European Network for the Advancement of Artificial Cognitive Systems

Coordination Dynamics
(Bodies, Brains, Behaviour, etc.)

Inaugural Meeting
Nice, France
16-17th February, 2006

Outline

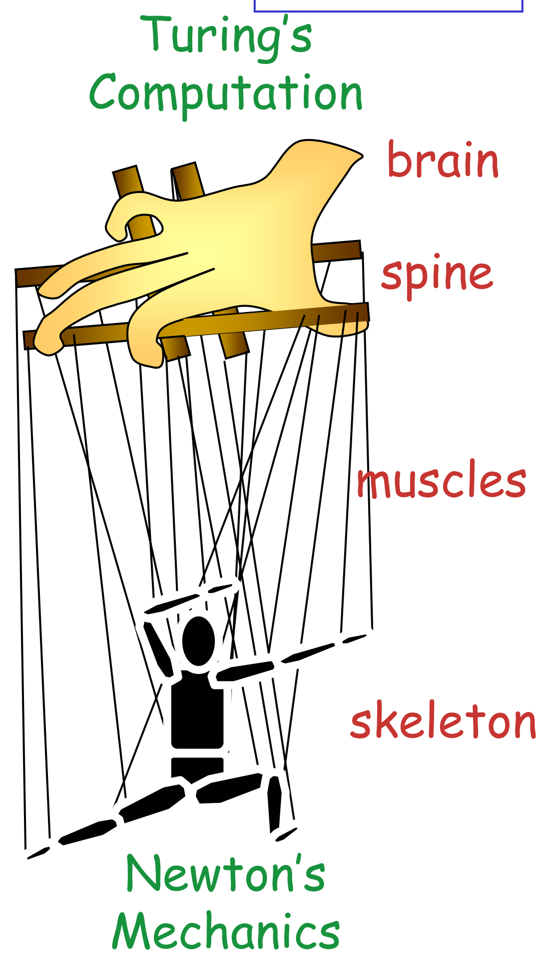
1. Natural ~ Artificial
2. The central thesis; informationally coupled SODS
3. Coordination of bodies; horse ~ rider
4. Coordination of brain and behavior on several levels
5. Coordination between brains
6. Basic Coordination Dynamics
7. New principle of brain ~ mind: Metastable Coordination Dynamics
8. Human ~ machine interaction: Outlook
9. The Complementary Nature

Artifactual ~ "Natural"

strictly neural?
plan *then* execute?
intelligent executive intervening often?
internal model(s)?
only logical constraints?
noiseless?
context-independent parts?
preassembled movements?

Asimo: An example of intelligent design by clever designers

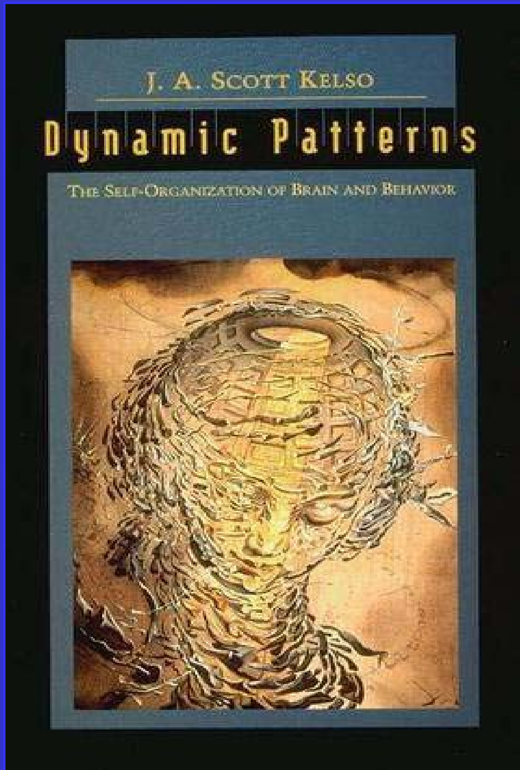
Designer determines behavior and the process by which it's achieved



"Intelligent" design ~ self-organization

Mechanical ~ creative; matter ~ mind

Coordination Dynamics - A Science of Coordination



- A conceptual framework for understanding how the parts and processes of living things come together and break apart
- Describes, explains and predicts how patterns of behavior form, adapt, persist and change in natural systems
- Addresses coordination within a part of a system, between different parts of a system, and between different kinds of systems on multiple levels
- *Informationally coupled* self-organizing systems

Thesis

Mind, brain, body and world share a common underlying dynamics—equations of motion for key pattern variables—patterns of behavior, patterns of brain activity, patterns of the mind…

“Metastability is an entirely new conception of brain functioning where the individual parts of the brain exhibit tendencies to function autonomously at the same time as they exhibit tendencies for coordinated activity (Kelso, 1991; 1995; Kaplan, 1998; Friston, 2000)”

Fingelkurts & Fingelkurts, *Int. J. Neurosci*., 2004

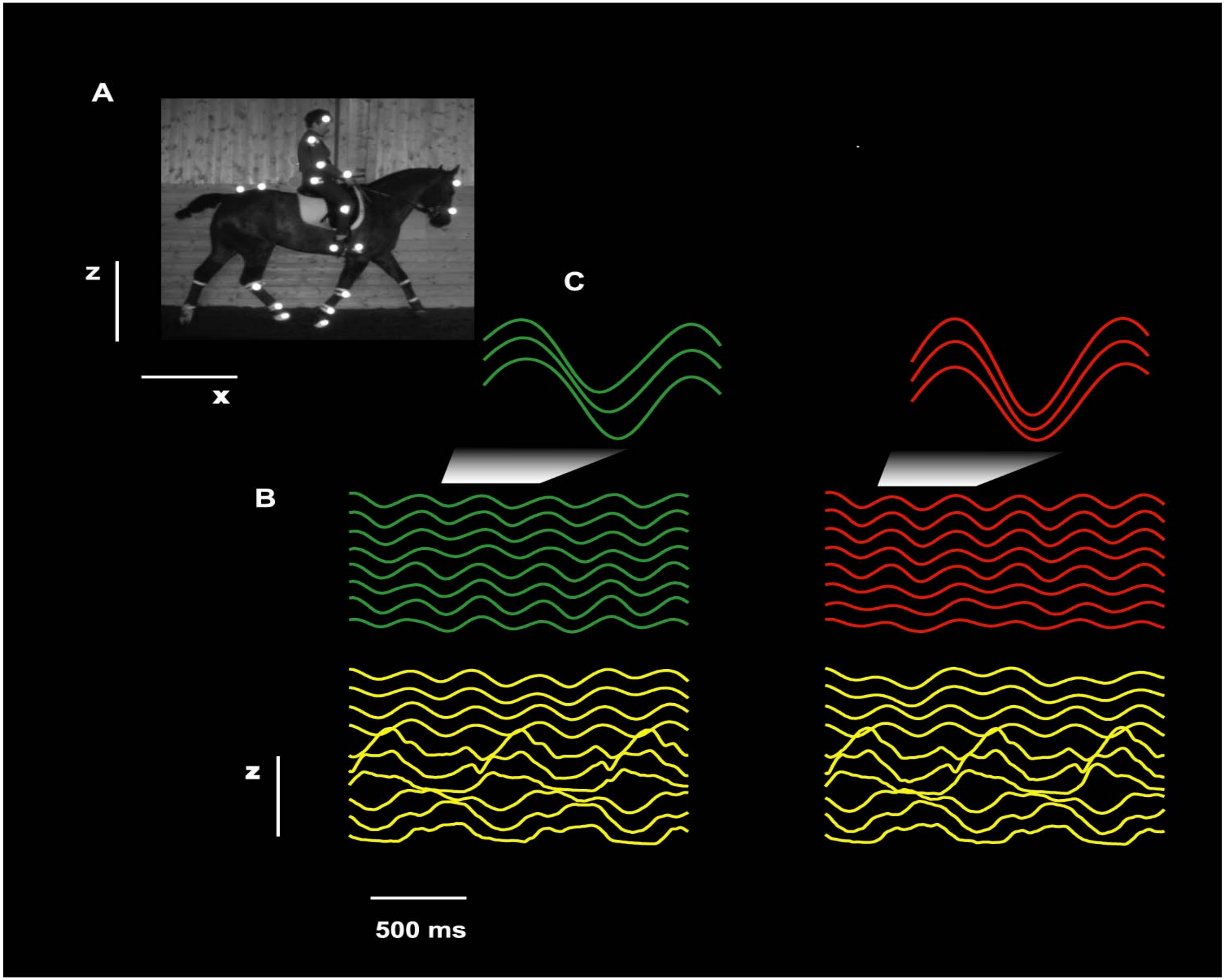
individual ~ collective

integration ~ segregation

competition ~ cooperation

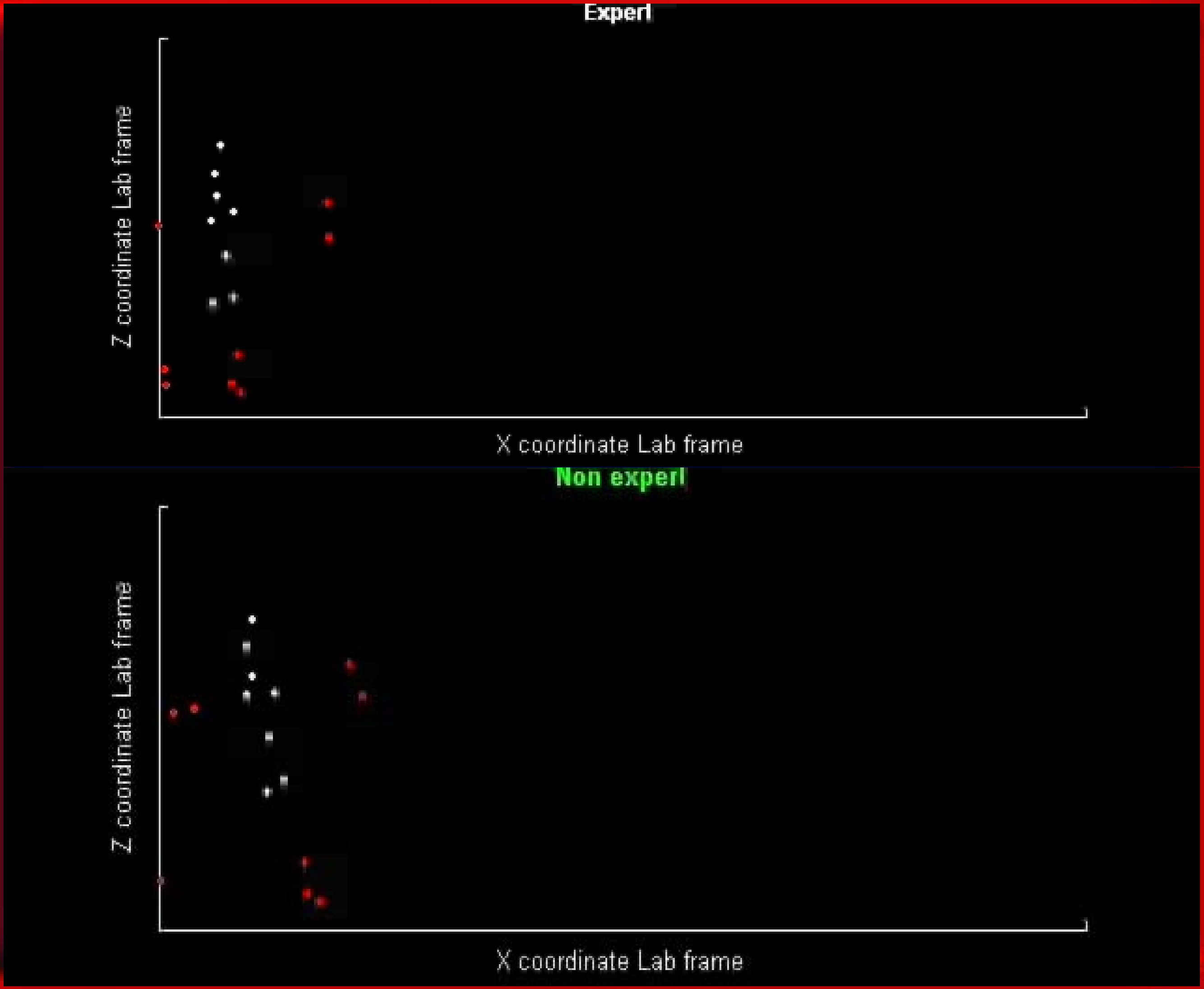
convergence ~ divergence, etc.

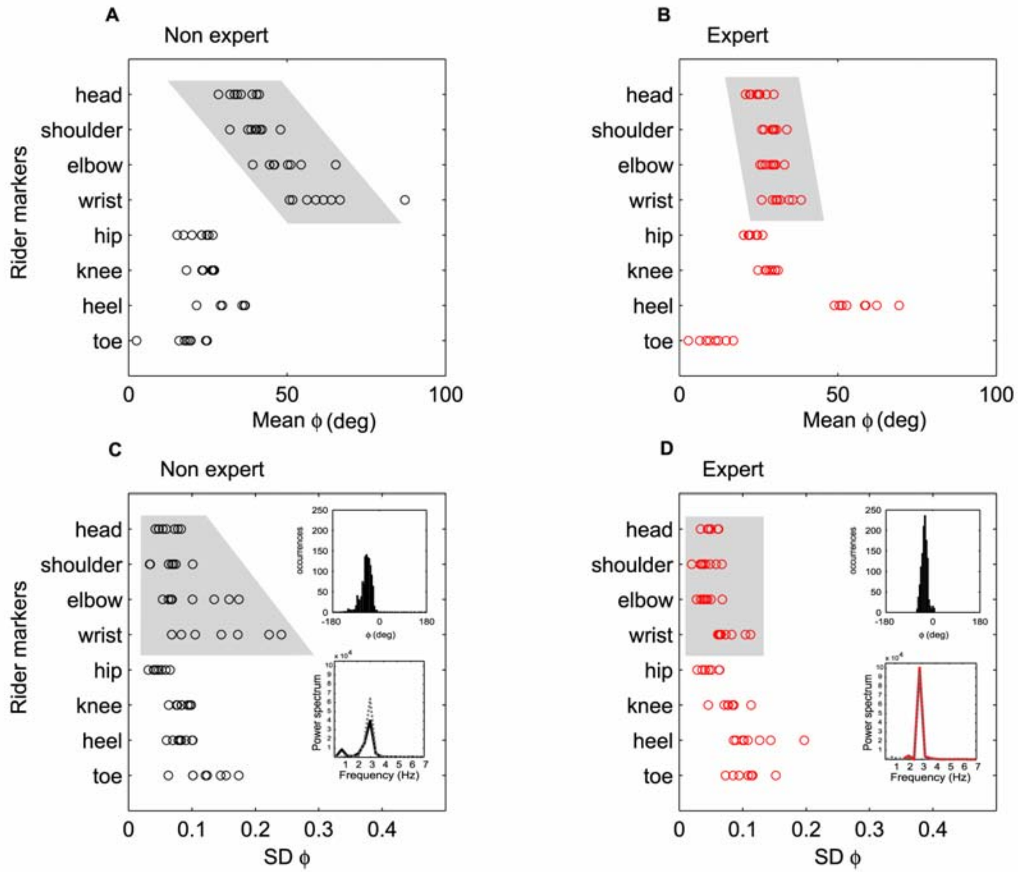
Horse ~ Rider Coordination



Lagarde, Peham, Licka & Kelso, 2005

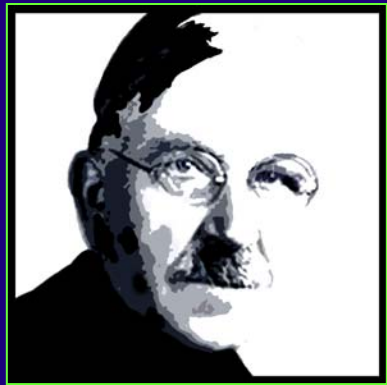
Horse ~ Rider : Novice ~ Expert




A
Non expert
head
shoulder
elbow
wrist
hip
knee
heel
toe
Rider markers
0
50
100
Mean ϕ (deg)
B
Expert
C
Non expert
SD ϕ
0.1
0.2
0.3
0.4
D
Expert
occurrences
ϕ (deg)
Power spectrum
Frequency (Hz)

The paradigm shift

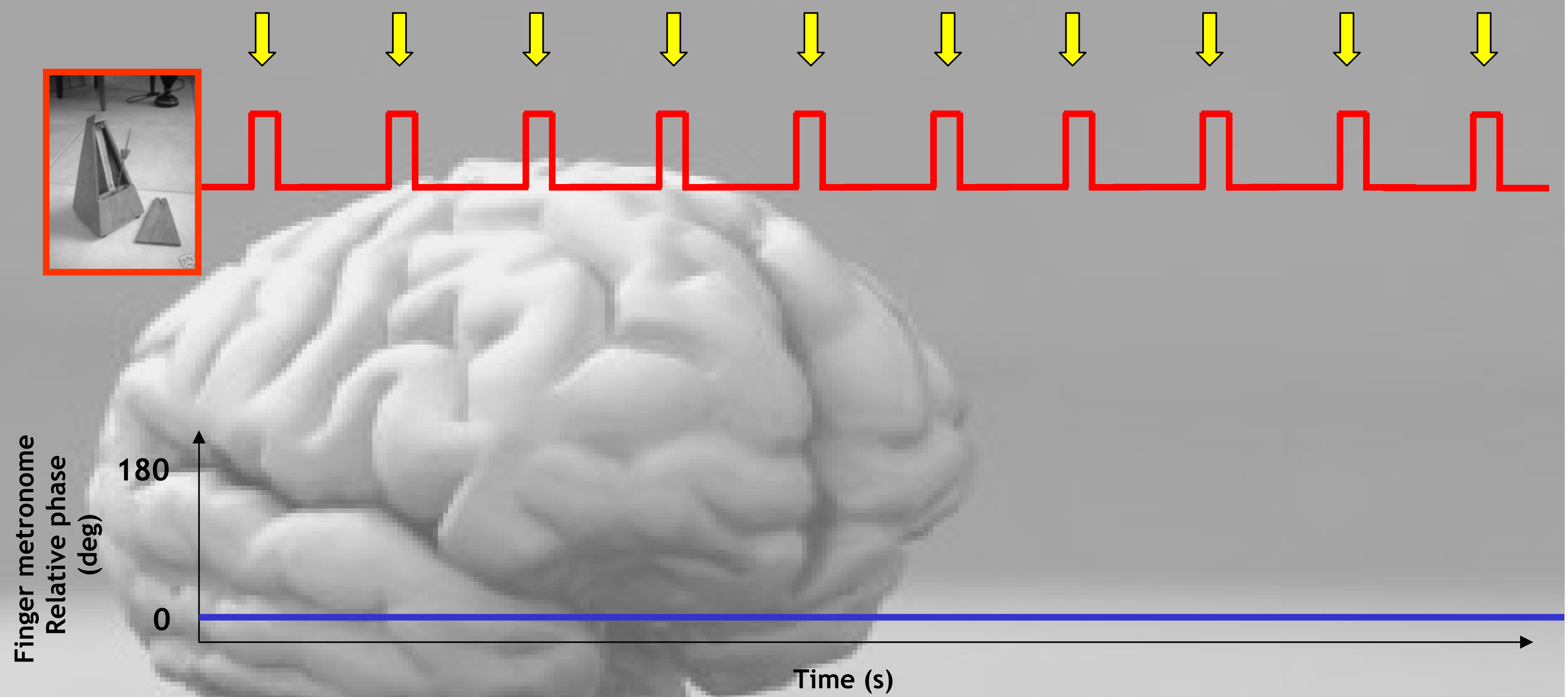
- Qualitative change allows the clear distinction between one pattern and another (N.B. Coordination variables and coordination dynamics are NOT KNOWN a priori!)
- Near critical points, essential processes governing pattern stability, flexibility and selection can be uncovered
- …theoretically motivated measures are available to test predicted features of self-organization
- Control parameters can be determined that promote instabilities and change
- Relation of levels: around transitions patterns arise as (meta) stable coordination tendencies in a system of nonlinearly coupled components.



