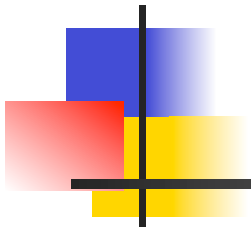


Neuroimaging: Theoretical challenges for cognitive science

PIRSTEC

Colloque de prospective

23 octobre 2009

Introduction

- Talk located at the intersection of
  - Functional neuroimaging
  - Philosophy
  - Theoretical cognitive science

- Aim = to explore interdisciplinary dimensions of the different notions of *connectivity* employed within the neuroimaging community

  - Anatomical connectivity
  - Functional connectivity
  - Effective connectivity

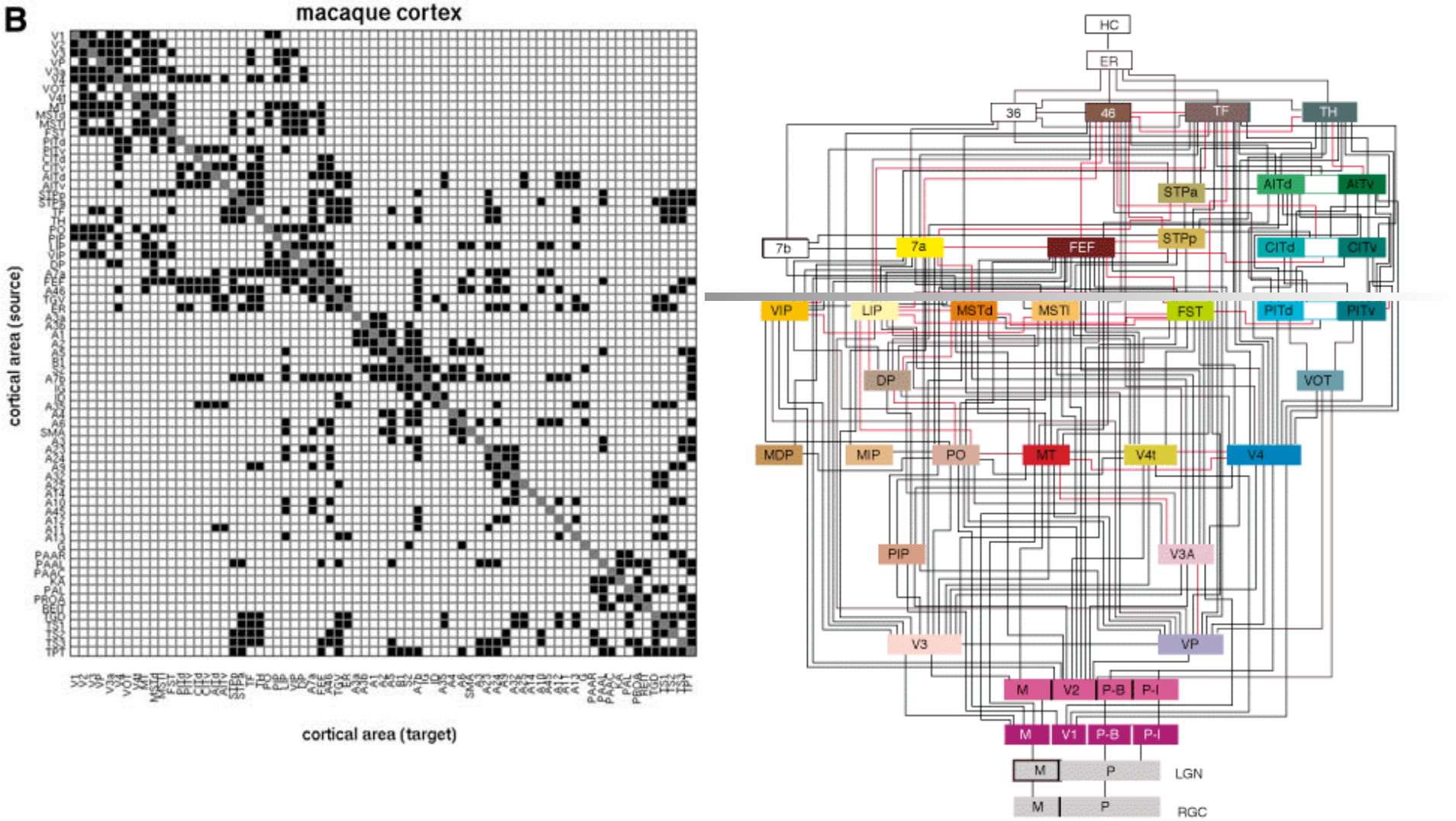
Anatomical connectivity

- Given by the anatomical connections between different cortical structures
- Can be mapped using Diffusion Tensor Imaging
  - Using the diffusion of water molecules to track axonal connections between cortical regions
- The most reliable data are derived from tracing studies (invasive)

Modeling anatomical connectivity

- Network diagrams of cortical regions in non-human primates
- E.g. Felleman & Van Essen 1991

- Large-scale cortical networks can be analyzed graph-theoretically
- Seem to have small-world connectivity patterns (Sporns, Tononi, and Edelman 2000)



Connectivity matrix and wiring diagram for macaque visual cortex
(based on Felleman and Van Essen 1991)

Functional connectivity

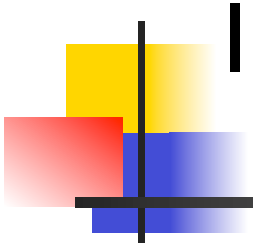
- Standardly defined in terms of statistical correlations between spatially remote neurophysiological events
- Frequently used to identify task-specific brain networks
    - and also idea of default mode “network” including cingulate cortex and ventral anterior cingulate cortex (Grecius et al. 2003)
- Researchers have claimed that some functional networks are impaired in particular disorders (e.g. schizophrenia)

Standard analysis of fMRI data

- STEP 1
- Model correlation between BOLD response in individual volume elements (voxels) and some experimentally controlled variable

- STEP 2
- Create a statistical parametric map (SPM) that shows which voxels have time-series correlated with a certain task component

