Consciousness as the emergent property of the interaction between brain body & environment

the crucial role of haptic perception

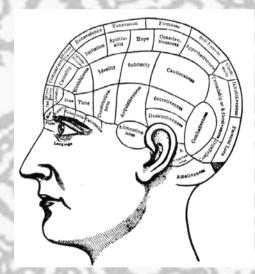
# Pietro Morasso

Università di Genova

Neurolab - DIST



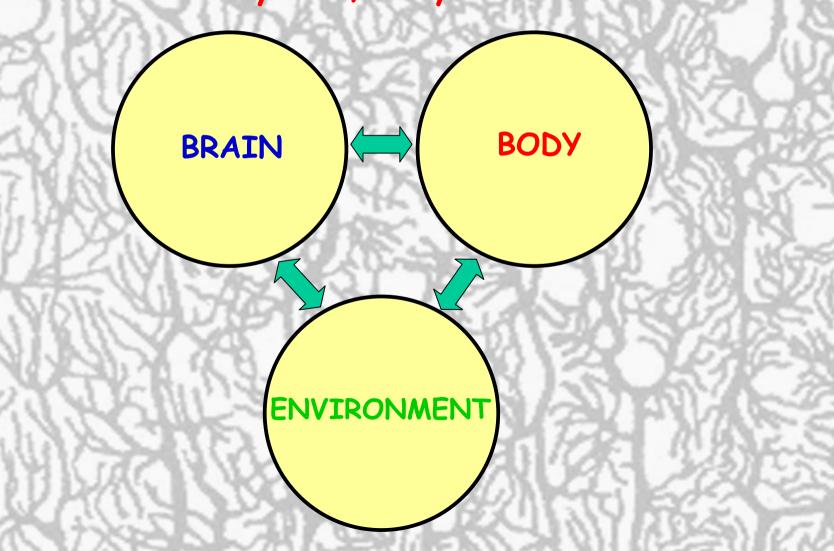
## Consciousness cannot be a purely mental phenomenon



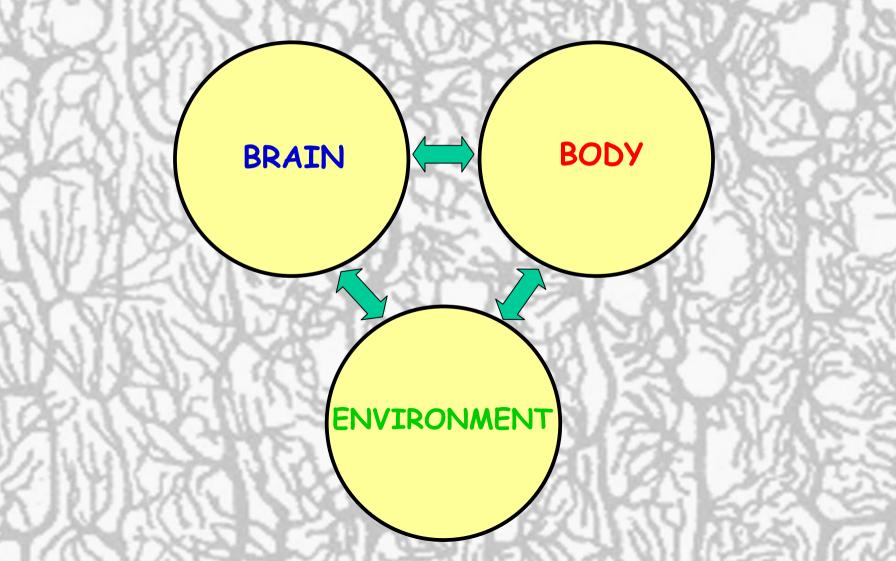
### because the Brain has a Body

(Chiel & Beer , TINS 1997)

# Adaptive behavior is an emergent property of the interaction of the nervous system, body and environment

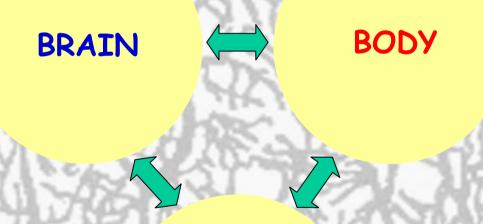


... continuous exchange of signals/energy between the nervous system, the body and the environment ....