Action ~ Perception; reaction ~ anticipation; the magic of touch (binding, etc)

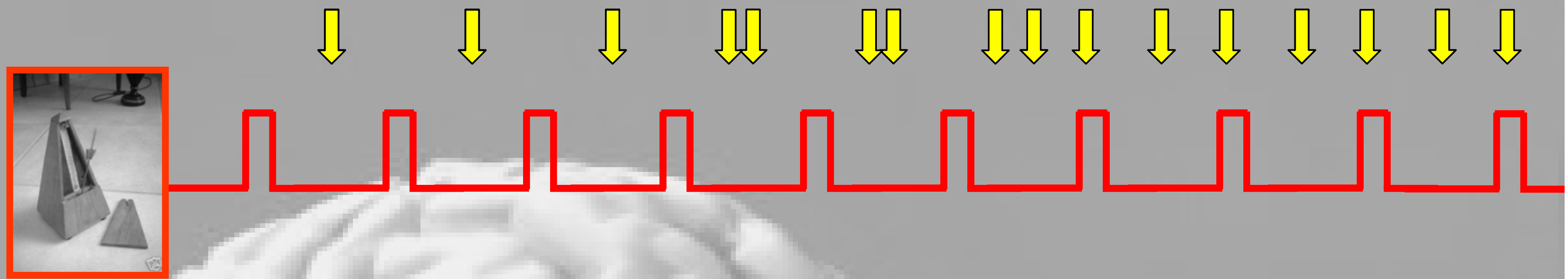
"*Stimuli and response do not exist separately but inside a context-dependent coordination*" (Dewey, 1896)

Synchronization: *on-the-beat coordination*

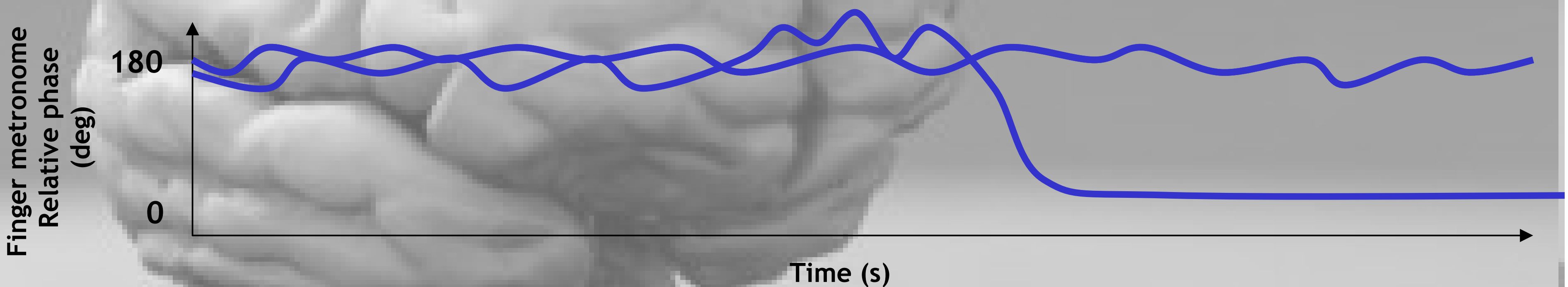


Kelso et al., 1990

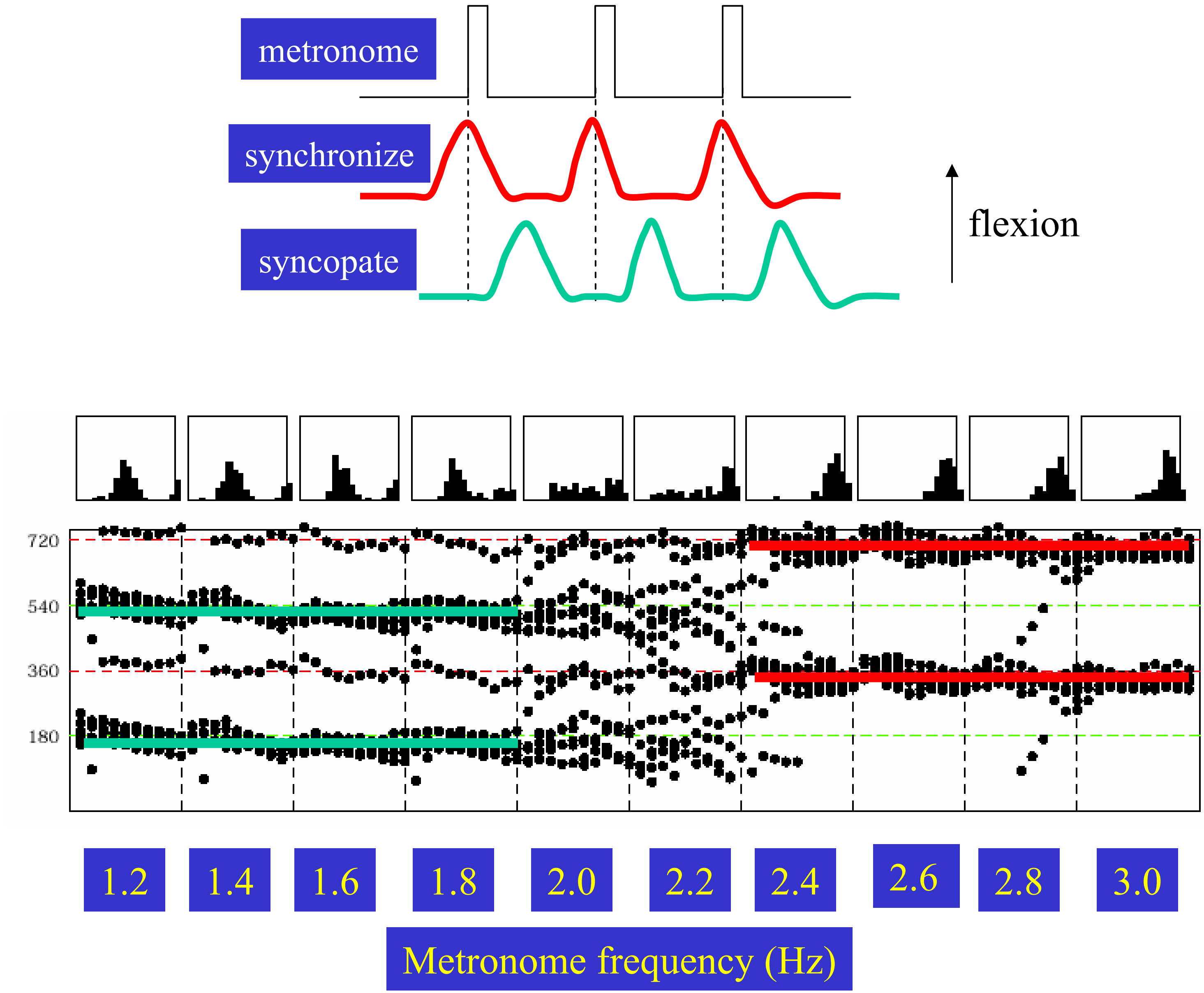
Syncopation: *off-the-beat coordination*



Phase transition from syncopation to synchronization

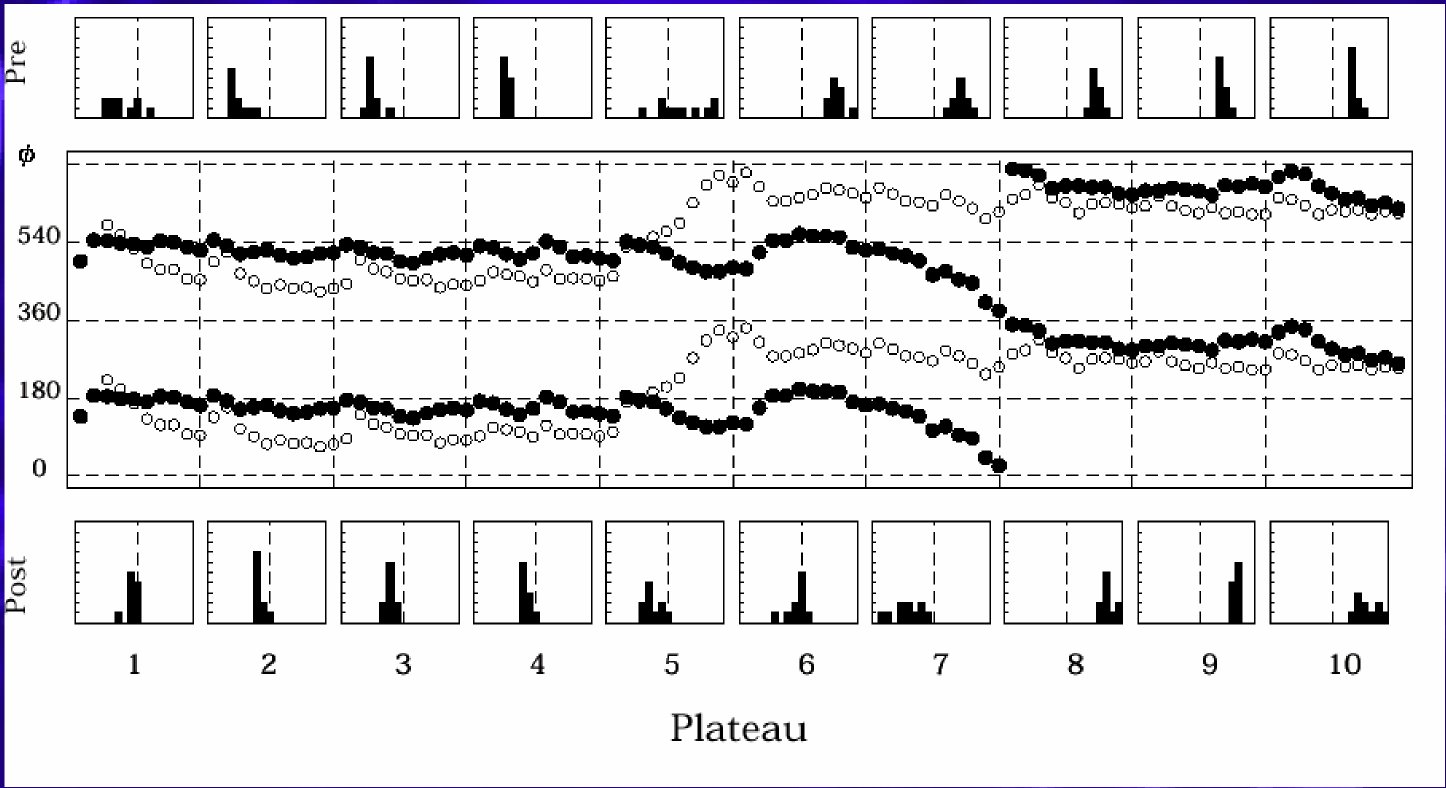


Kelso et al., 1990

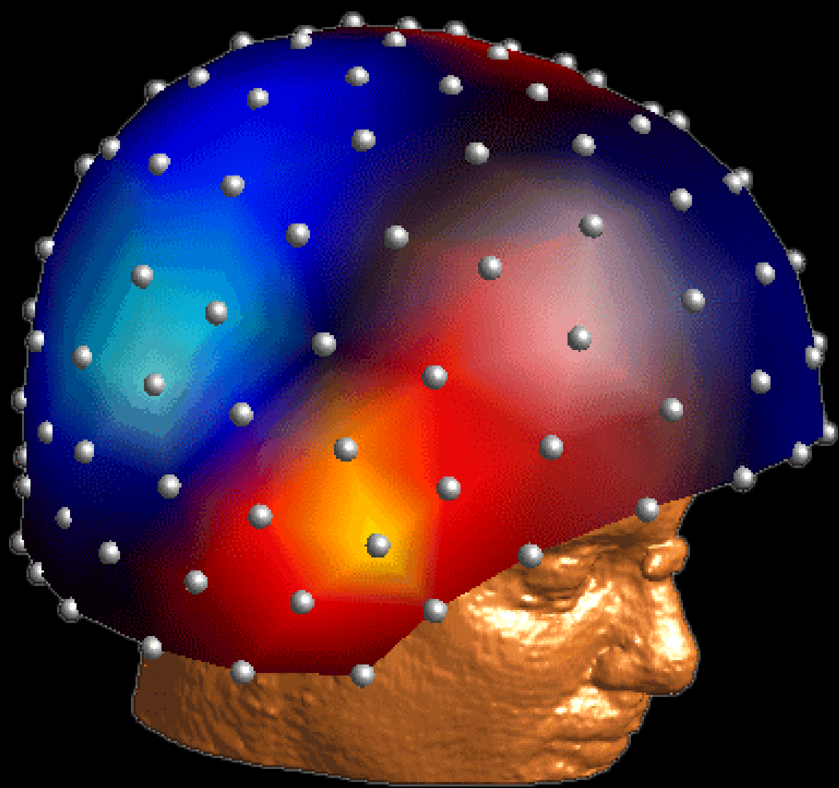


metronome
synchronize
syncopate
flexion
720
540
360
180
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0
Metronome frequency (Hz)

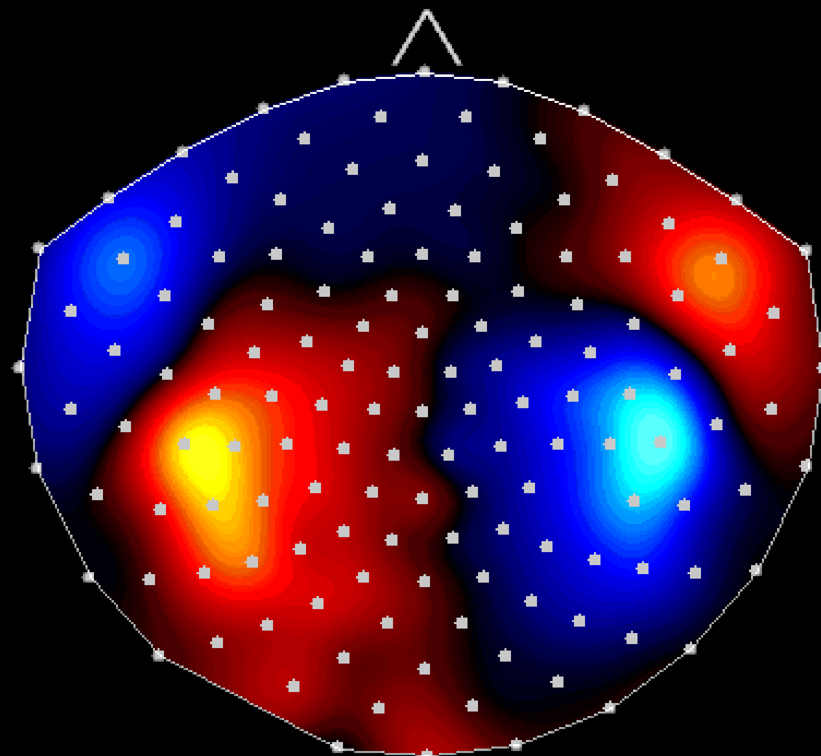
Learning delays transitions in behavior…