Implicit modeling assumptions



- The connections between elements of the system (e.g. specific voxels) are not taken into account in creating the SPM
- The analysis treats experimental variables as inputs that act directly on system elements
- What the SPM identifies are system elements that are correlated in the same way with the task
- This tells us nothing about how those system elements are related to each other

Limits of functional connectivity

- “Patterns of functional connectivity are statistical signatures of hidden causal processes occurring within and among specific and time-varying subsets of neurons and brain regions. The identification of which subsets are currently causally engaged in a given task requires the inclusion of and reference to a structural model in order to access effective connectivity patterns.”

- Sporns and Tononi 2007

A familiar problem?

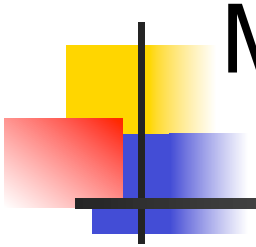
- Interpreting functional connectivity is an exercise in distinguishing causal relations between two brain areas from non-causal correlation due to
- common response to external stimulus
- common inputs
- common cause in third brain area
- Important connections with the philosophy of science
  - analysis of causation
  - causal Bayes nets
-

Effective connectivity

- “The influence one neural system exerts on another” (Friston and Büchel 2003)

- “The functional connectivity between two brain regions simply tells us how correlated their activities are. Their effective connectivity, on the other hand, is the explicit influence that one region’s activity has on the activity of the second along the direct anatomical pathway linking the two.”
- (Horwitz, Friston, Taylor 2000)

Models of effective connectivity



- Information about effective connectivity is not standardly derived from imaging data
- Rather, assumptions about effective connectivity are used to interpret imaging data
- These assumptions are derived from anatomical connectivity data