... motor neuronal input is shaped by the biophysics of the sensory organs ... motor neuronal output is transformed by the biomechanics of the body ...

constraints & affordances .



ENVIRONMENT

... hydrostatic skeletons (tentacles, tongues, trunks) vs. hard skeletons (reachability vs. fine force control) Musical metaphor: the brain is not the director of a symphonic orchestra ...

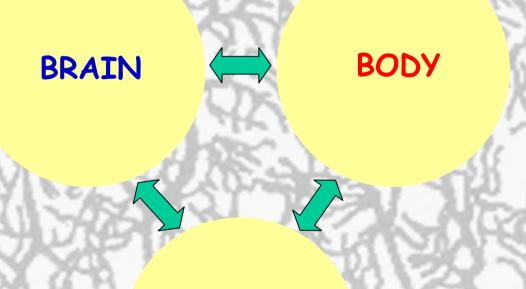
BRAIN

BODY



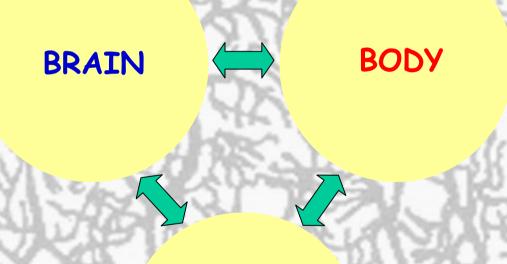
.. but a player in a jazz jam session ...

# Adaptive behavior is an emergent property but ...



#### ENVIRONMENT

... it cannot emerge without neural plasticity (plasticity = necessary but not sufficient property) Is consciousness an emergent property of the same sensory-motor-cognitive process?



ENVIRONMENT

Consciousness = ability to exhibit adaptive behavior ?

What is the neural substrate of conscious experience ? The entire brain (W. James):

the stream of consciousness is highly integrated and unified.

 $\blacktriangleright$  Consciousness/awareness is graded  $\Rightarrow$  "consciousness space" with a fuzzy boundary between conscious and unconscious states

 Adaptive behavior requires a sufficient degree of awareness
As adaptive behavior is not a pure property of the brain but an emergent property of the brain, body, environment interaction, so is consciousness

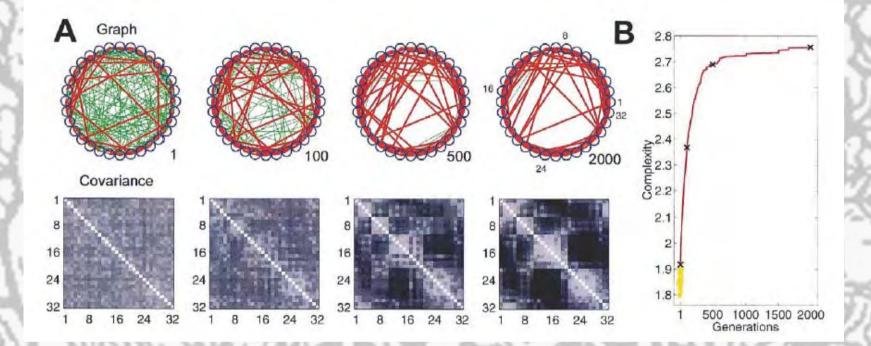
> Consciousness and adaptive behavior are inseparable twins

#### The importance of theoretical neuroanatomy

As biomechanics of the motor apparatus and the biophysics of the sensory organs constrain and shape the brain-bodyenvironment interaction ...

... so the biophysics of neurons, synapses, and glia constrain and shape the ways in which conscious experience can emerge and articulate itself

#### Theoretical neuroanatomy



Quantitative measure of neural complexity C(X), which expresses the interplay between **functional segregation** and **functional integration**: the extent to which small subsets of a system are functionally segregated while large subsets are functionally integrated. Evolution through graph selection.

Integration and differentiation are general properties of conscious experience. Substantial evidence indicates that the integration of distributed neuronal populations through reentrant interactions is required for conscious experience.