Neuromagnetic Field Activity from a 143-SQuID Array



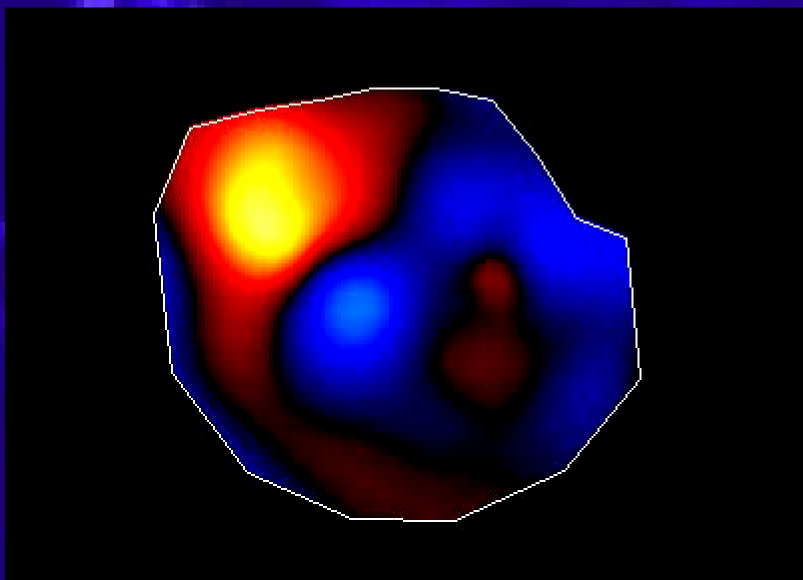
On subject's head

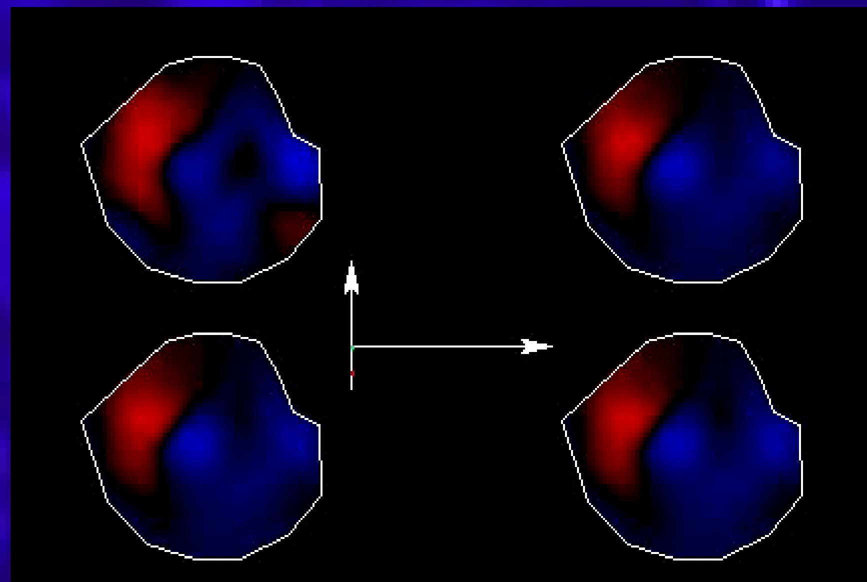


In polar projection

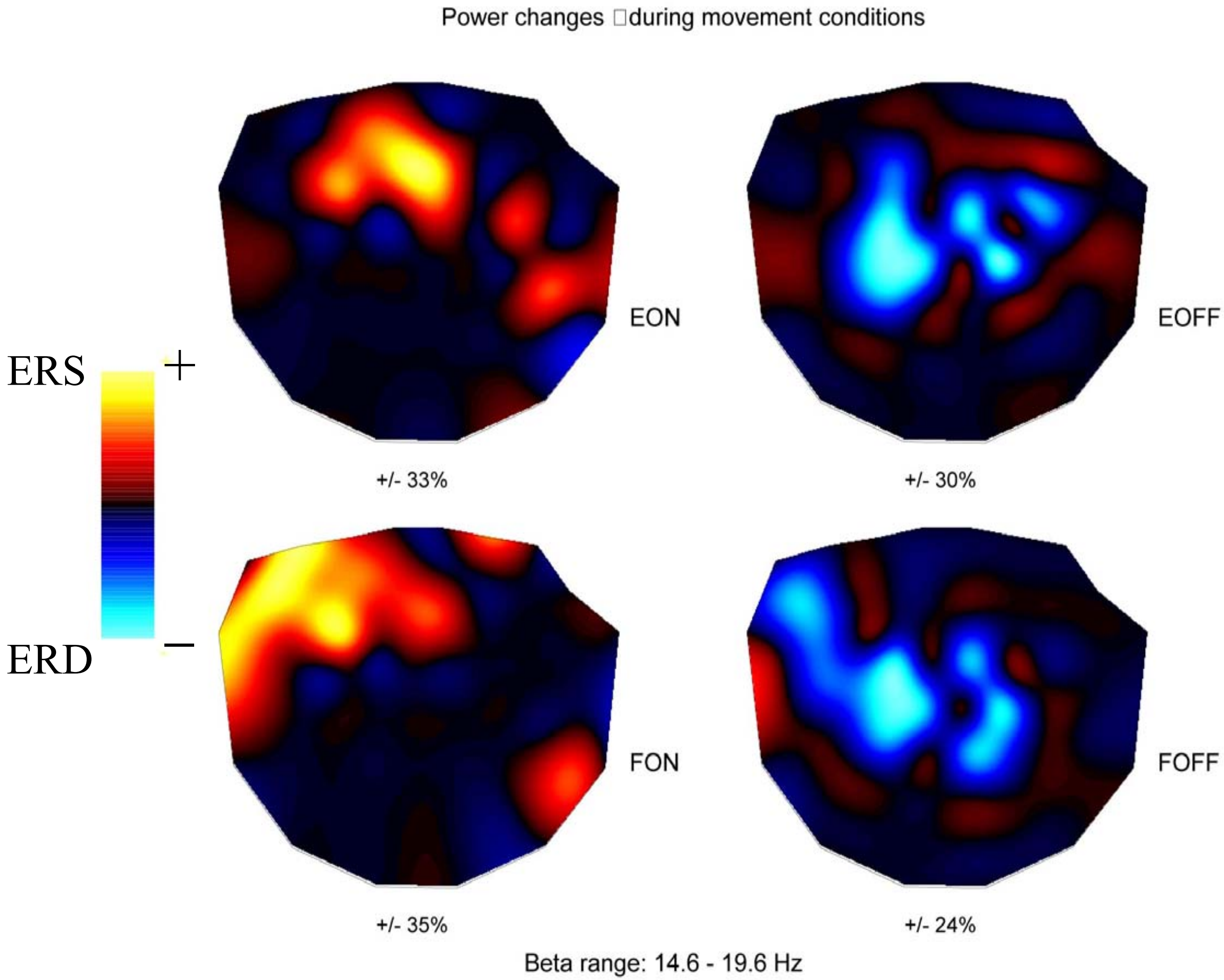
Example

Spatiotemporal dynamics of human brain

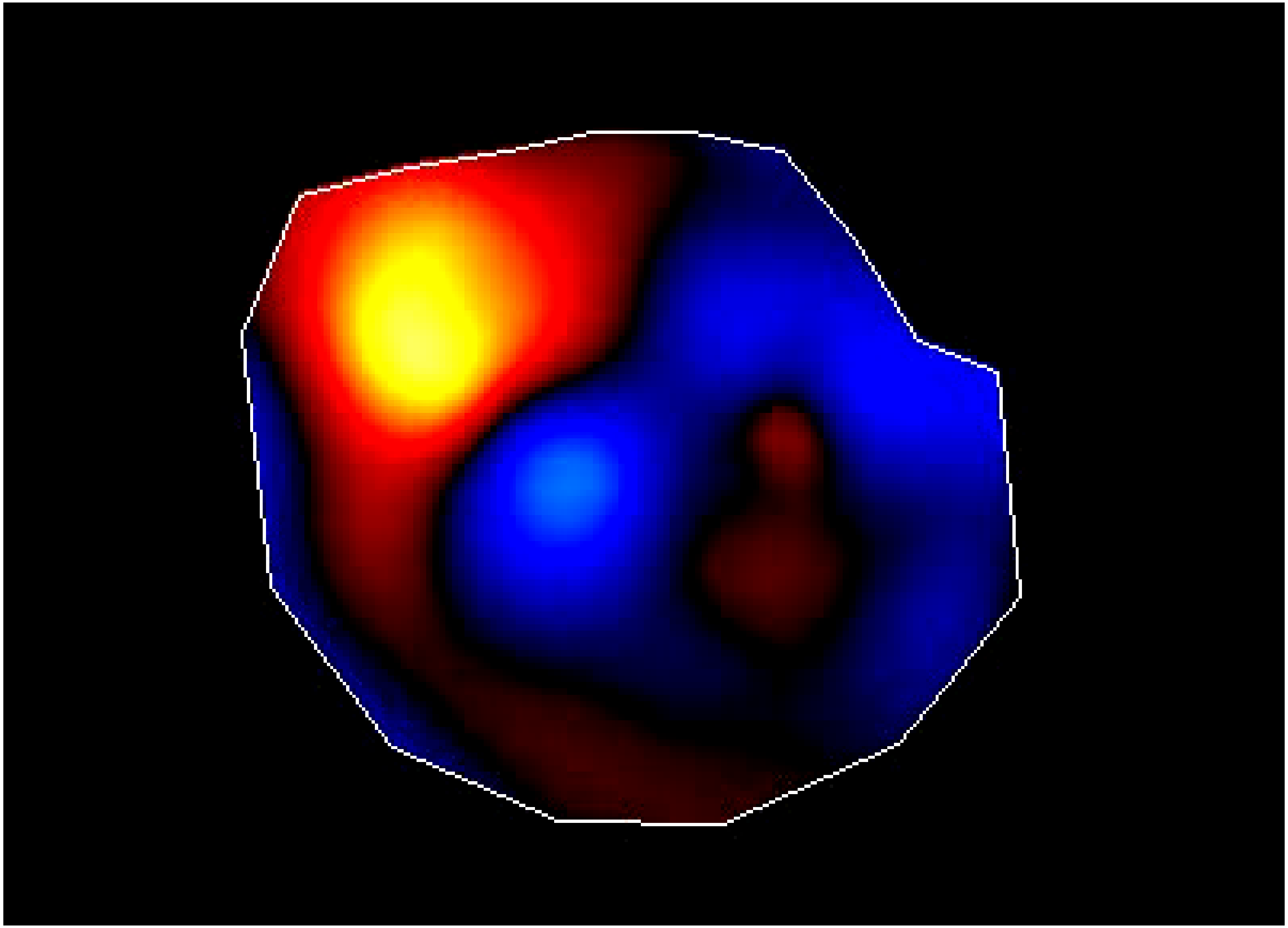




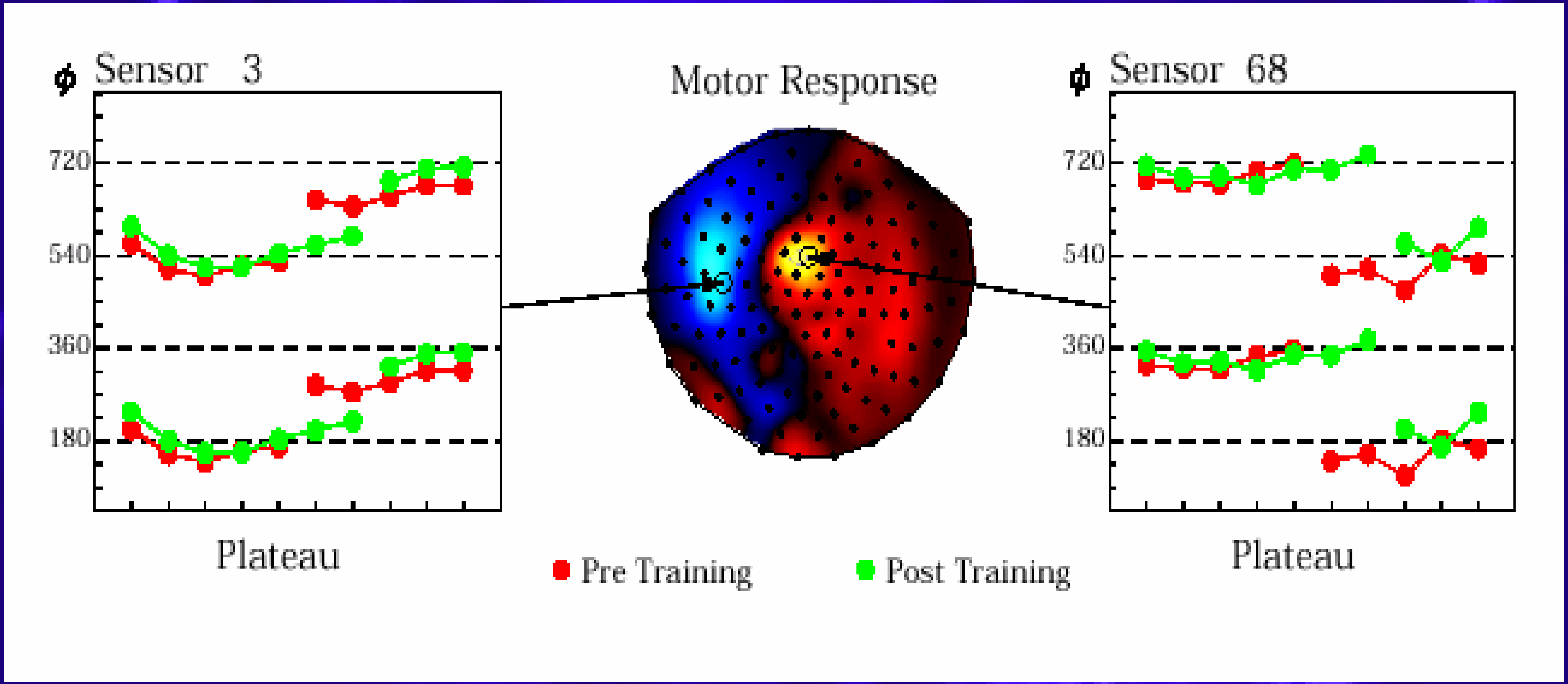
Beta (15-20Hz) Activity Differentiates between Synchronization and Syncopation Conditions



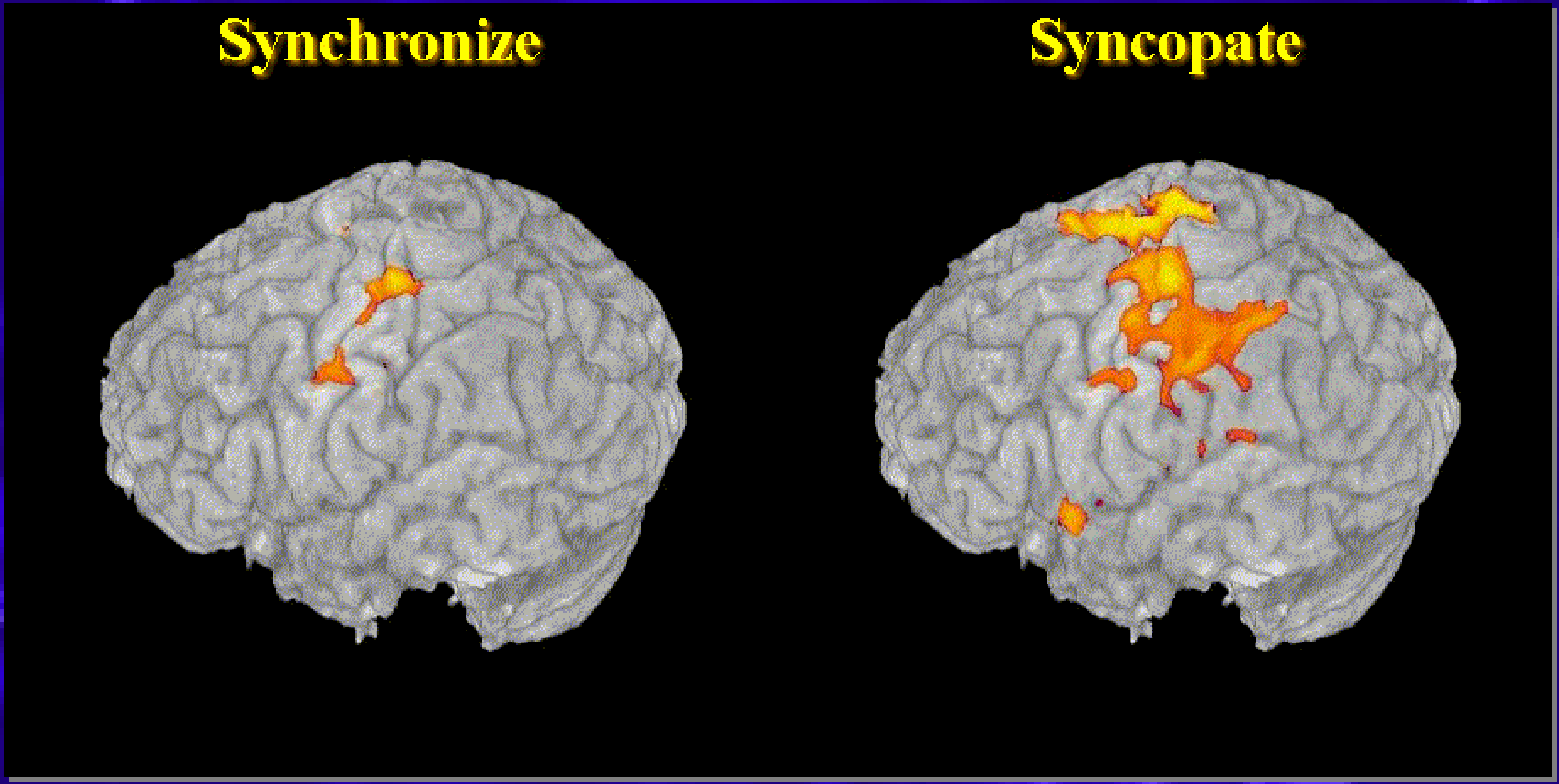
Chen, Ding & Kelso, *EBR* (2003)

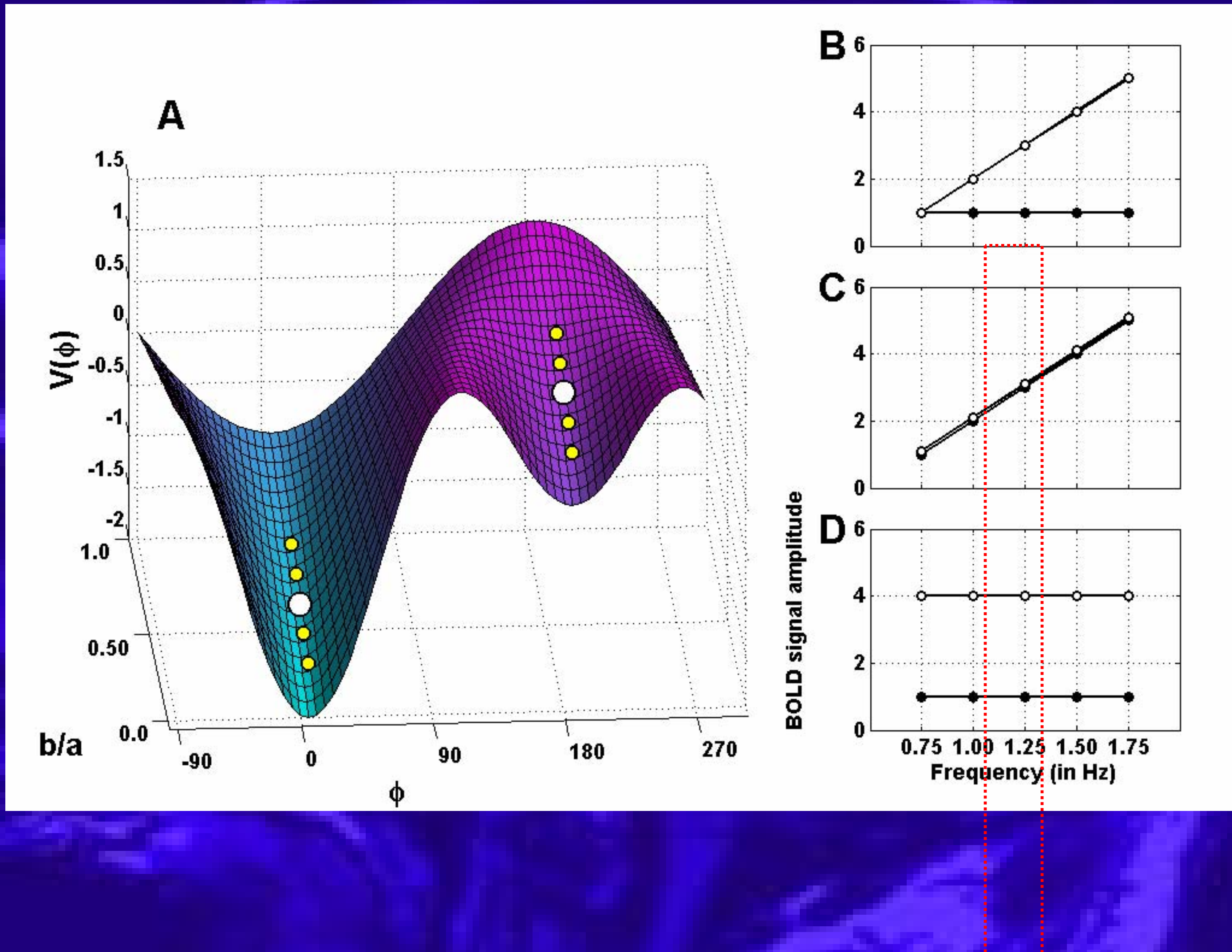


And in the brain too....



Functional Organization of the Brain is History- and Context-Dependent





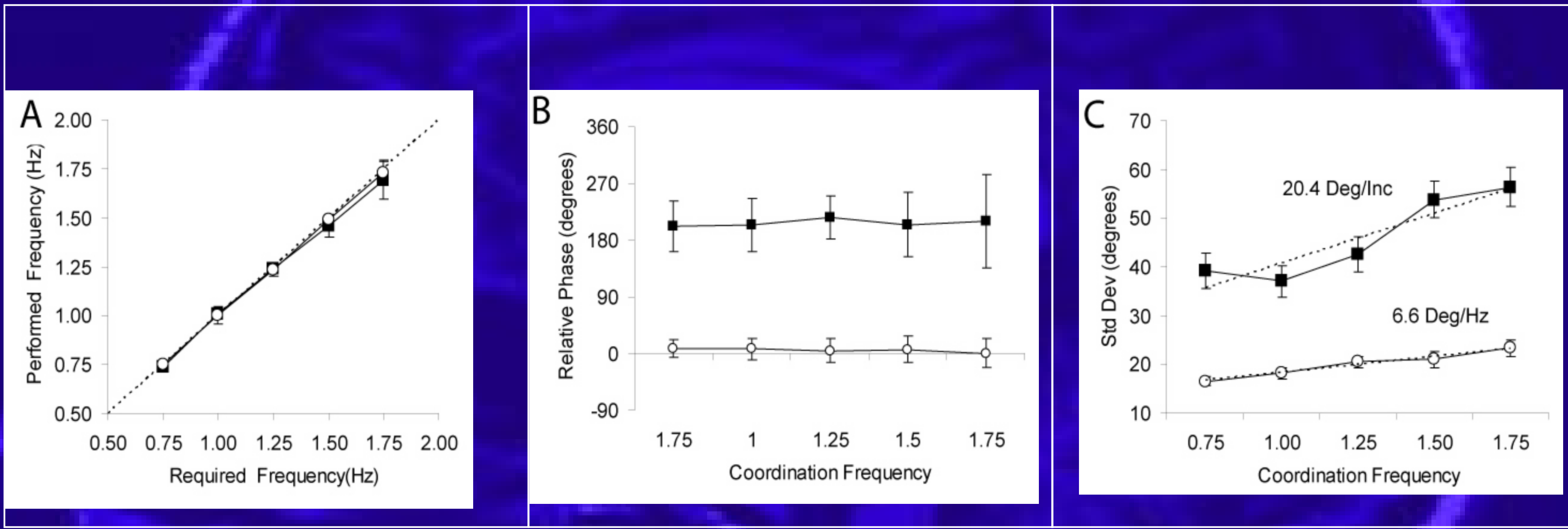
A
1.5
1
0.5
0
-0.5
-1
-1.5
-2
V(ϕ)
1.0
0.50
0.0
b/a
-90
0
90
180
270
ϕ
B
C
D
6
4
2
0
BOLD signal amplitude
0.75
1.00
1.25
1.50
1.75
Frequency (in Hz)

Performance Measures

A. Accuracy of performed coordination rate

B. Accuracy of performed relative phase

C. Relative stability of patterns across rate



■ **Syncopation** ○ **Synchronization**

In both coordination tasks, Ss accurately produce the mean required rate (frequency) and relative phase.

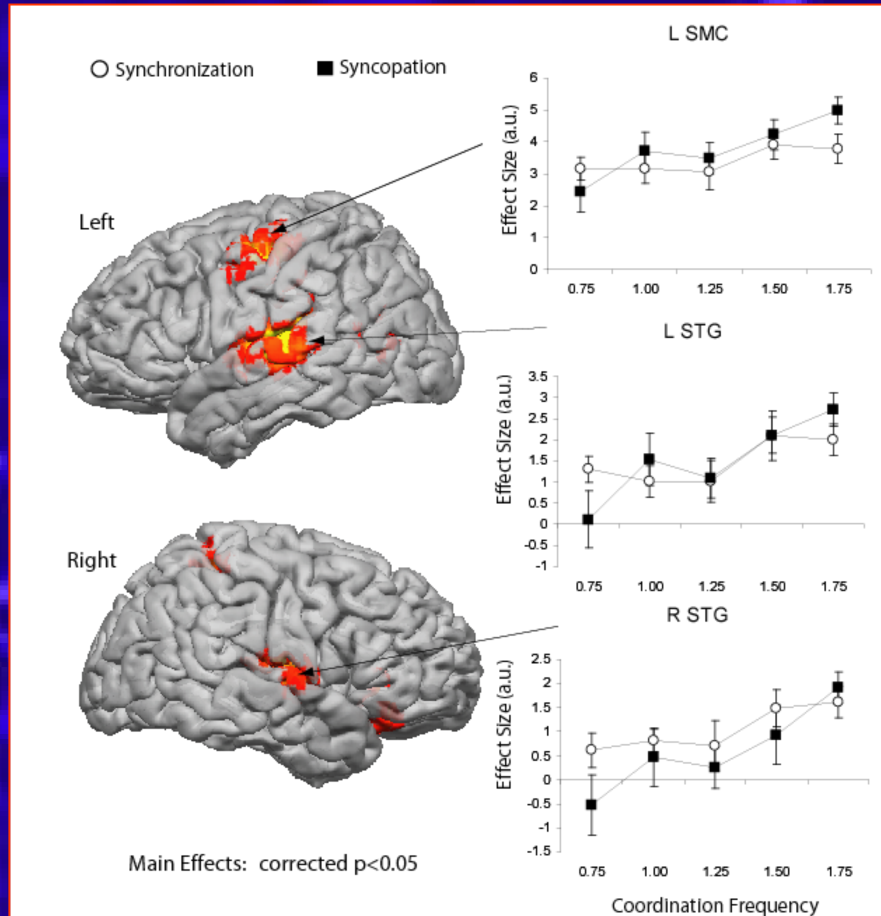
But syncopation pattern is much less *stable* (higher sd) than synchronization, especially as frequency increases.

KJ Jantzen

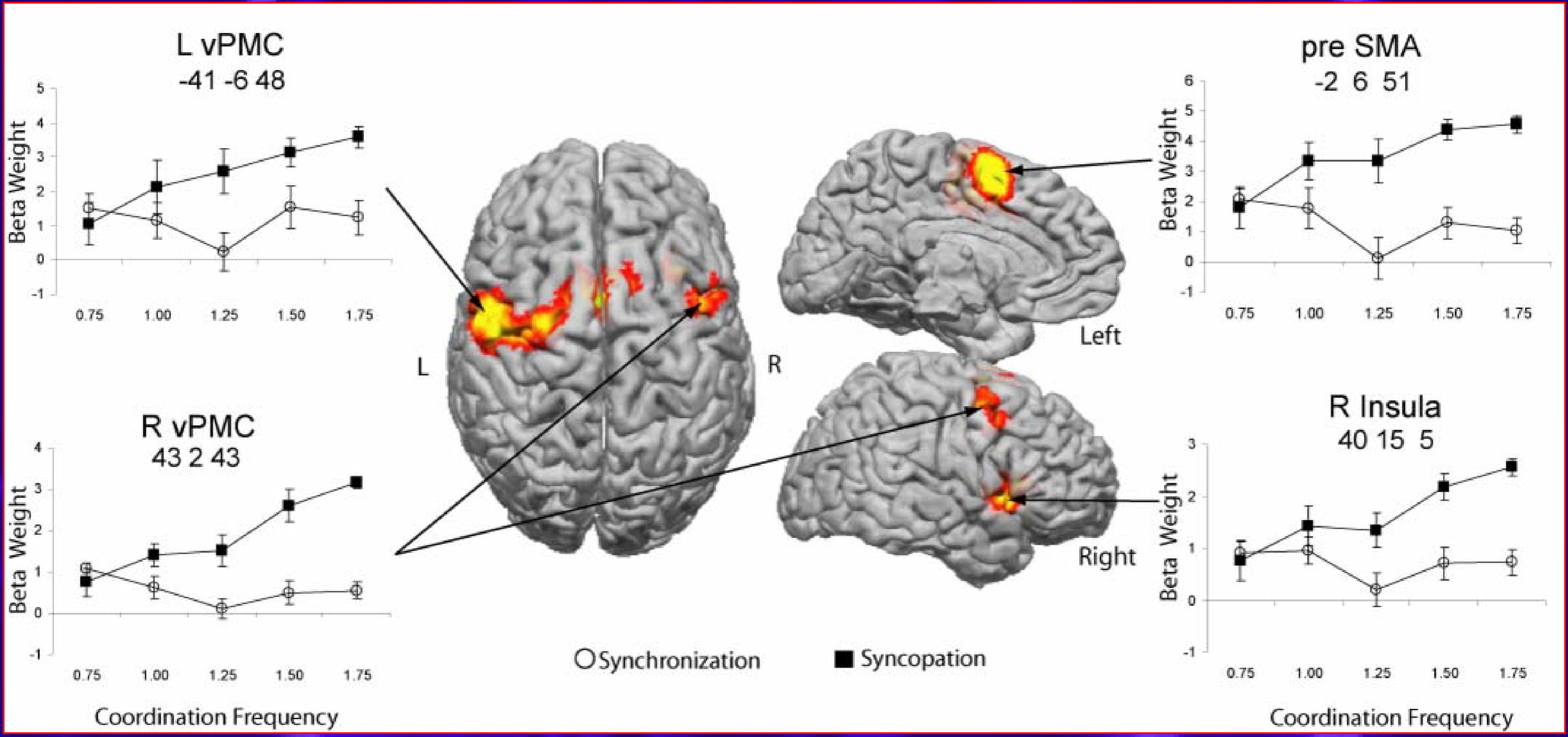
Brain Areas Sensitive to Rate Regardless of Pattern stability

Brain areas showing rate dependent increases in BOLD for BOTH coordination patterns

- **Contralateral Sensorimotor Cortex**
  - **L SMC**
- **Bilateral Superior Temporal Gyrus**
  - **L STG & R STG**



Neural correlates of pattern stability



Some brain areas are directly related to the *stability* of the coordination pattern, not to speed or accuracy.