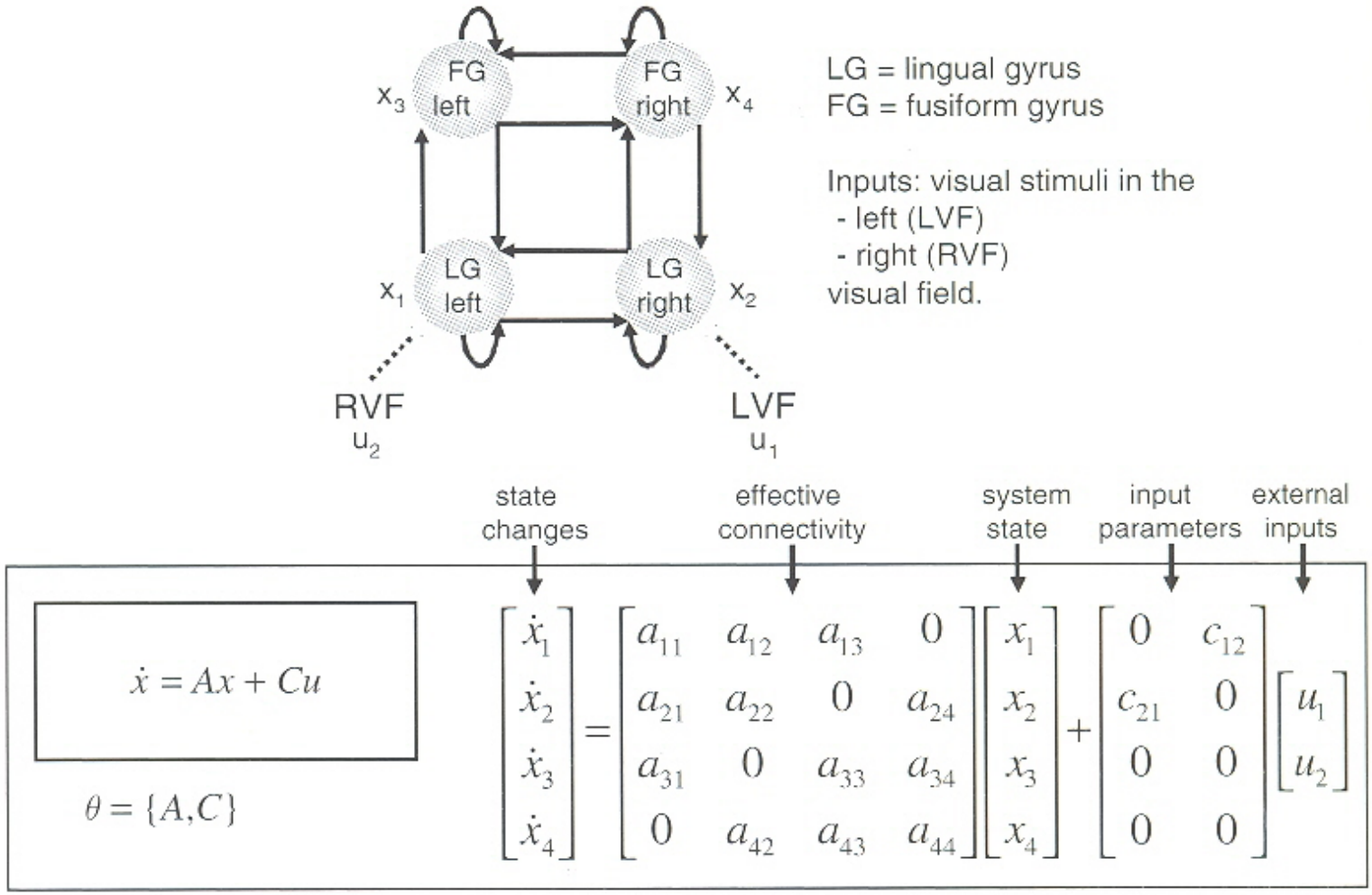
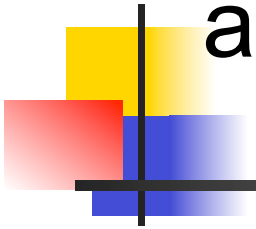


Fig. 1. A simple linear dynamic system as an example for a concrete implementation of (3), describing interactions between the lingual (LG) and the fusiform gyri (FG) in both hemispheres. The top panel shows the system structure and the sensory inputs (visual stimuli displayed in the left and right peripheral visual field) that perturb the system. The lower panel shows the state equation in matrix form