Sporns, Tononi & Edelman (2002) Theoretical neuroanatomy and the connectivity of the cerebral cortex

#### Theoretical neuroanatomy the Human Connectome project

The human genome is composed of approximately 3x10<sup>9</sup> base pairs, containing around 20,000-30,000 genes

The **human connectome** is much larger ( $10^{11}$  neurons with  $10^{15}$  connections) Connectome: the union a binary connection matrix and connection-specific physiological data  $\rightarrow$  structural description that combines connection topology and biophysics

As connectivity increases so does the relative proportion of **white matter** in the brain.

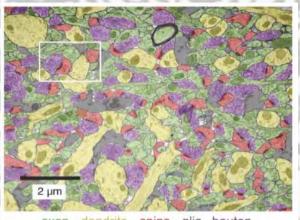
The relative contribution of cerebral white matter has increased throughout phylogeny to such an extent that its volume and metabolic requirements may present a limitation to further increases in connectional complexity

#### Micro/Meso/Macro scales

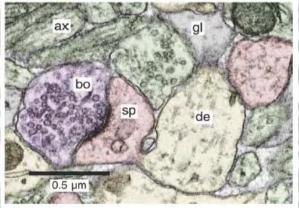
Central hypothesis is that the pattern of elements and connections as captured in the connectome places specific constraints on brain dynamics, and thus shapes the operations and processes of human cognition. In turn, data recording the activity of the human brain in combination with the structural model provided by the connectome will help to discern causal interactions in large-scale brain networks.

Tononi (2005) Human connectome PLoS Computational Biology

#### Theoretical neuroanatomy - wiring optimization



axon dendrite spine glia bouton



- $1\,\mu l$  of cortex contains
- $10^5$  neurons,
- 10<sup>9</sup> synapses,
- 4 km axons

Early in the game of life evolution has set the basic biophysical properties of axons and dendrites.

Later on, it appears that evolution has optimized neural circuits in such a way to minimize

- the conduction delays in axons,
- > the passive cable attenuation in dendrites,

the length of "wire" used to construct circuits, and to maximize

>the density o f synapses.

A formal optimization, consistent with the biophysical properties of axons and dendrites, yields an overall figure of 3/5 as the relative fraction of volume occupied by wiring.

In reality the wire fraction is close to that value.

Chklovskii, Schikorski & Stevens, Wiring optimization in cortical circuits. Neuron 2002

### Theoretical neuroanatomy $\Rightarrow$ information integration

 Theory. Consciousness corresponds to the capacity of a system to integrate information.
This claim is motivated by two key phenomenological properties of consciousness: <u>differentiation</u> - the availability of a very large number of conscious experiences; and <u>integration</u> - the unity of each such experience.

> The theory states that the quantity of consciousness available to a system can be measured as the amount  $\Phi$  of causally <u>effective information</u> that can be integrated across the informational weakest link of a subset of elements.

> A complex is a subset of elements with  $\Phi$  >0 that is not part of a subset of higher  $\Phi$ .

> The theory claims that the quality of consciousness is determined by the informational relationships among the elements of a complex.

> Each particular conscious experience is specified by the value, at any given time, of the variables mediating informational interactions among the elements of a complex.

#### Supporting neurobiological observations:

> the association of consciousness with certain neural systems rather than with others;

> neural processes underlying consciousness can influence or be influenced by neural processes that remain unconscious;

The reduction of consciousness during dreamless sleep and generalized seizures;

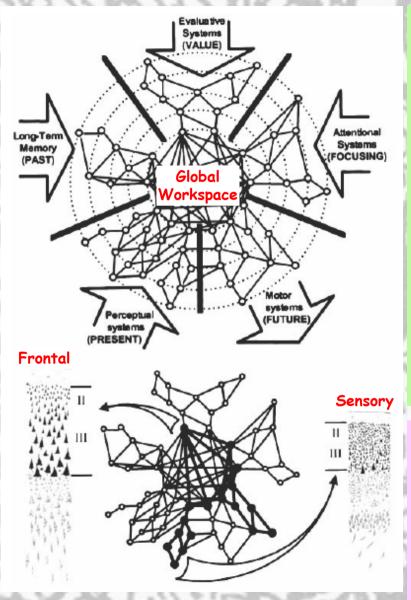
time requirements on neural interactions that support consciousness.