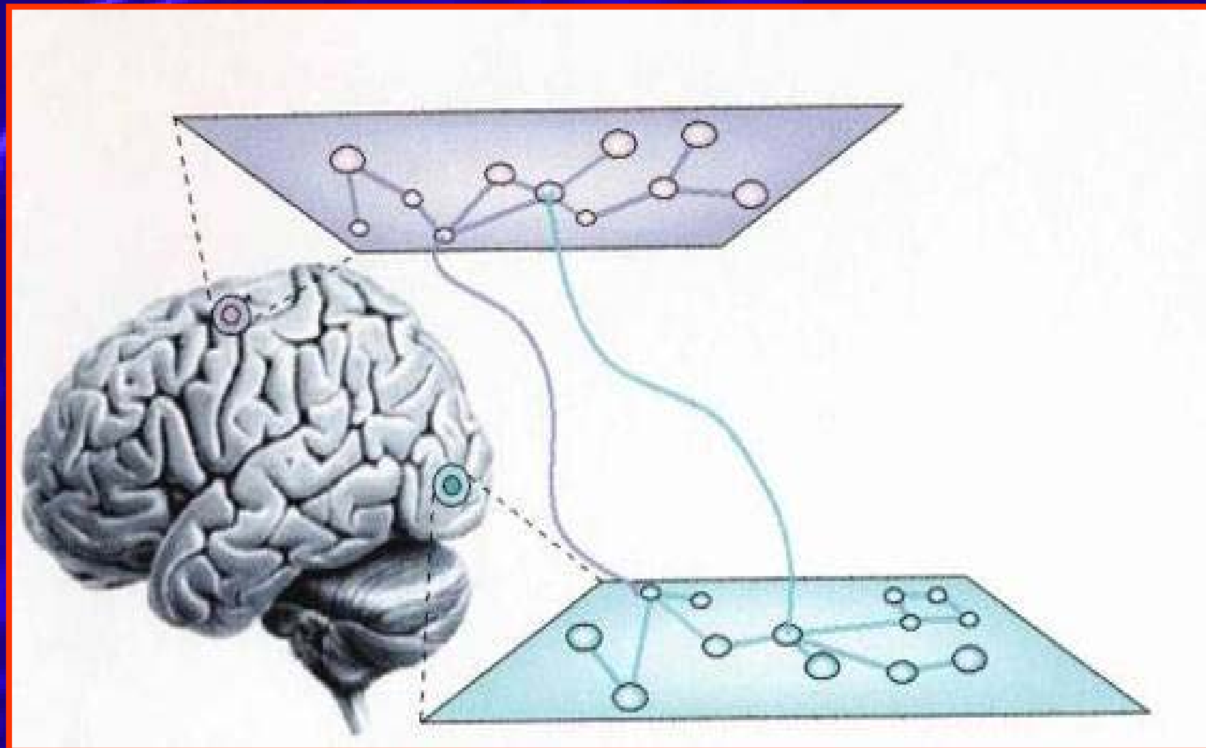
BOLD and BEHAVIOR

- Stability measures of behavioral and cognitive performance are directly related to the magnitude of the BOLD effect. How hard the "parts" of the brain have to work depends on pattern stability

- The dynamic concept of stability (which can be measured) replaces vague ideas about "task difficulty" and "task complexity"

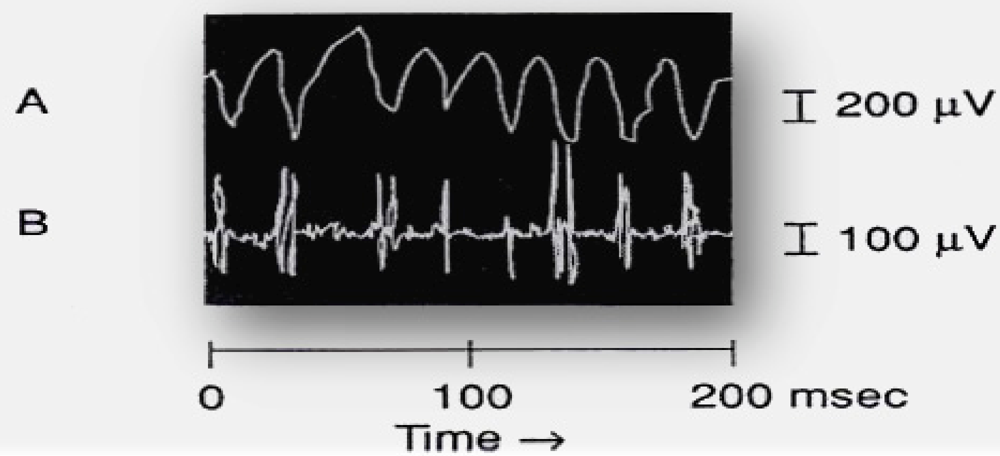
- Big emphasis on brain connectivity. But what if the "parts"—specialized brain regions—carry some of the coupling or the potential to couple?

Coordination Dynamics of the Human Brain



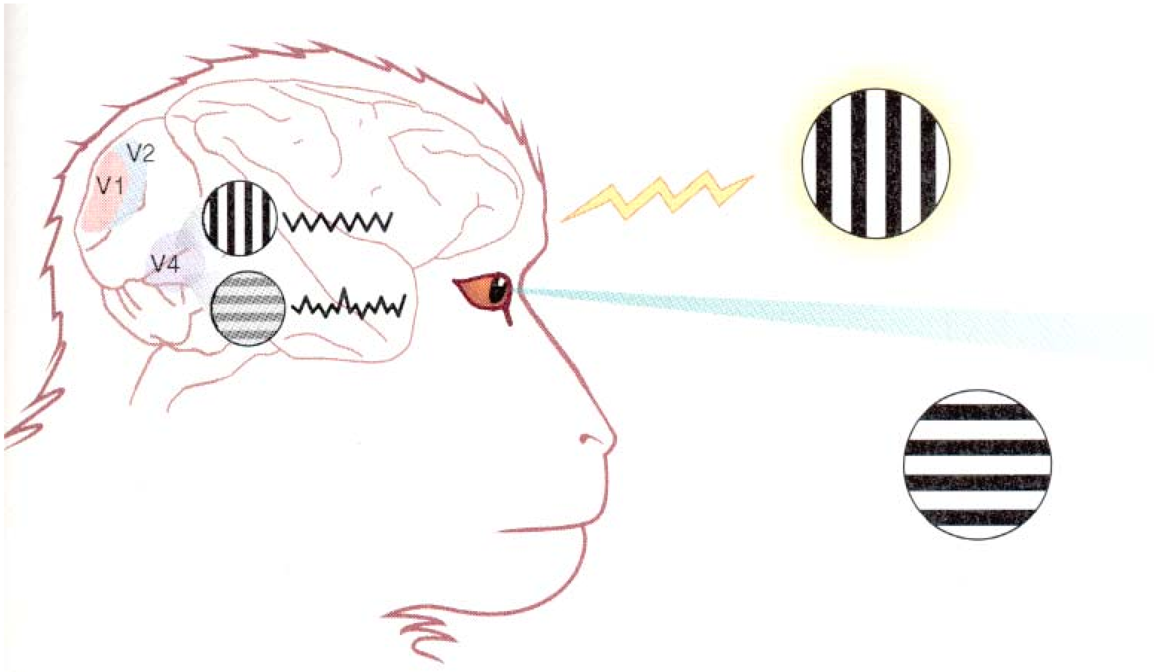
Research News

The Mind Revealed?



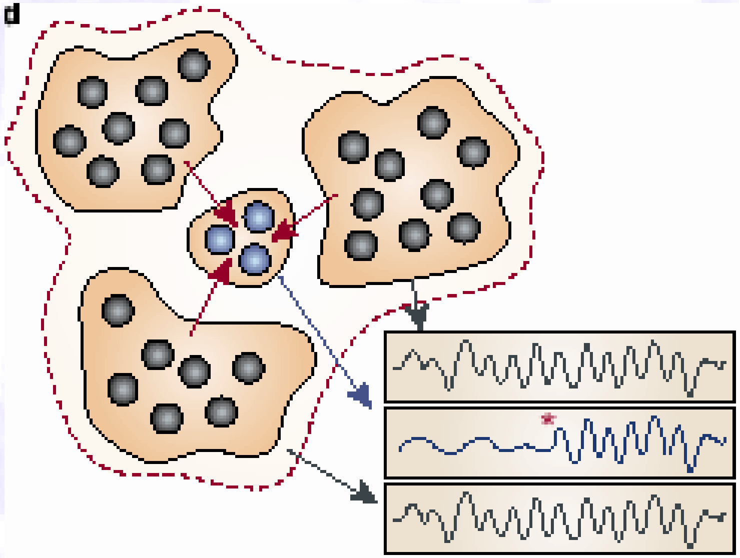
Drums Keep Pounding a Rhythm in the Brain

Michael P. Stryker

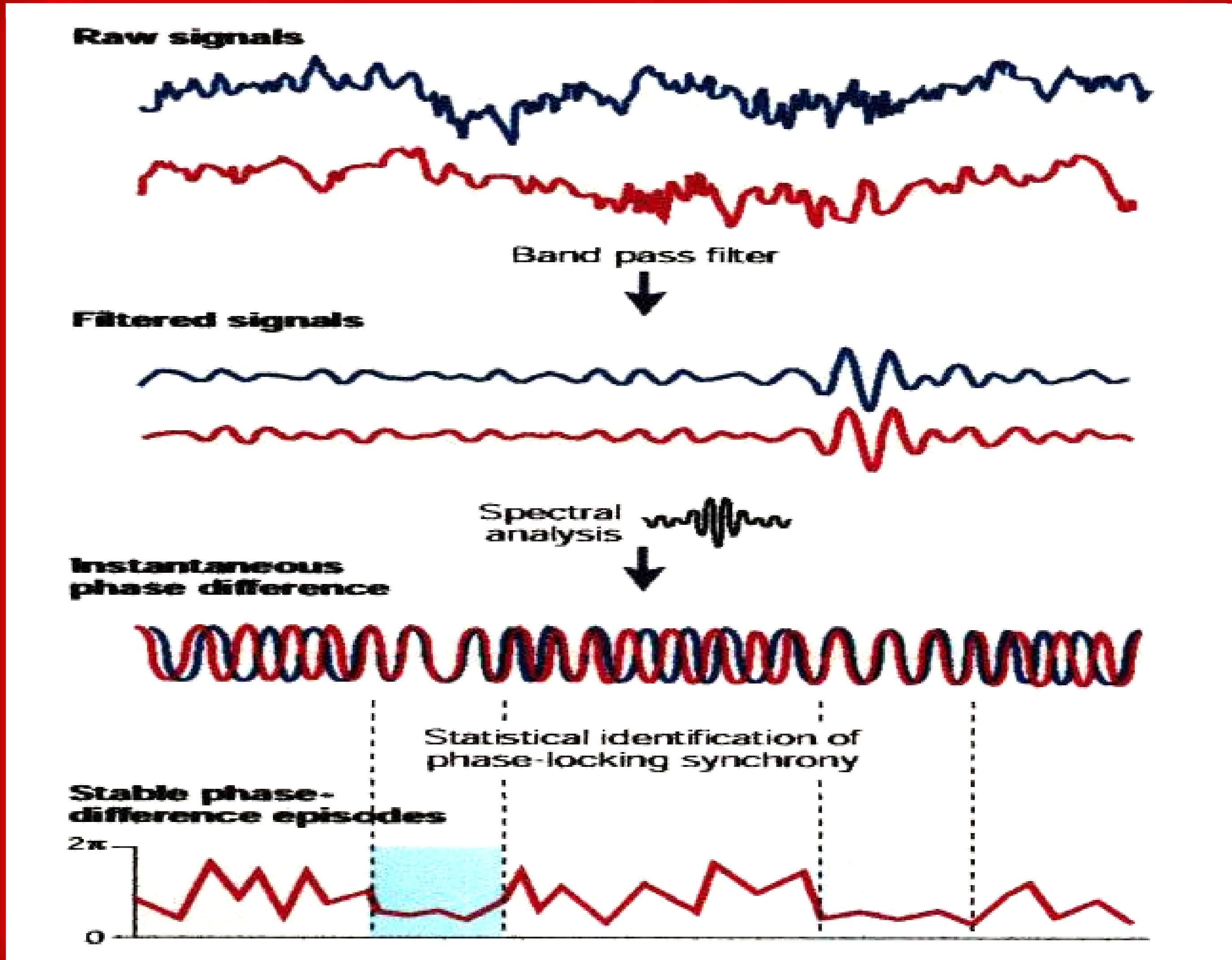


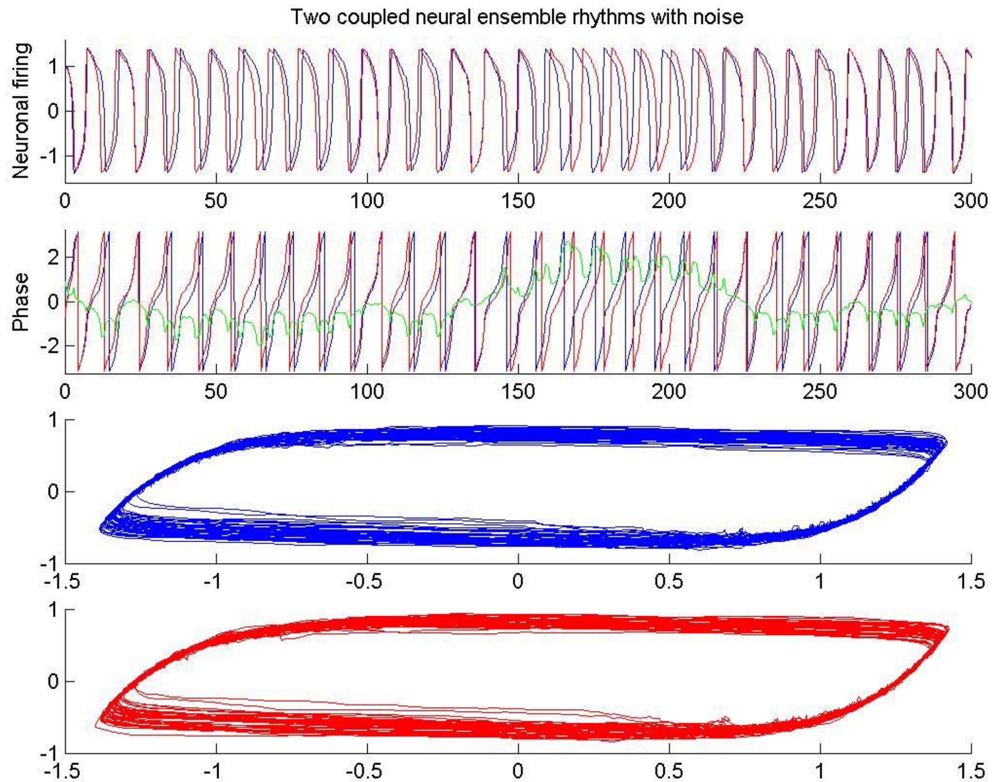
Science Vol 291 23 February 2001

Synchrony



"…a temporal binding mechanism could establish relationships between neuronal responses over large distances, solving the integration problem imposed by the anatomical segregation of specialized processing areas."

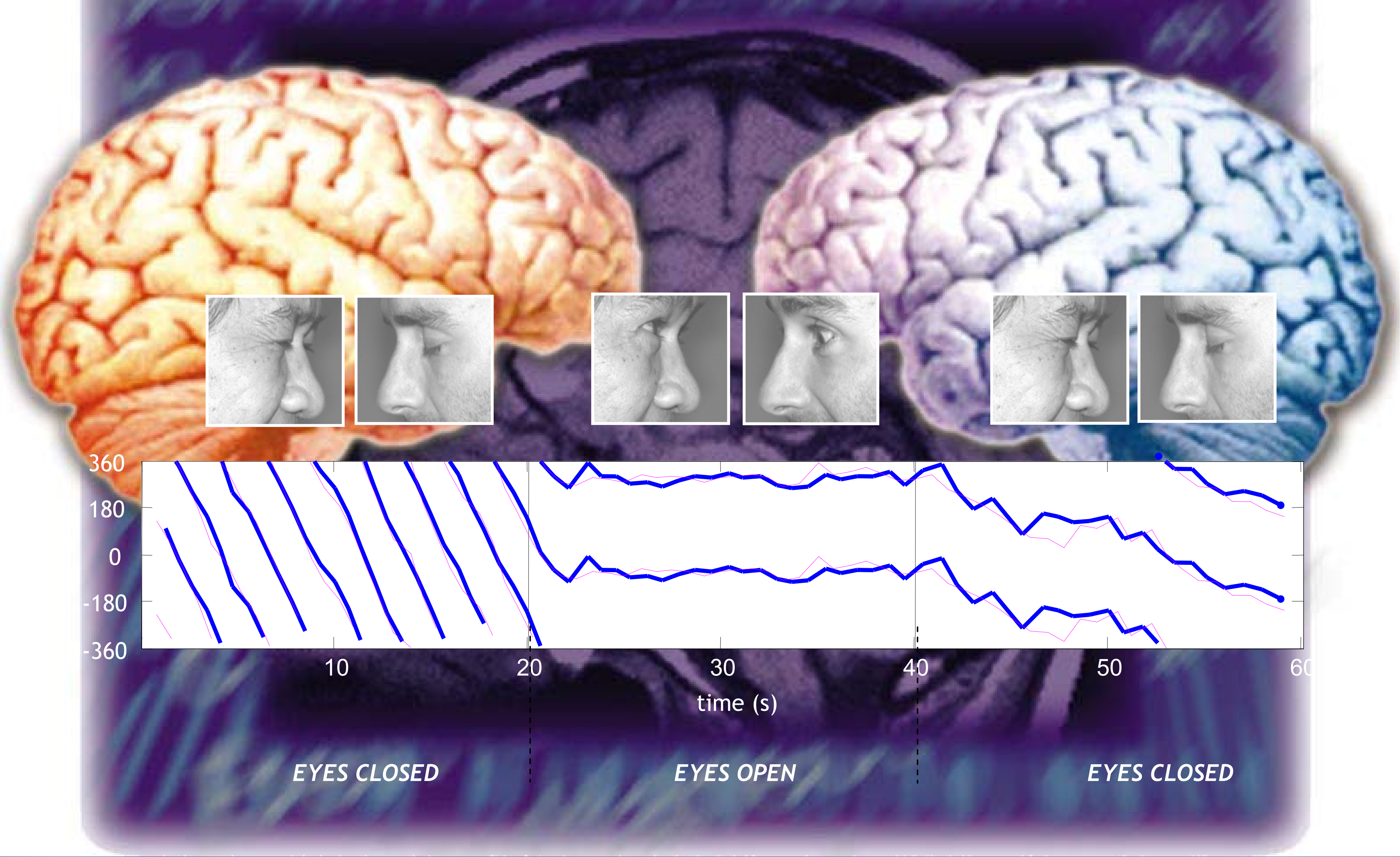

Raw signals
Band pass filter
Filtered signals
Spectral analysis
Instantaneous phase difference
Statistical identification of phase-locking synchrony
Stable phase-difference episodes
2π
0

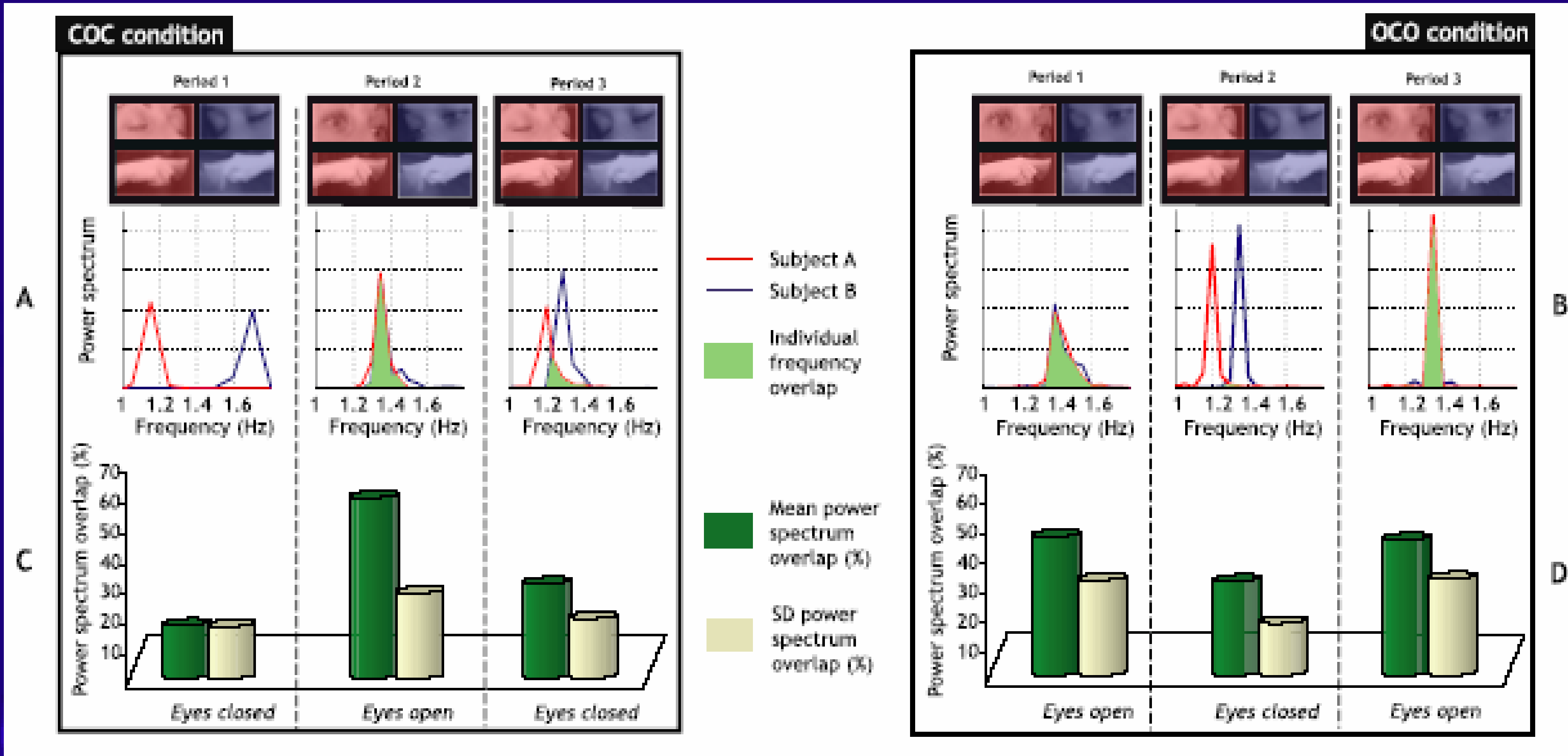


$$\frac{dX}{dt} = F(X) = \frac{\partial}{\partial t} S(X - Y) + noise$$

$$\frac{dY}{dt} = F(Y) = \frac{\partial}{\partial t} S(Y - X) + noise$$

The sight of two brains talking





COC condition
OCO condition
Period 1
Period 2
Period 3
A
B
C
D
Power spectrum
1 1.2 1.4 1.6
Frequency (Hz)
Subject A
Subject B
Individual frequency overlap
Mean power spectrum overlap (%)
SD power spectrum overlap (%)
Power spectrum overlap (%)
70
60
50
40
30
20
10
Eyes closed
Eyes open
Eyes closed
Eyes open
Eyes closed
Eyes open

MODIFICATION OF THE DYNAMICS DUE TO INTERACTION ?

