictionary. Using various transforms or dictionaries for example STFT and CWT or CDT and we able to extract** different morphological properties (or other words, different sparsity profiles) and get more insight about hidden structure and underlying components.

We developed a unique technology based on tensor factorizations. Data are collected in the form tensor and decomposed into spatial and time frequency components. This allows us to estimate and extract components and features corresponding to specific mental tasks, emotions and music perception. Tensor is obtained for motor imagery related EEG signals.

If EEG Human brain data are represented in space, time and frequency, then we can extract spatial, temporal and spectral components

We developed new measure of synchrony called **Stochastic Event Synchrony (SES) which is complimentary to existing measures and have good sensitivity.** *In order to understand mechanism of music perception we have investigated various synchrony measures (more than 30)*
Why we use EEG ? It is simple no invasive cheap, affordable for every one, mobile. Moreover, we have developed technology to analyse EEG data. Our investigations confirmed that EEG is useful in study dynamic of brain.

We are developing tools and software not only for EEG/MEG but also for Electromyography, fNIRS, fMRI, PET

These tools using novel approaches such as tensors decomposition multiway ICA, NMF, NTF, EMD.

This software allows us to detect fine temporal and spatial and spectral structures of task related activity and mental tasks.

As the brain is highly dynamic system, accurate estimation of neural activity is necessary to fully model the information flow among functionally specialized regions or sub-networks whose aggregate activities underlies music perception, cognition, emotion and actions.

I hope that the multi-way analysis and tensor factorizations have great potentials and future perspectives for exploring dynamic of human brain especially mental tasks, emotions, music perception. Modern **advanced signal processing, mathematics and machine learning is not only useful but also necessary in brain science.**

End of the supplement

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