#### Implications: Consciousness is a quantity that

- > is graded,
- is present in infants and animals,
- > it should be possible to build conscious artifacts.

G. Tononi, Information integration theory of consciousness, BMC Neuroscience 2004

#### Global computational workspace



Two main computational spaces underlie brain processes during effortful tasks.: > a set of specialized and perceptual, motor, memory, evaluative, and attentional modules; > a unique global workspace composed of distributed and heavily interconnected neurons with long-range axons,

Workspace neurons are mobilized in effortful tasks for which the specialized processors do not suffice  $\Rightarrow$  selective mobilization/suppression of specific processor neurons.

Task performance: workspace neurons become spontaneously coactivated, forming discrete though variable spatio-temporal patterns, modulated by vigilance/reward signals.

Distributed architecture of neurons with longdistance connectivity that provides a "global workspace", interconnecting multiple specialized brain areas in a coordinated, though variable manner, and whose intense mobilization might be associated with a subjective feeling of conscious effort.

Dehaene, Kerszberg, Changeaux (1998) A neuronal model of global workspace in effortful cognitive tasks.

The Brain has a Body the central role of haptic perception

Haptic perception is related to touch but it cannot be reduced to touch

It is active, not passive

It fuses

- > tactile information
- kinestetic information
- > force information
- sense of effort
- > sensorimotor expectations

Haptic experiences are the essence of most activities of daily life:

- palpating
- > weighing
- > pushing
- > hitting
- > cutting
- ➤ caressing
- grasping

By means of haptic experiences we acquire information on the physical properties of objects:

- weight
- > mass
- compliance
- stiffness
- fragility
- > texture

 $\triangleright$ 

# and probably for the formation of self-consciousness

# and probably for the formation of self-consciousness



### and probably

for the formation of self-consciousness



and for the mistic experience of sex in Tantra and other cultures less sexophobic than our own

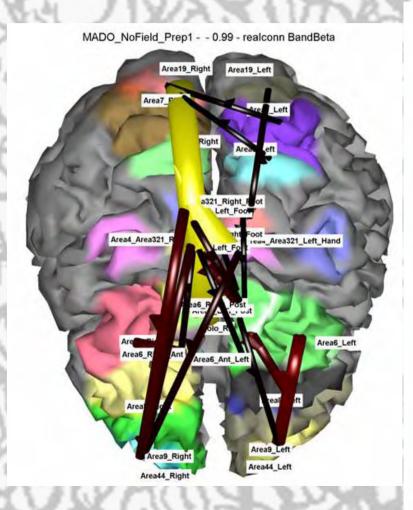
Haptic experience & sensorimotor learning modification of EEG patterns when learning in curly force fields

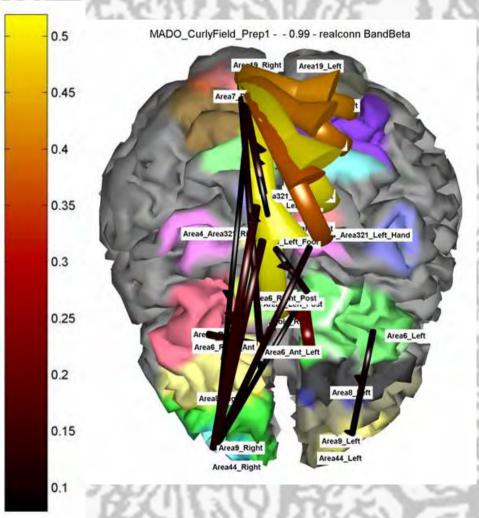


High-resolution EEG: work in progress, in cooperation with the Neurophysiology Lab, Santa Lucia Foundation, Rome, Italy



Haptic experience & sensorimotor learning modification of EEG patterns when learning in curly force fields





# Haptic experience & robot therapy with severely impaired hemiparetic patients

- Clinical study with minimally assistive strategy
- 10 stroke patients;
- > Fugl-Meyer score  $\leq$  10;
- > 10 training sessions (1-2 per week).