Some possible factors: memory, structural instability, boundary conditions, etc

Before interaction

$$\ddot{x}_1 + i_1(x_1, \dot{x}_1, a_1) + \omega_1^2 x_1 = 0$$
$$\ddot{x}_2 + i_2(x_2, \dot{x}_2, a_2) + \omega_2^2 x_2 = 0$$

$i_{1,2}$, $\omega_{1,2}$ = intrinsic

UNCOUPLED

During interaction

$$\ddot{x}_1 + I_1(x_1, \dot{x}_1, A_1) + \omega_1^2 x_1 = F_1(x_1, \dot{x}_1, x_2, \dot{x}_2)$$
$$\ddot{x}_2 + I_2(x_2, \dot{x}_2, A_2) + \omega_2^2 x_2 = F_2(x_2, \dot{x}_2, x_1, \dot{x}_1)$$

$I_{1,2}$, $\omega_{1,2}$ = intrinsic modulated by context, boundary conditions

COUPLED

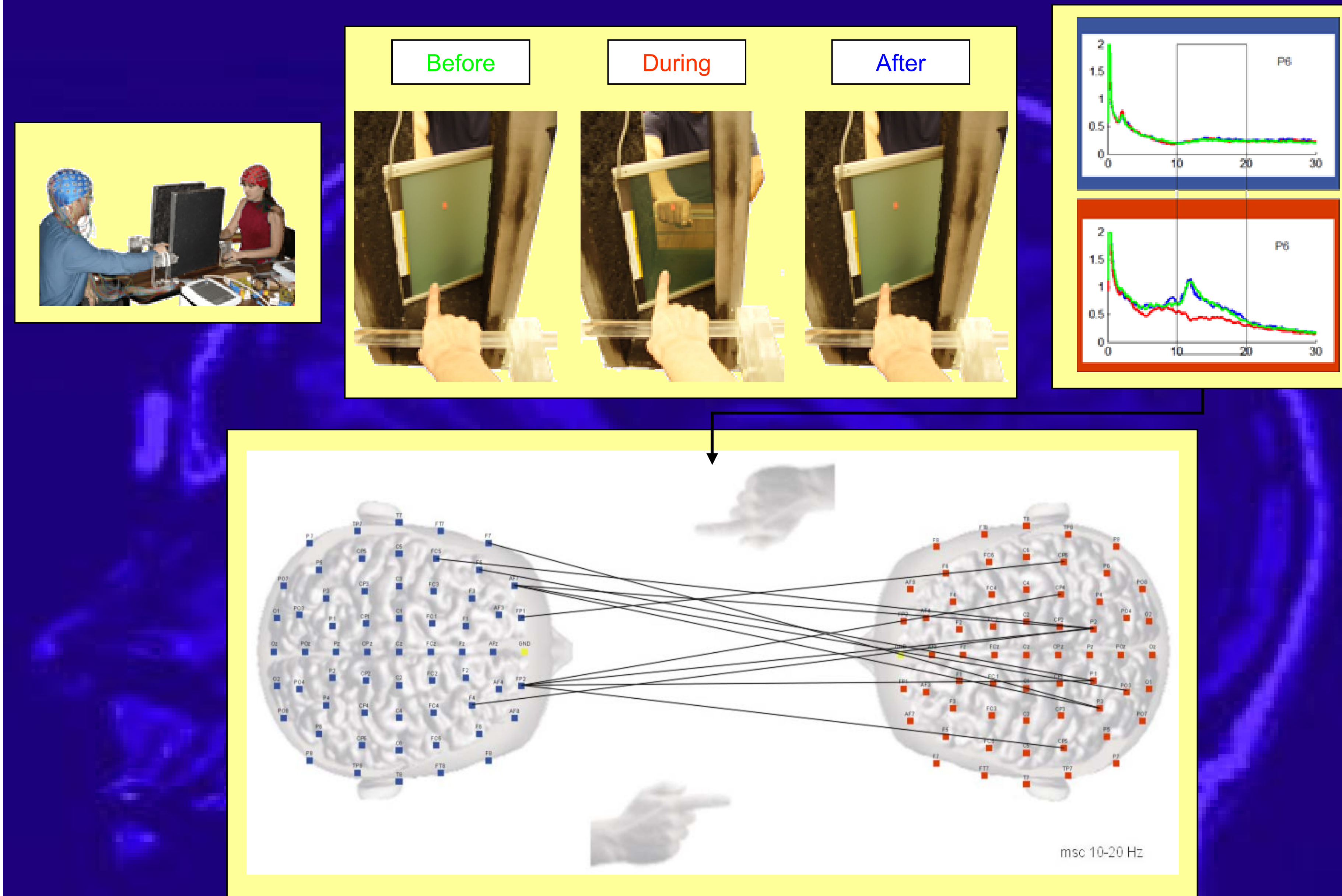
After interaction

$$\ddot{x}_1 + I_1(x_1, \dot{x}_1, A_1) + \omega_1^2 x_1 = 0$$
$$\ddot{x}_2 + I_2(x_2, \dot{x}_2, A_2) + \omega_2^2 x_2 = 0$$

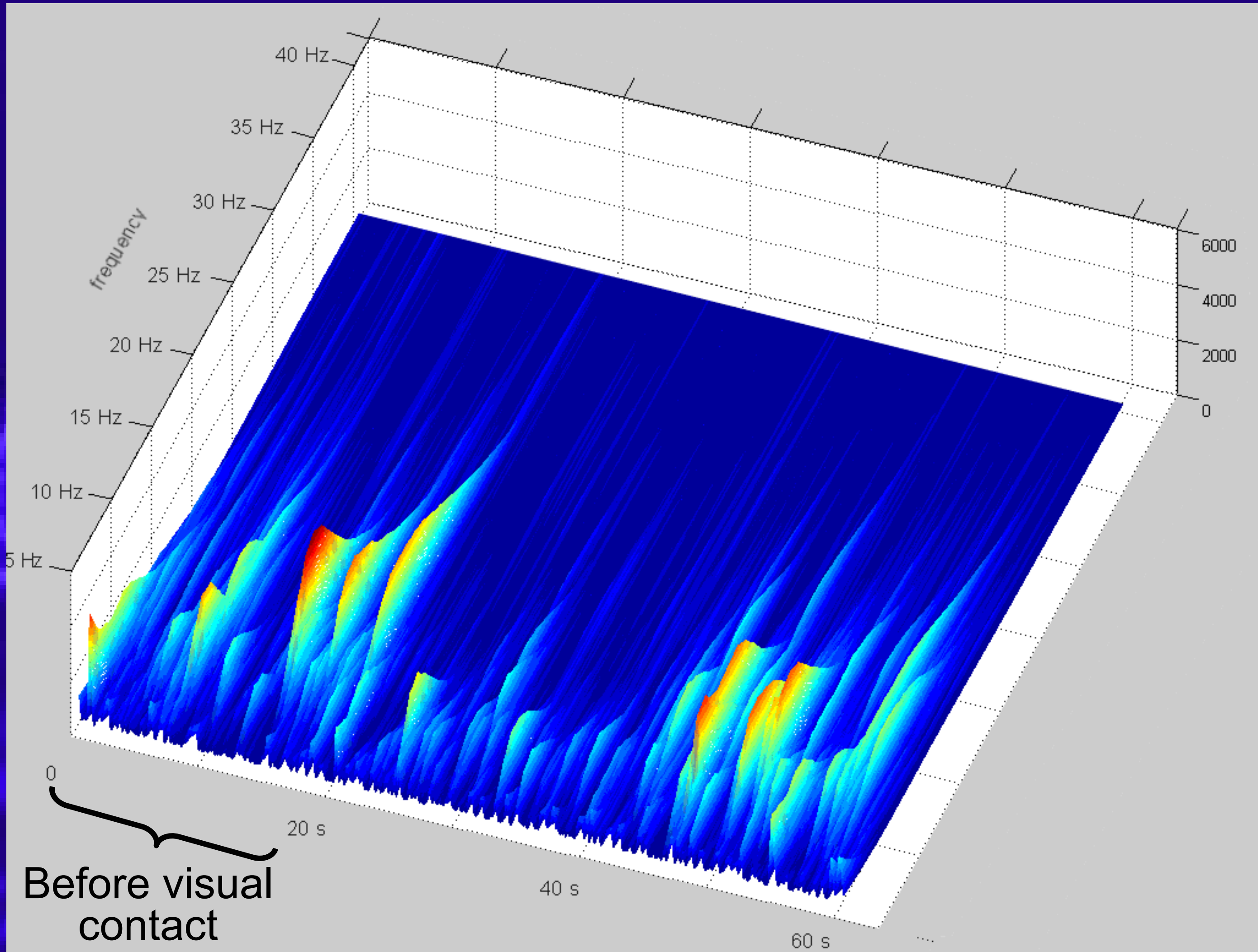
$I_{1,2}$, $\omega_{1,2}$ = intrinsic

UNCOUPLED…but modified by interaction!

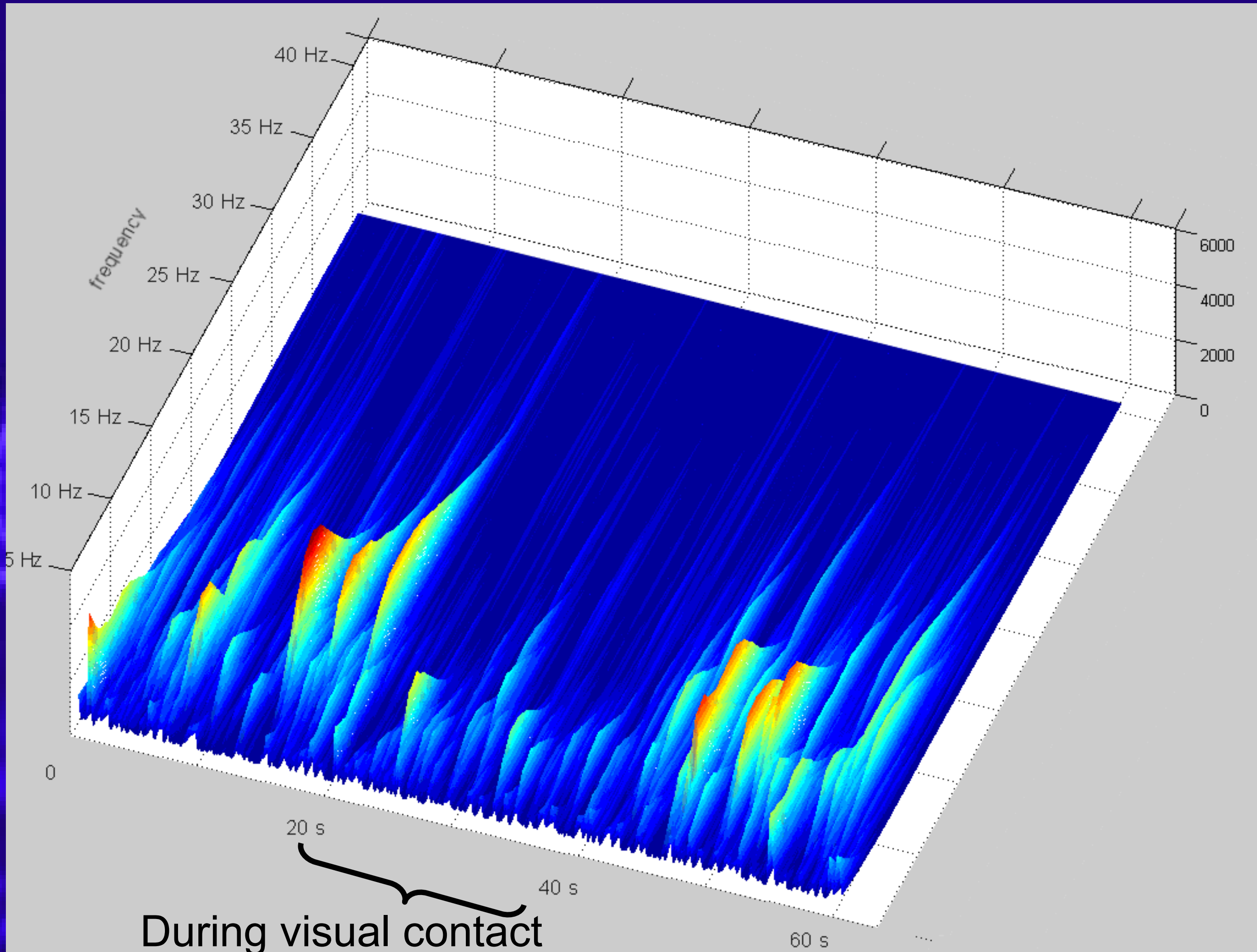
DeGuzman



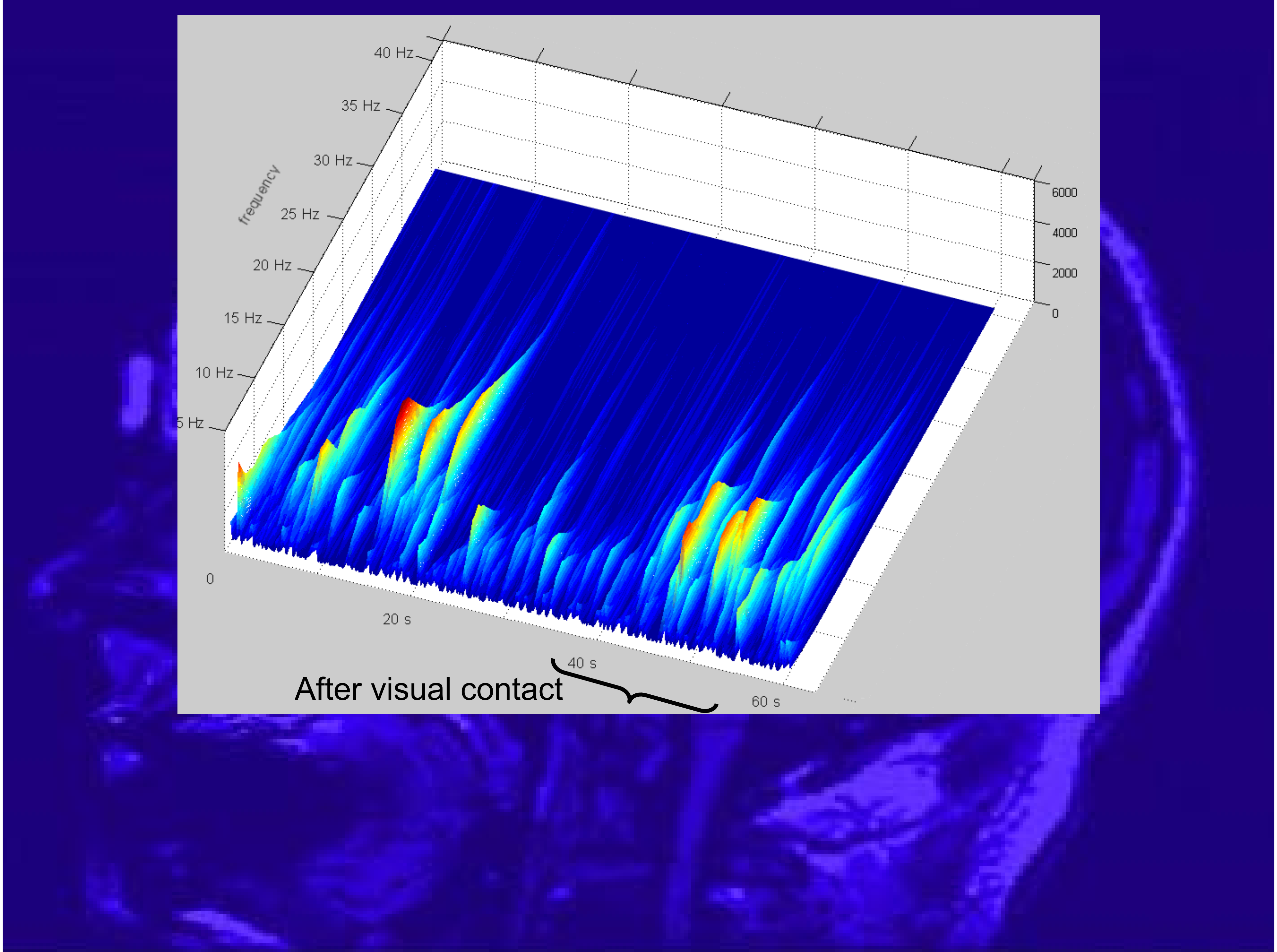
Before
During
After
P6
2
1.5
1
0.5
0
0
10
20
30
P6
2
1.5
1
0.5
0
0
10
20
30
msc 10-20 Hz



40 Hz
35 Hz
30 Hz
frequency
25 Hz
20 Hz
15 Hz
10 Hz
5 Hz
6000
4000
2000
0
0
20 s
40 s
60 s
Before visual contact



40 Hz
35 Hz
30 Hz
25 Hz
20 Hz
15 Hz
10 Hz
5 Hz
frequency
6000
4000
2000
0
0
20 s
40 s
60 s
During visual contact



40 Hz
35 Hz
30 Hz
25 Hz
20 Hz
15 Hz
10 Hz
5 Hz
frequency
0
20 s
40 s
60 s
6000
4000
2000
0
After visual contact

What have we got here?

- Coordinated phase-and frequency locked states; (functional integration; binding; dynamic linking)
- No coordination (segregation; independence of neural populations)
- Transitions (a kind of dynamic decision-making)
- Partial coordination (transient tendencies to couple coexist with tendencies of components to remain independent; high "neural complexity")

How to explain? Understand?

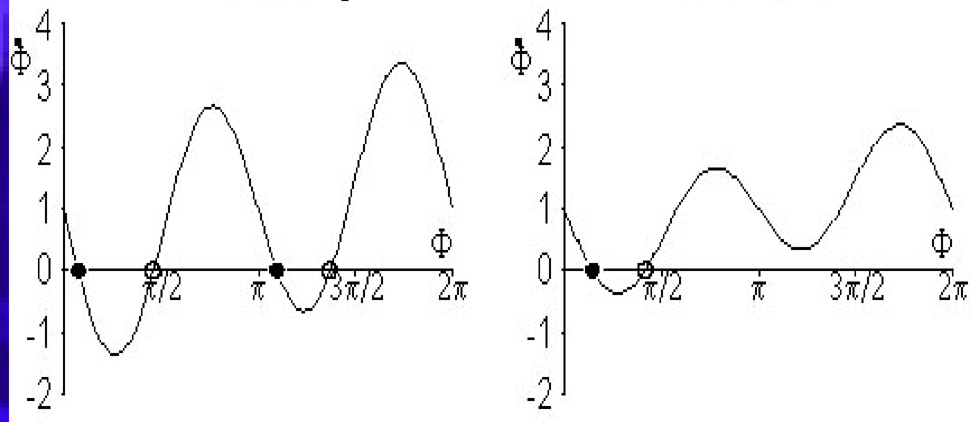
$$\dot{\phi} = \Delta\omega - a\sin\phi - 2b\sin 2\phi + \sqrt{Q}\xi_t$$

Elementary Law of Coordination

Elementary Law of Coordination

Integration | **Integration ~ Segregation**

multistability | transitions | metastability

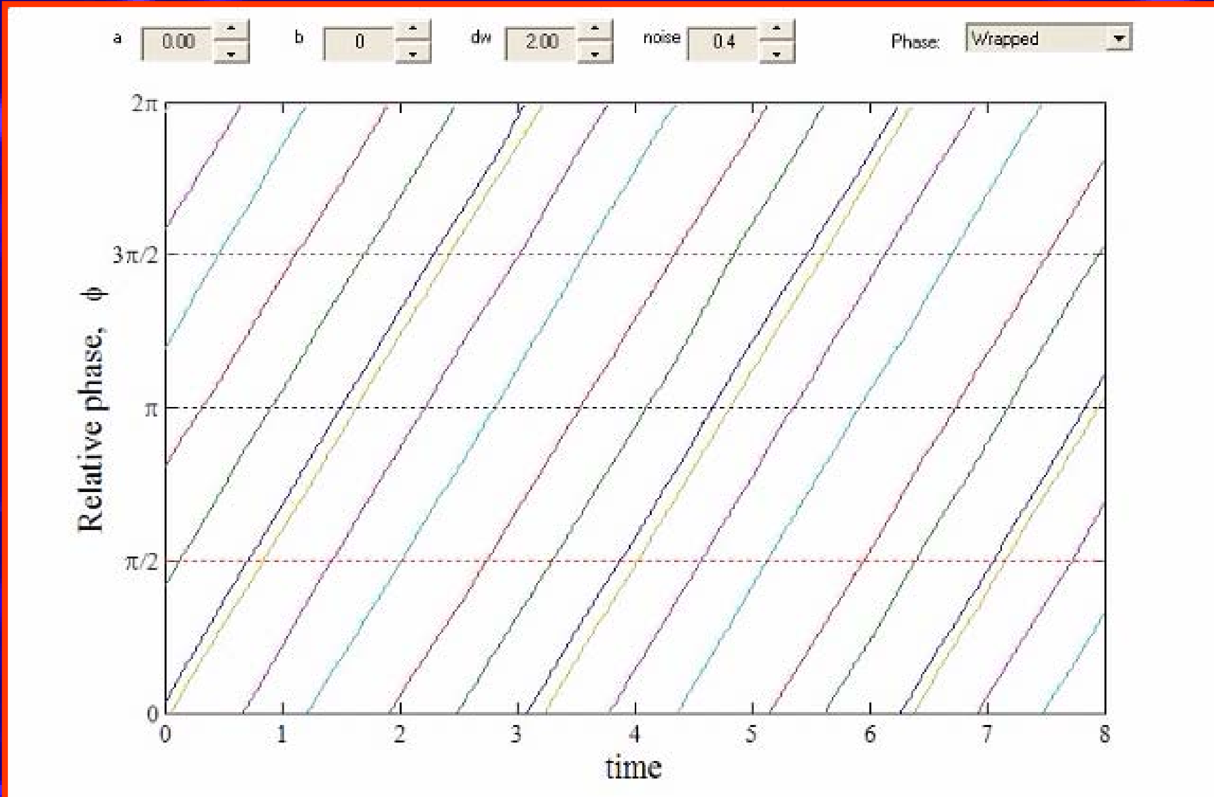


CEVA | SVI | ASA

Phase evolution as a function of increasing coupling

Fixed asymetry: dw = 2

Increasing coupling: a = 0 – 2.2, in 0.01 steps

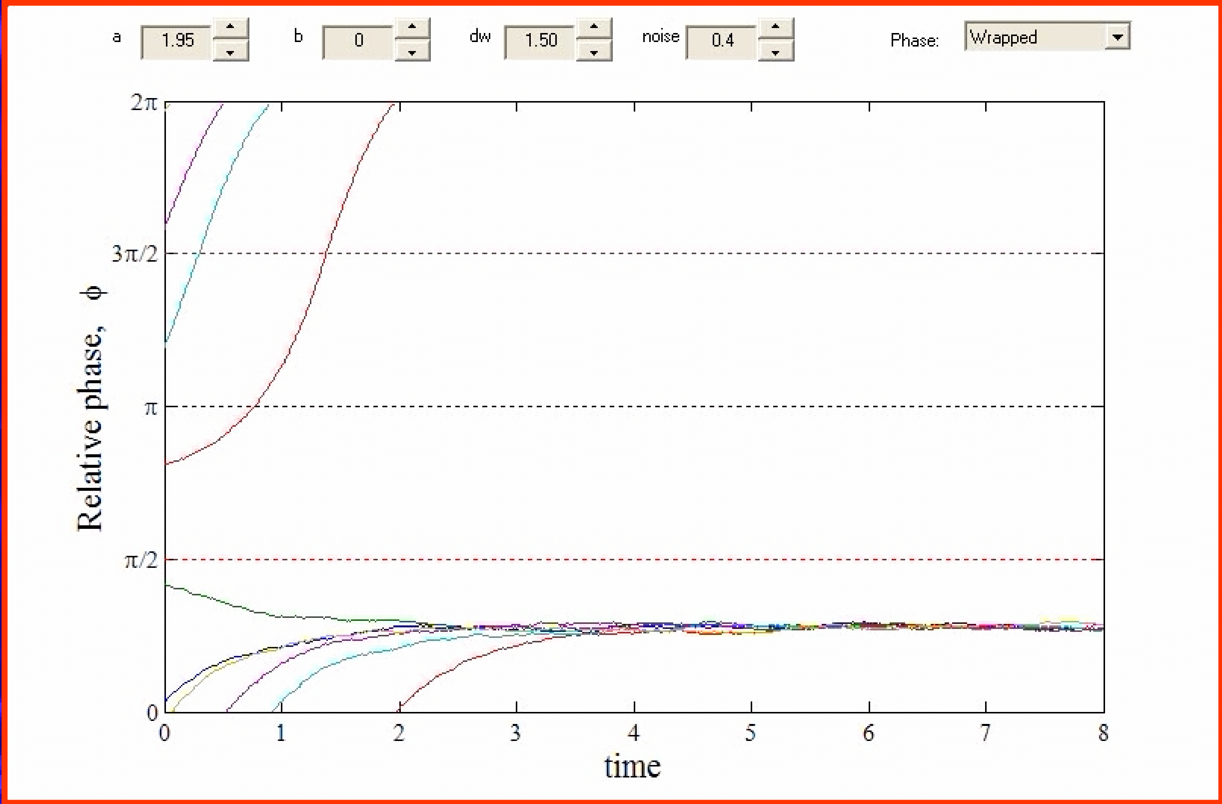


Relative phase dynamics:

$$\frac{d\phi}{dt} = \delta\omega - a \sin\phi - b \sin 2\phi + \eta(t)$$

Phase evolution as a function of component differences

Fixed coupling: a = 1.95 | **Frequency difference: dw = 1.5 - 3, in 0.01 steps**



Relative phase dynamics:

$$\frac{d\phi}{dt} = \delta\omega - a\sin\phi - b\sin 2\phi + \eta(t)$$

CD entails and explains "metastability"

"Poetry is more a threshold than a path, one constantly approached and constantly departed from, at which reader and writer undergo in their different ways the experience of being at the same time summoned and released."

- Seamus Heaney (1939-)

"Metastability --an entirely new conception of brain functioning where the individual parts of the brain exhibit tendencies to function autonomously at the same time as they exhibit tendencies for coordinated activity

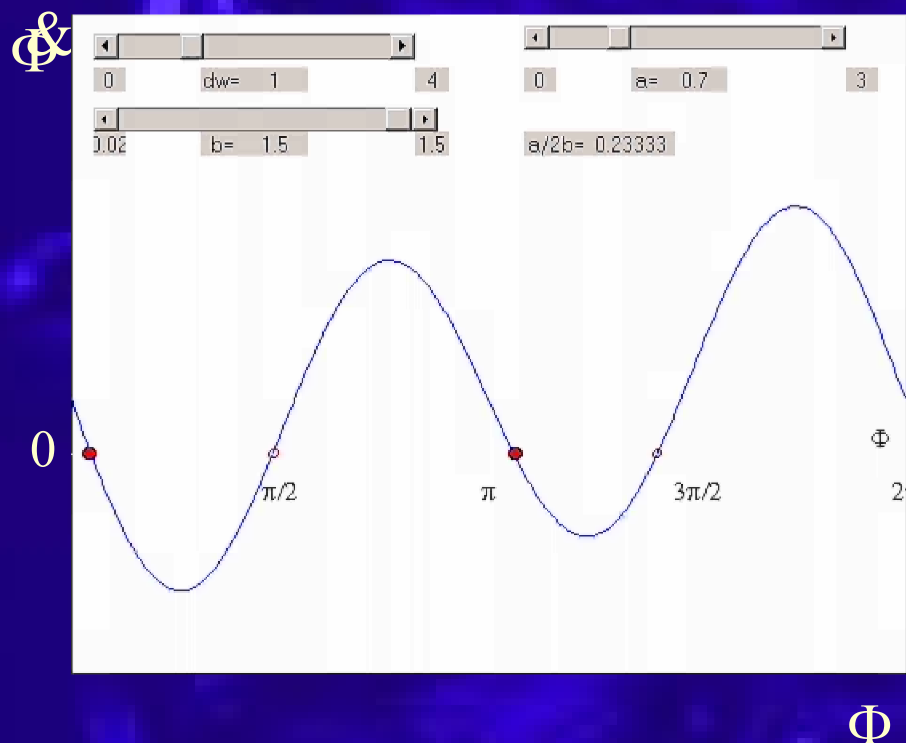
euCognition
www.euCognition.org

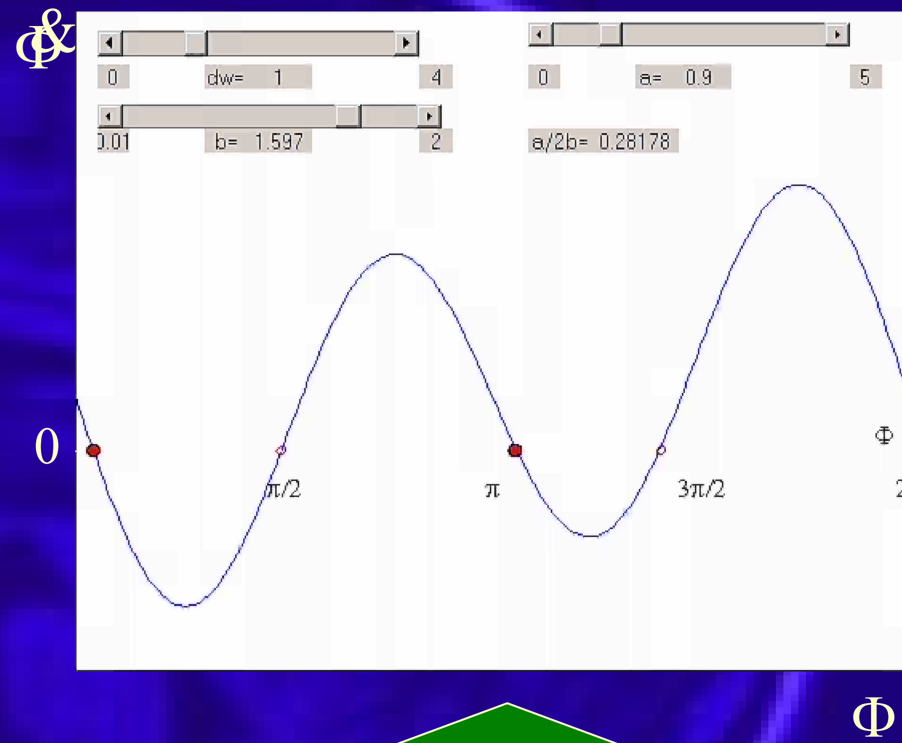
Why is brain metastable?

- Can visit everywhere in the relevant state space of the coordination dynamics yet still exhibit preferences~dispositions

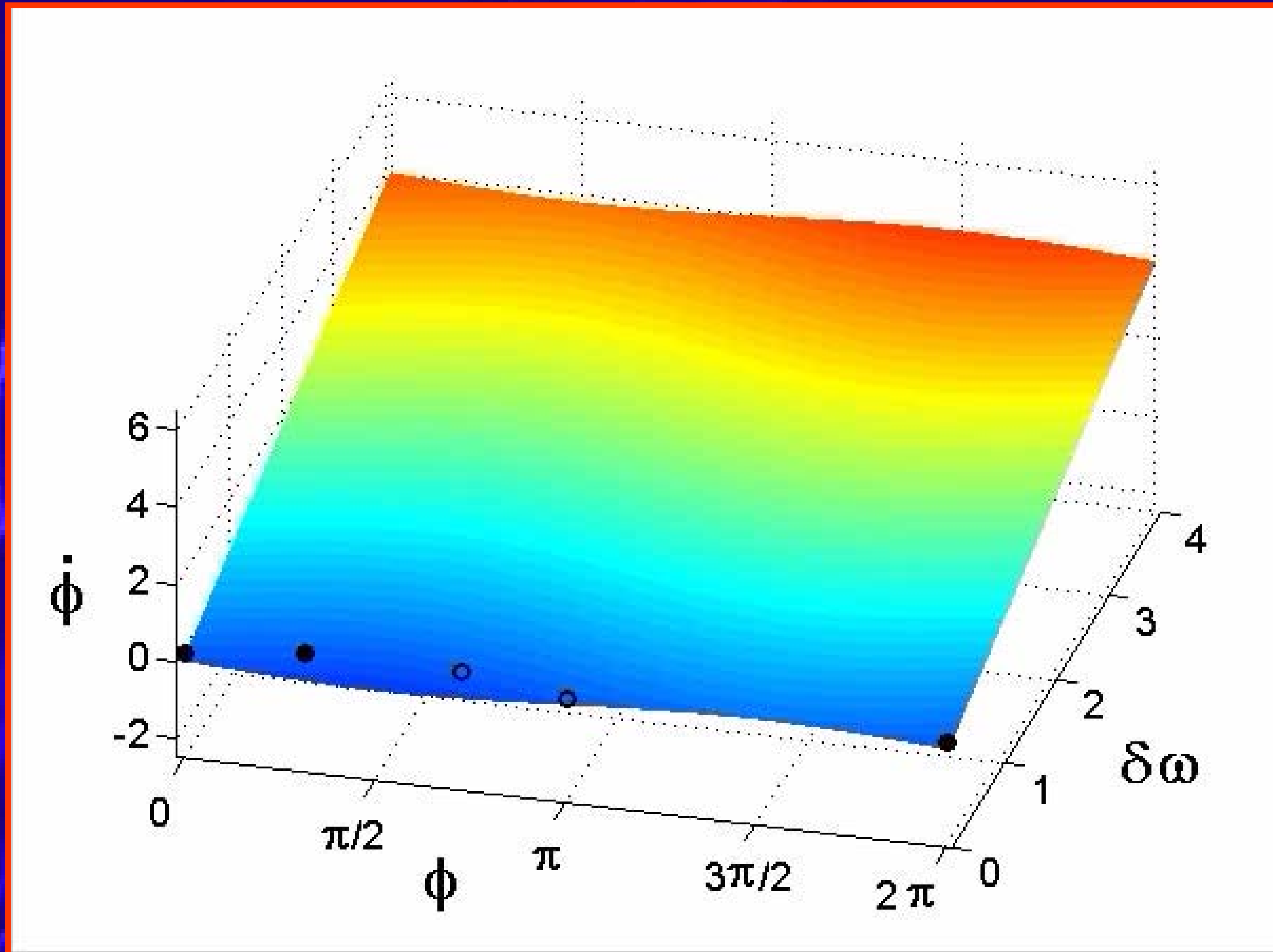
- Slightest input can kick it into meaningful coordination states, thereby creating (and destroying) information

Varying coupling





Varying intrinsic differences



6
4
2
0
-2
φ̇
0
π/2
π
3π/2
2 π
φ
0
1
2
3
4
δω

Coordination Dynamics: Coupling ~ Components

- Coordination Dynamics: a theoretical ~ empirical framework for coordination and its breakdown
- Two key factors: coupling strength (e.g. synaptic connectivity) and intrinsic frequency differences (e.g., between neural ensembles)
- Brain—and all complex systems-- are metastable: *tendency* to integrate (phase gather, cooperate) coexists with *tendency* to segregate (phase scatter, compete) *at the same time* (integration ~ segregation)
- Why? Creation of meaningful information

What is the source of the informational coupling?

- Progression of Social Coordination Paradigm

- Human ~ machine interaction: Coordination with a virtual partner

- Replace the other person with an artificial stimulus that mutually couples to the actor

In a sense, this is a test of the extended HKB model !

Note: Original HKB study and modelling addressed movement dynamics

Now: Embodiment as well as biological motion..

Progression of Movement Coordination Paradigm

Model analysis: Extended HKB system

$$\ddot{x} + (Ax^2 + B\dot{x}^2 - \gamma)\dot{x} + \omega^2 x = (\dot{x} - \dot{y})(\alpha + \beta(x - y)^2)$$
$$\ddot{y} + (Ay^2 + B\dot{y}^2 - \gamma)\dot{y} + \omega^2 y = (\dot{y} - \dot{x})(\alpha + \beta(y - x)^2)$$

NOTE: The NL coupling between intrinsically NL components gives rise to “emergent” multistability/multifunctionality; transitions/switching, multiple metastable tendencies, etc…

Question: What is the source of the informational coupling and how can one control it?

Possibility: Replace a partner with a virtual one that exhibits some biologically relevant features such as embodiment, interactivity, and variability. Interactivity from the artificial stimulus can be implemented via HKB coupling. To get variability, one may exploit asymmetry as well as introduce parametric noise.

Embodied stimulus + Biological motion

Can be disembodied through image transformation
e.g. Generic DOT or real HAND

Interactivity

Variability

Others

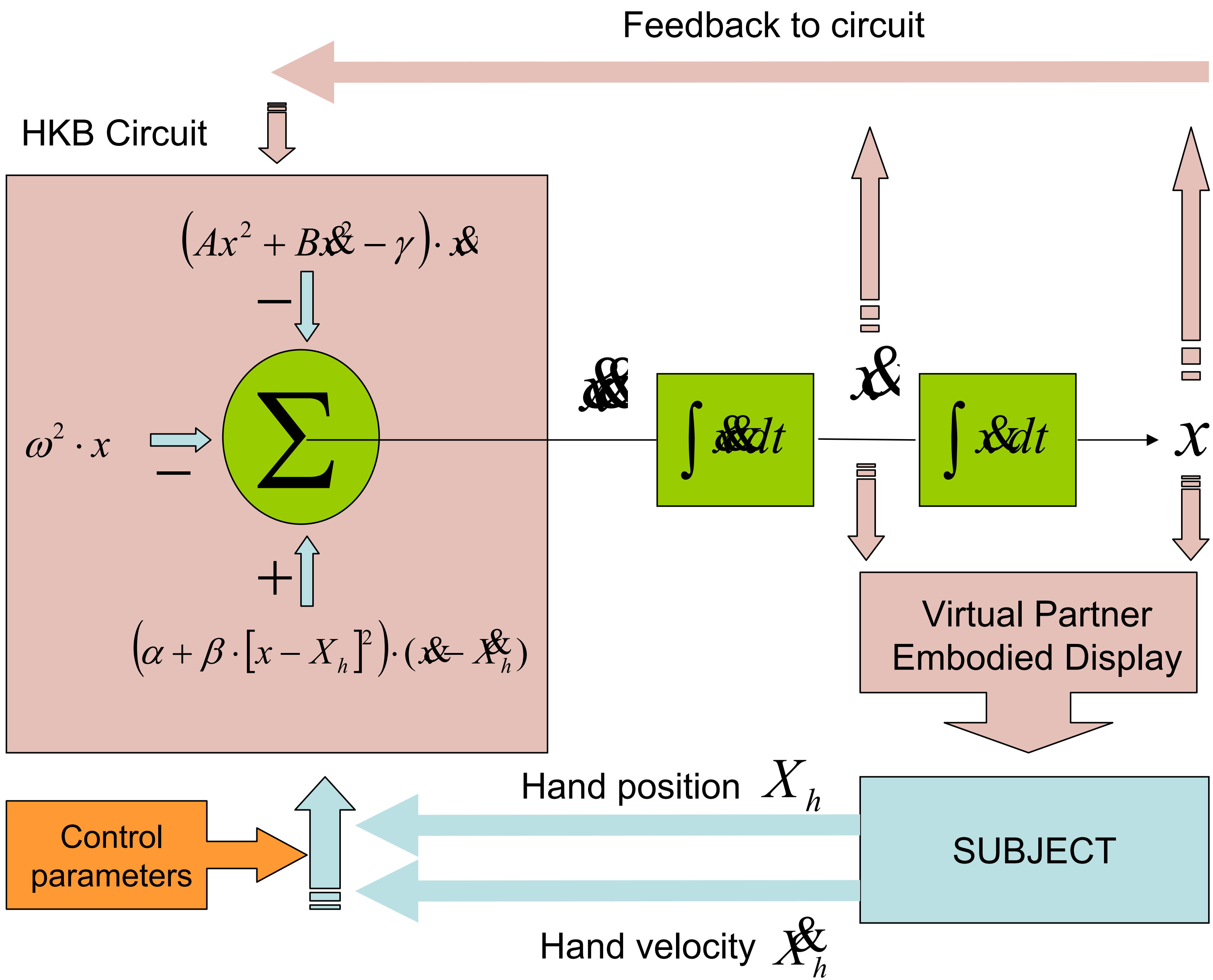
$$\ddot{x} + (Ax^2 + B\dot{x}^2 - \gamma)\dot{x} + \omega^2 x = (\dot{x} - X_h)(\alpha + \beta(x - \dot{X}_h)^2)$$