Massive flexion pattern: the patients are unable to fully extend the arm without assistance.

Minimally assistive strategy:

Visual + haptic target

The haptic representation of a target is an attractive force field, whose intensity is set to the minimum level that allows the patient to reach the target

The force level is reduced during training







# Motor rehabilitation and consciousness

Robot therapy (as well as human physical therapy) is a dense haptic experience for both the patient and the therapist

In the rehabilitation process, if effective and successful, the patient regains

- Motor capability
- > Consciousness of the damaged part of the body/brain.

Anche l'altro ... cominciò a appiccicare francobolli di occhiate sopra Tommaso qua e là per tutto il corpo.

Pier Paolo Pasolini, Una vita violenta, 1959



Stanley Kubrick, a proposito di Arancia Meccanica (intervista di Michel Ciment, 1980):

Alex, a livello onirico e simbolico, rappresenta l'inconscio. <u>L'inconscio non ha</u> <u>coscienza</u>. Nel proprio inconscio ciascuno di noi uccide e violenta

.... alzò una mano flettendo le dita e si chiese, come già le era capitato di fare altre volte, come fosse entrata in possesso di quella cosa, quella specie di morsa di ragno carnoso al suo completo servizio. Che avesse un barlume di vita propria? Piegò un dito e tornò a distenderlo. Il mistero era sigillato nell'attimo prima del movimento, l'istante che separava la quiete dal moto, quando l'intenzione raggiungeva il suo effetto. Era come il frangersi di un'onda. Se fosse riuscita a tenersi sulla cresta, pensava, non era escluso che avrebbe scoperto, quella parte di sé responsabile del fenomeno. Si portò l'indice vicino alla faccia e prese a fissarlo, ordinandogli di muoversi .... e quando alla fine lo piegò, il gesto parve partire dal dito stesso, non da un punto ignoto della sua mente. Quando sapeva di doversi muovere? Quand'era che lei lo muoveva? Era impossibile cogliersi di sorpresa. Esisteva soltanto il prima e il dopo. Non c'erano segni di cuciture, linee di giunzione, eppure sapeva che al di là del tessuto liscio che la foderava si trovava la vera se stessa - la sua anima forse? - alla quale spettava la decisione di smettere di fingere, per dare l'ordine definitivo.

Ian McEwan, Espiazione, 2002

Per ore e ore ... il vasaio fece e disfece e rifece statuine di infermiere e di mandarini .... In verità, sono pochi coloro che sanno dell'esistenza di un piccolo cervello in ciascuna delle dita della mano, in gualche punto tra falange, falangina e falangetta. Quell'altro organo che chiamiamo cervello, quello con cui veniamo al mondo, quello che trasportiamo nel cranio e che trasporta noi affinché noi trasportiamo lui, non è mai riuscito a produrre altro che intenzioni vaghe, generiche, diffuse, e soprattutto poco variate, riguardo a ciò che le mani e le dita dovranno fare .... Si noti che, guando nasciamo, le dita non hanno ancora un cervello, che ci si va formando a poco a poco con il passare del tempo e l'aiuto di ciò che vedono gli occhi. L'aiuto degli occhi è importante, tanto quanto l'aiuto di ciò che da essi viene visto. Ecco perché quanto di meglio le dita hanno sempre saputo fare è stato proprio rivelare l'occulto. Quello che nel cervello potrebbe essere percepito come scienza infusa, magica o soprannaturale, qualsiasi cosa significhino soprannaturale, magico e infuso, sono state le dita e i loro piccoli cervelli a insegnarglielo. Perché il cervello della testa sapesse cos'era la pietra, prima c'è stato bisogno che le dita la toccassero, ne sentissero l'asperità, il peso e la densità, c'è stato bisogno che vi si ferissero ....

José Saramago, La caverna, 2000.





#### Farfalla di luce

... mi resta in mano solo la forma della sua fuga ...

Juan Ramon Jimenez

#### Mariposa de luz

... solo queda en mi mano la forma de su huída ... Juan Ramon Jimenez