$x, \dot{x}$

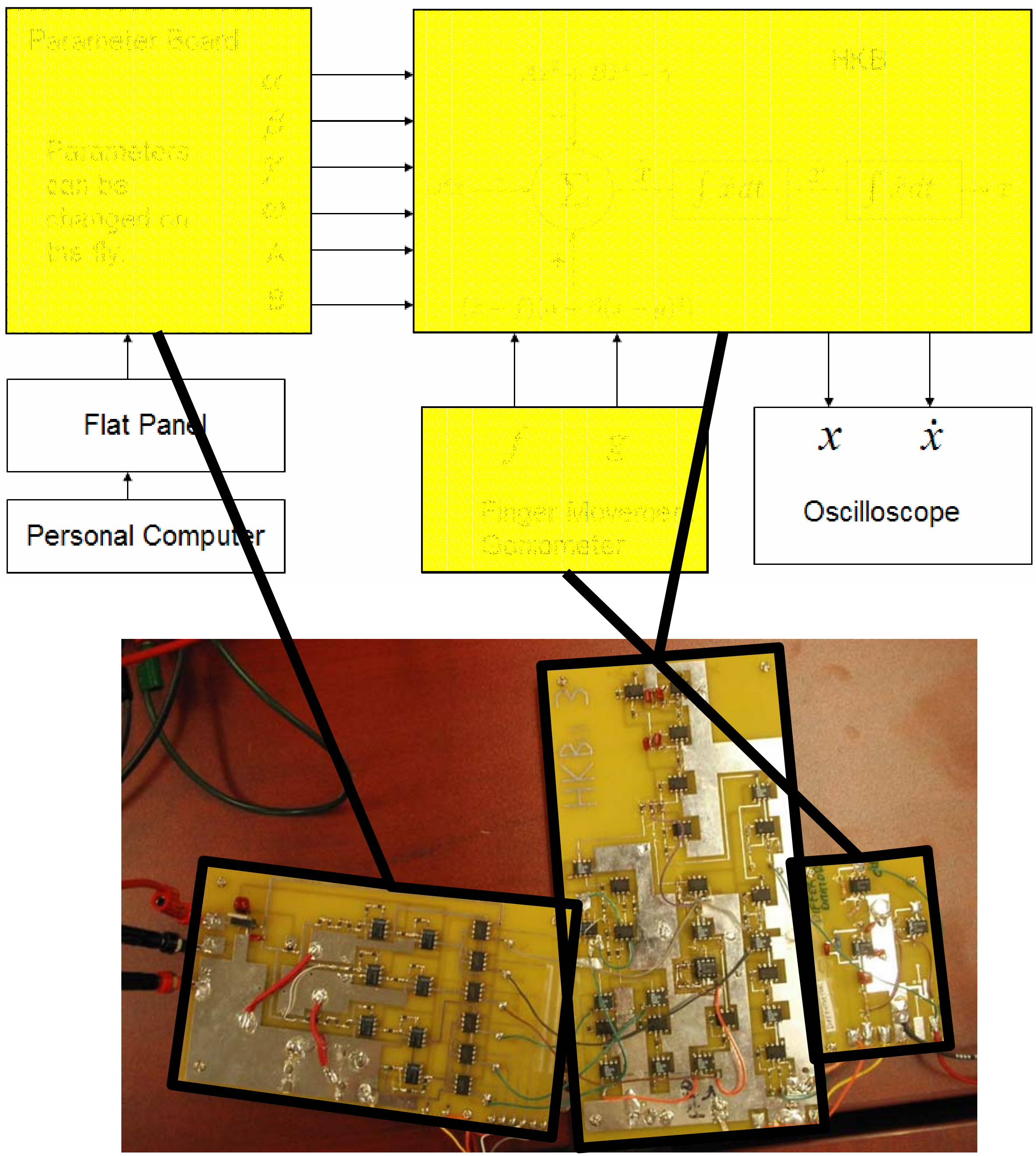
Simulated social HKB response from computer

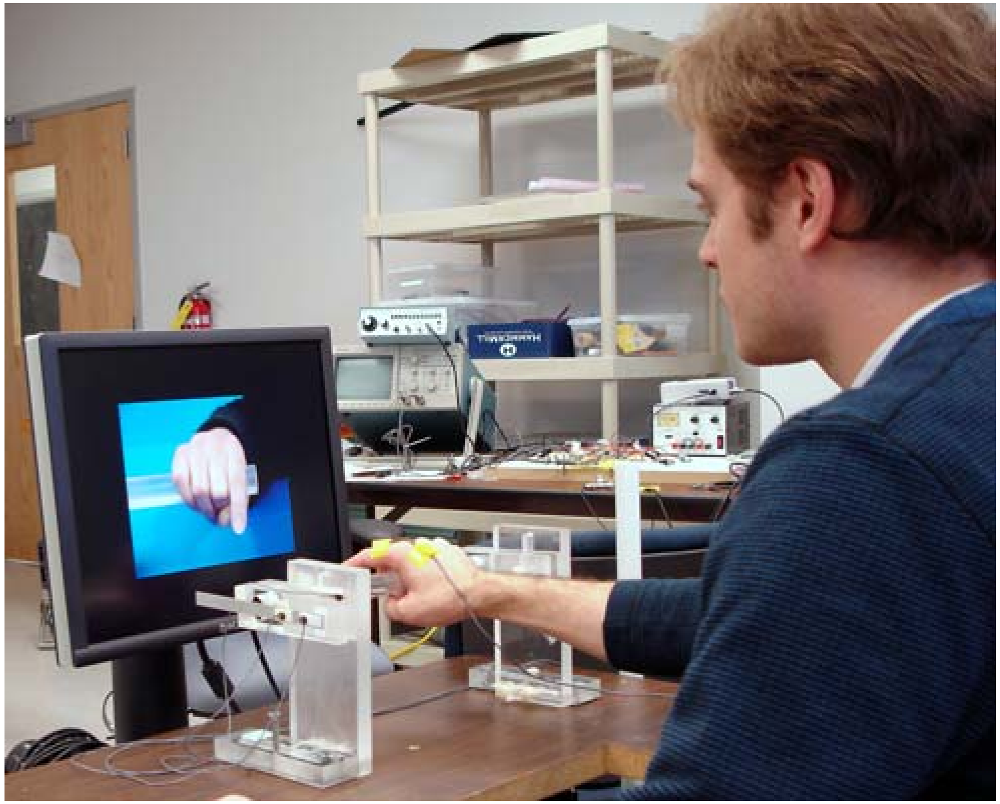
$X_h, \dot{X}_h$

Human input



Feedback to circuit
HKB Circuit
Virtual Partner
Embodied Display
Hand position
SUBJECT
Control
parameters
Hand velocity


Parameter Board
Parameters can be changed on the fly.
HKB
Flat Panel
Personal Computer
x
ẋ
Oscilloscope

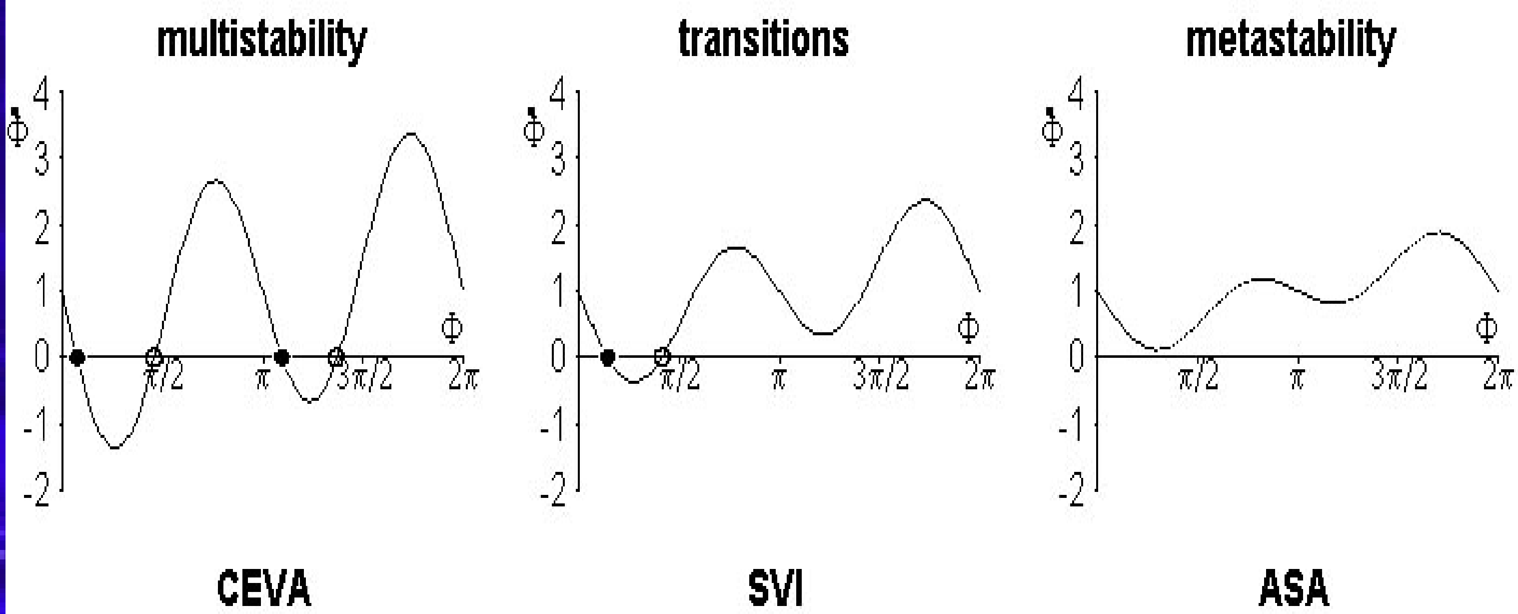


$$\dot{\phi} = \Delta\omega - a\sin\phi - 2b\sin 2\phi + \sqrt{Q}\xi_t$$

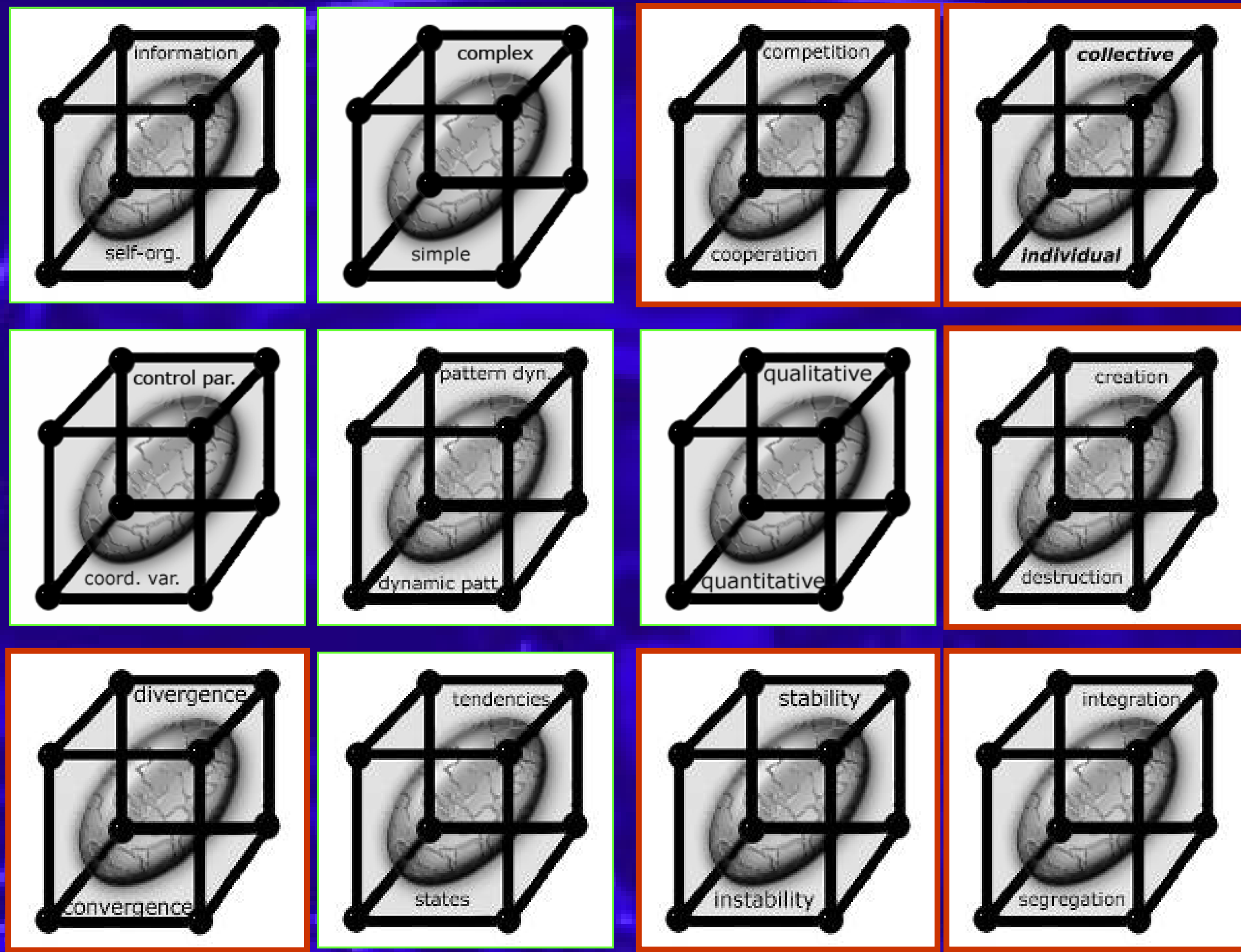
Patterns of Mind

Patterns of Mind

Integration **Integration ~ Segregation**



Some Complementary Pairs found in Coordination Dynamics



Hitting the Nail on the Head

"To report that he (Switters) was of two minds is not to imply, exactly, that he was torn by dilemma. Though hardly a stranger to contrariety, Switters had always seemed to take a both/and approach to life, as opposed to the more conventional and restrictive either/or. (To say that he took both a both/and and an either/or approach may be overstating the extent of his yin/yanginess)."

- Tom Robbins (1936-) from *Fierce Invalids Home from Hot Climates*

Two CP~CD strategies

The complementary pair CP~CD says:

- coordination dynamics entails complementary pairs, as well as their interpretation (this has been found)
- complementary pairs entail coordination dynamics. (this has been found within coordination dynamics

These realizations and findings immediately lend themselves to some tangible strategies to employ the philosophy~science CP~CD:

CP of CD

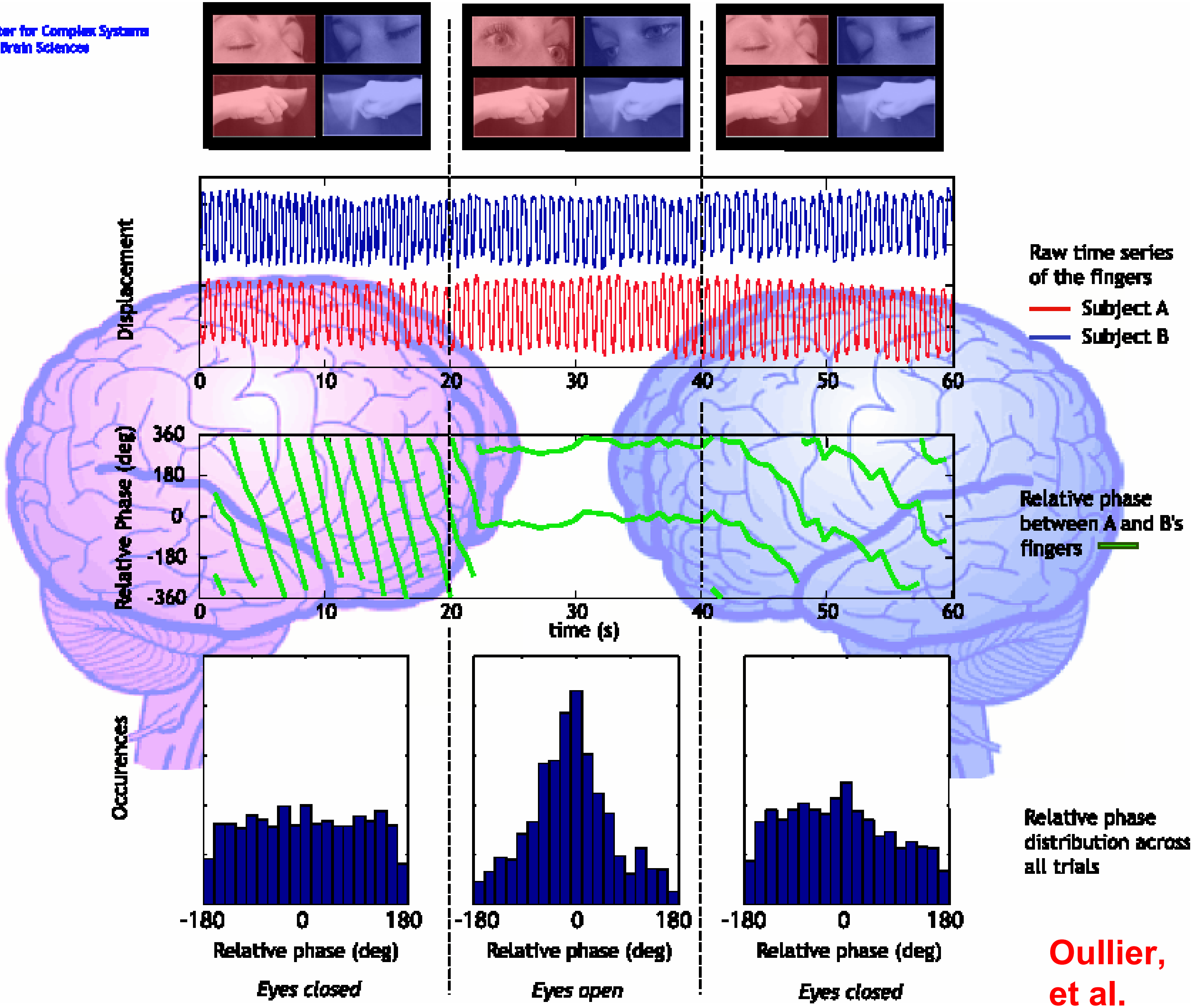
"To study the complementary pairs of coordination dynamics in order to aid and advance the science of coordination dynamics itself."

CD of CP

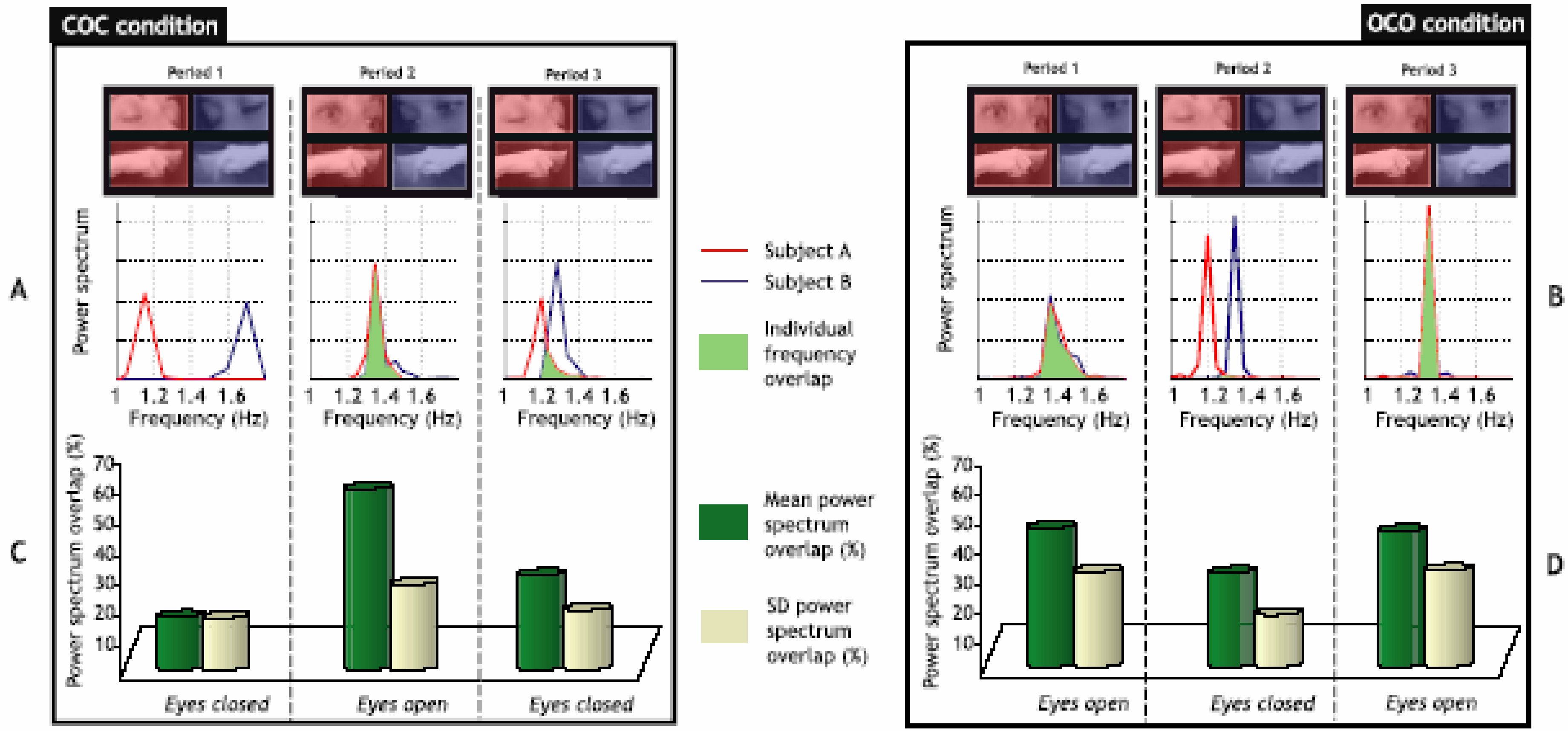
"To use the concepts, methods and tools of coordination dynamics to understand complementary pairs wherever they are found."


The Complementary Nature
The Complementary Nature
kelso ~ engstrøm
~
j.a.s. kelso ~ d.a. engstrøm
thecomplementarynature.com

Theory ~	Experiment
H.Haken	K.J. Jantzen
G.Schöner	O. Oullier
V. Jirsa	F. Steinberg
A.Fuchs	J. Lagarde
G.DeGuzman	D. Engstrøm
	E. Tognoli



Oullier, et al.


COC condition
OCO condition
Period 1
Period 2
Period 3
A
B
C
D
Power spectrum
1 1.2 1.4 1.6
Frequency (Hz)
Subject A
Subject B
Individual frequency overlap
Mean power spectrum overlap (%)
SD power spectrum overlap (%)
Power spectrum overlap (%)
70 60 50 40 30 20 10
Eyes closed
Eyes open
Eyes closed
Eyes open
Eyes closed
Eyes open

MODIFICATION OF THE DYNAMICS DUE TO INTERACTION ?

Some possible factors: memory, structural instability, boundary conditions, etc

Before interaction

$$\ddot{x}_1 + i_1(x_1, \dot{x}_1, a_1) + \omega_1^2 x_1 = 0$$
$$\ddot{x}_2 + i_2(x_2, \dot{x}_2, a_2) + \omega_2^2 x_2 = 0$$

$i_{1,2}$, $\omega_{1,2}$ = intrinsic

UNCOUPLED

During interaction

$$\ddot{x}_1 + I_1(x_1, \dot{x}_1, A_1) + \omega_1^2 x_1 = F_1(x_1, \dot{x}_1, x_2, \dot{x}_2)$$
$$\ddot{x}_2 + I_2(x_2, \dot{x}_2, A_2) + \omega_2^2 x_2 = F_2(x_2, \dot{x}_2, x_1, \dot{x}_1)$$

$I_{1,2}$, $\omega_{1,2}$ = intrinsic modulated by context, boundary conditions

COUPLED

After interaction

$$\ddot{x}_1 + I_1(x_1, \dot{x}_1, A_1) + \omega_1^2 x_1 = 0$$
$$\ddot{x}_2 + I_2(x_2, \dot{x}_2, A_2) + \omega_2^2 x_2 = 0$$

$I_{1,2}$, $\omega_{1,2}$ = intrinsic

UNCOUPLED…but modified by interaction!

DeGuzman

BOTTOM LINE……

Reductionism and Emergentism are a complementary pair (reductionism ~ emergentism; part ~ whole; component ~ coupling, bottom-up ~ top-down, etc)

YES. But they can be reconciled! What this will mean is a much deeper appreciation of **both** the components **and** the interactions ('coevolution'; no Cartesian cut; no 'component' without 'coupling and vice-versa—Call it what you want

In fact…the very distinction between components and coupling is blurred!
--Need formalisms for this (e.g. in differential equations, the LHS is components and the RHS is the coupling term)

Self-Organization in Complex Systems

"bird flocks,…ant colonies, highway traffic, market economies, immune systems—in all of these systems patterns are determined **not by** some centralized authority but by **local interactions** among decentralized components"

Resnick, 1995

Laws ~ Mechanisms

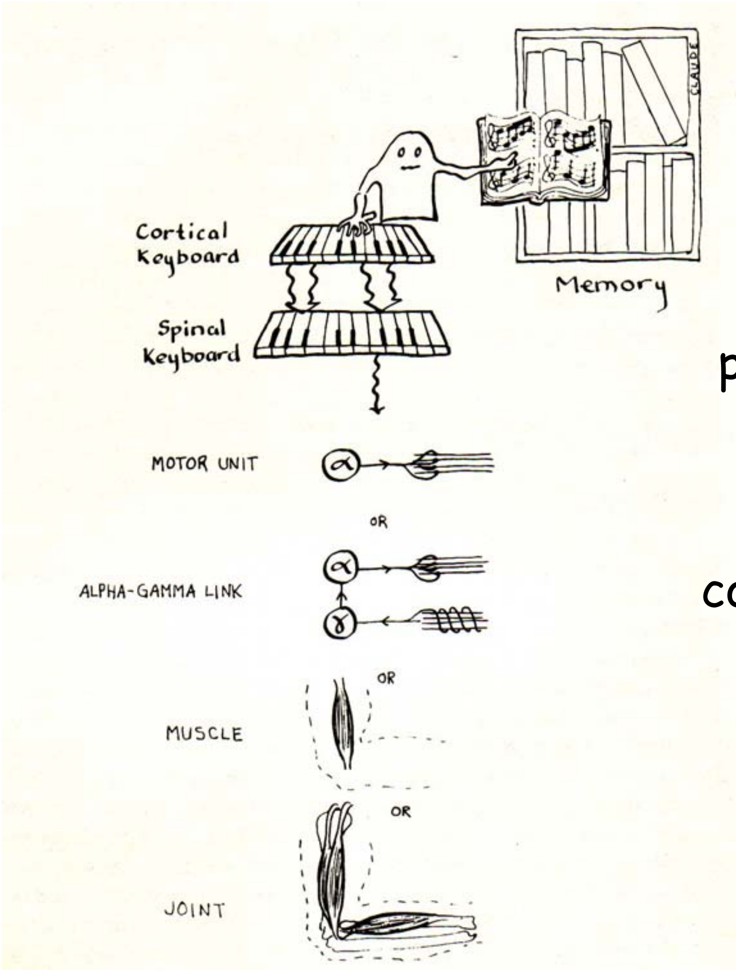
"The focal concern is not the identification of the **locus** of pattern generation but the extraction of **laws** of pattern generation"

(Turvey, 1990)

The either-or raises its head again!

A science of coordination and TCN demands BOTH!

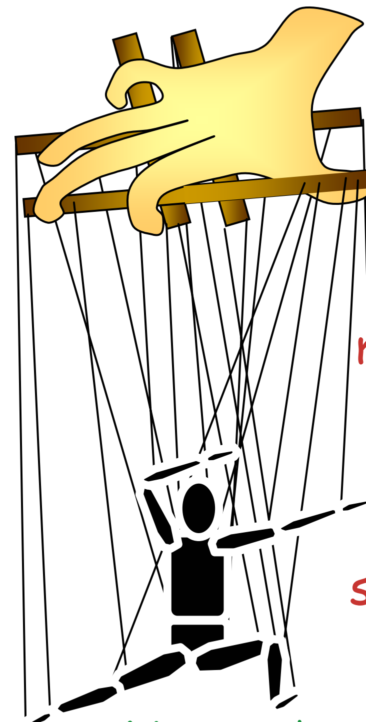
Nature of Control

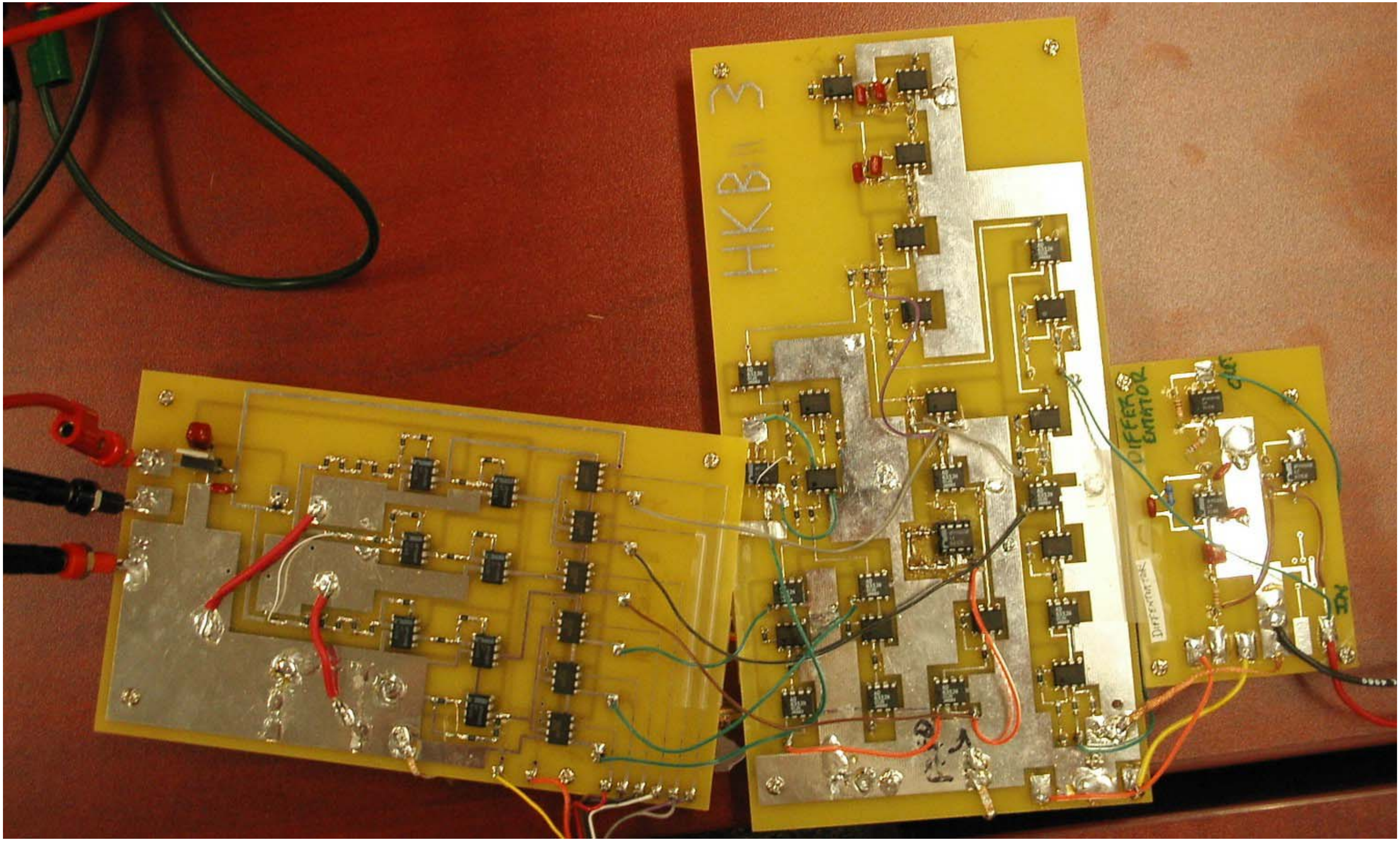


strictly neural?
plan *then* execute?
intelligent executive intervening often?
analytical model(s)?
only logical constraints?
preassembled movements?

context-independent parts?
spine as conduit?
submissive physics?
high dimensional?
impeding neural noise?
via standard variables?
fixed meters?

hierarchical?




HKB 3
DIFFER
ENTIATOR

"The Age of Reductionism is over.
We now live in an Age of Emergentism"

Laughlin, 2005

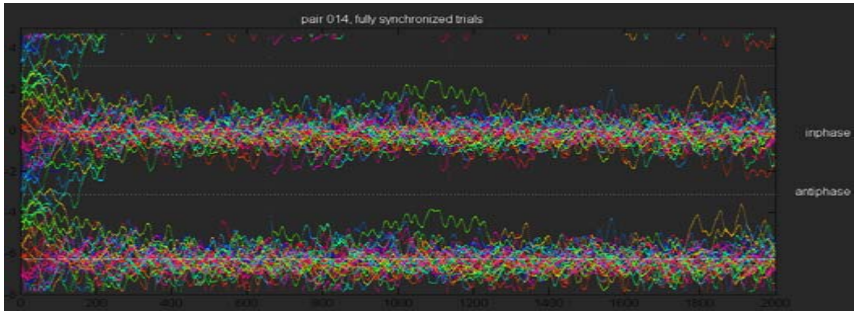
Why is that?

Standard reductionism can't explain the behavior of the whole in terms of the sum of the parts

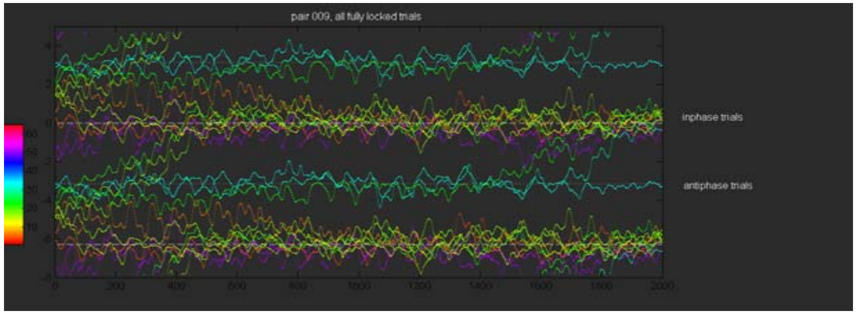
Complexity arises as a consequence of the INTERACTIONS among many agents

Progression of Finger Coordination Paradigm

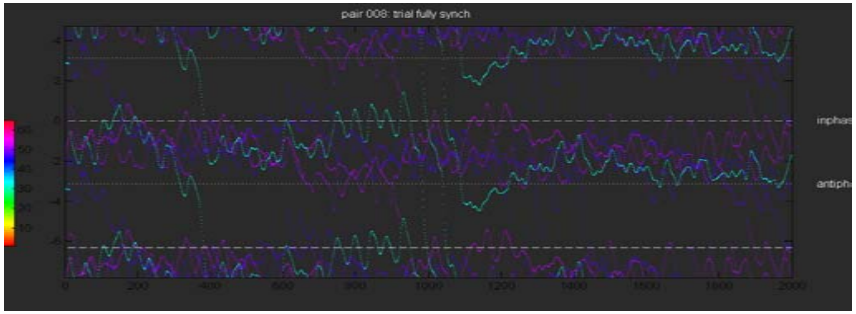
B. Two people manual coordination: Cumulative relative phases during visual contact for the stable trials for 3 pairs of subjects



Pair 1: All trials converge to in-phase



Pair 2: Most trials converge to in-phase; some converge to anti-phase



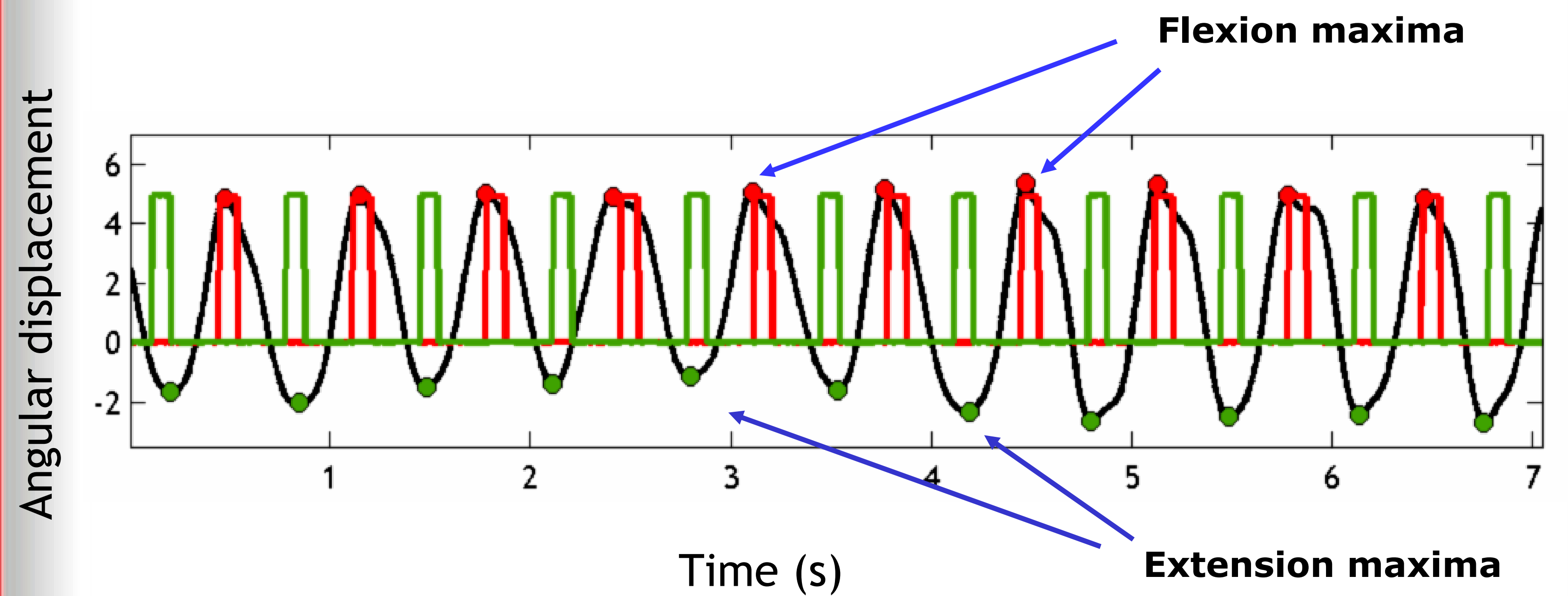
Pair 3: Weak coupling – phase drifts plus phase concentration around -1.5 radians.

HKB phase dynamics still valid?

The Complementary Nature

Multimodal Coordination: Touch, Sound and Movement

Flexion on Haptic & Extension on Auditory (FHEA)



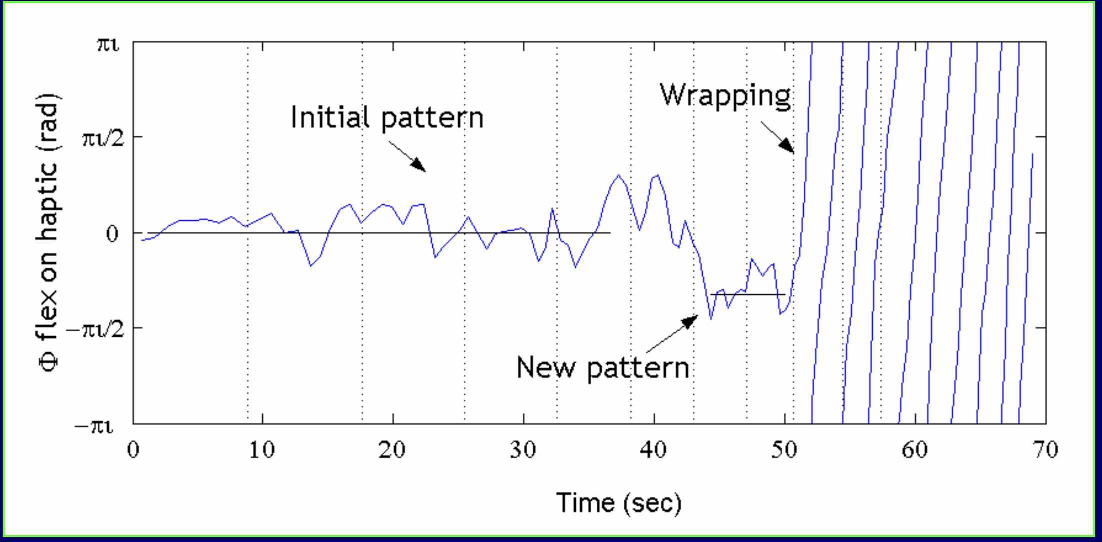
Haptic onset

Auditory

Multimodal Coordination

Initial condition:
Flex on Haptic & Extend on Audio

Relative phase between Flexion & Haptic onsets

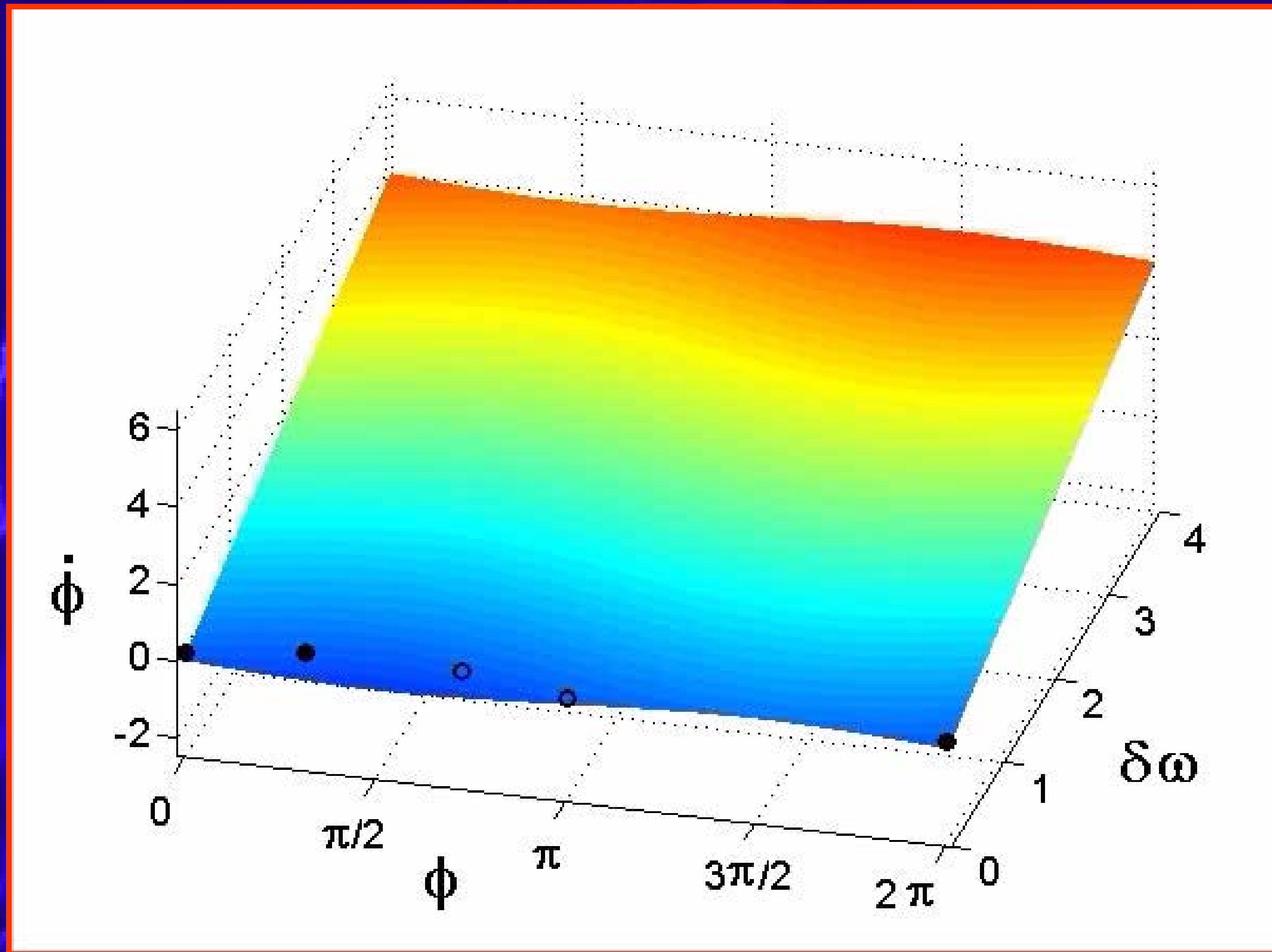


FLEX HAPTIC (extend audio)
switches to
FLEX AUDIO (extend haptic)

Stimulus ~ Response

"The reflex arc idea...is defective in that it assumes sensory stimulus and motor response as distinct psychical existences, while in reality they are always inside a coordination and the same occurrence plays either or both parts according to the shift in interest."

- John Dewey (1859-1952)


6
4
2
0
-2
$\dot{\phi}$
0
π/2
π
3π/2
2 π
ϕ
0
1
2
3
4
$\delta\omega$