Three key questions for philosophy and theoretical cognitive science

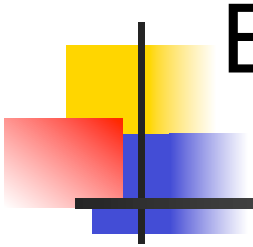


- What is the relation between anatomical connectivity and effective connectivity?
  - Intersections with debates about multiple realizability
- In what sense are models that exploit effective connectivity assumptions giving information about the causal flow of information processing?
  - Intersections with debates about mental causation
- What model of cognitive architecture do these models suggest?
- Intersections with debates about modularity

Exploring the first question

- Two different strands to the notion of effective connectivity
- (1) A quasi-anatomical notion, corresponding to the existence of direct cortical pathways between cortical regions
- (2) An information-processing notion, tracking the flow of information through a brain network

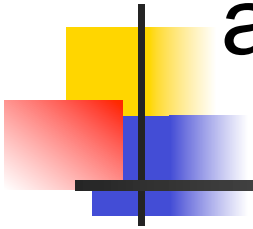
Exploring the first question



- In the quasi-anatomical sense, effective connectivity essentially provides a set of parameters for a systems analysis

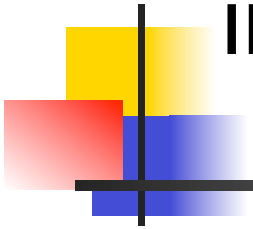
- In the information-processing sense, we need something that will allow us:
  - (a) to identify a series of discrete information-processing stages
  - (b) to correlate information-processing stages with neural areas (possibly distributed)

Effective connectivity in the anatomical sense



- Difficulty in spelling out what is to count as a cortical connection
- Unduly restrictive to count only direct cortical connections
- But on the other hand there is a risk that the notion becomes trivial
  - the brain is modeled graph-theoretically as a connected graph

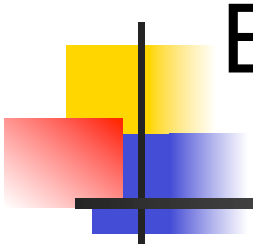
Effective connectivity in the information-processing sense



- fMRI tells us very little about *how* information-processing takes place
  - • No consensus on what type of neural activity correlates with the BOLD signal

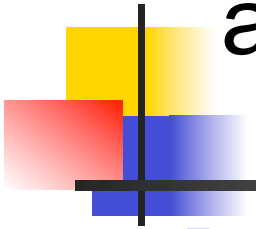
- But it might be expected to identify the *stages* in information flow
  - • To permit a vertical mapping onto information-processing models of specific neural areas
  - • To permit calibration with other tools for studying information-processing (e.g. neurophysiological/molecular biological/ computational)

Effective connectivity and causality



- At bottom the flow of information has to be a causal flow
  - Basic principle of both classical and connectionist models of information-processing
- So the question is: Can we use neuroimaging to derive causal models of information flow?
- This brings us to the second question

Three key questions for philosophy and theoretical cognitive science



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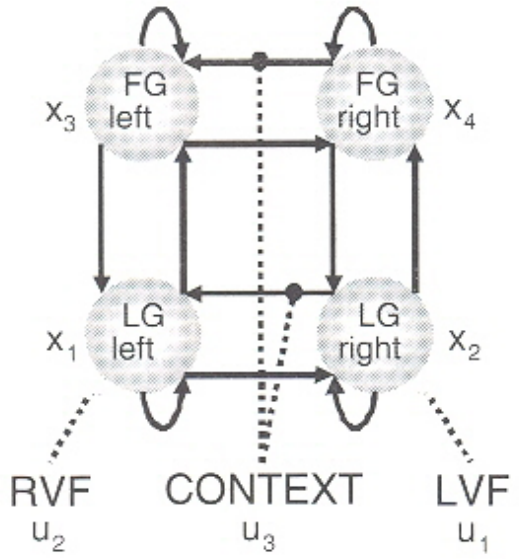


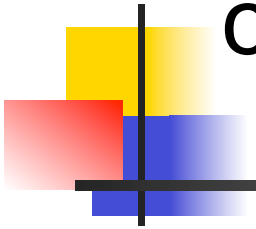
$$\dot{x} = (A + \sum_{j=1}^{m} u_j B^{(j)})x + Cu$$

$$\theta = \{A, B^{(1)} \ldots B^{(m)}, C\}$$

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \left\{ \begin{bmatrix} a_{11} & a_{12} & a_{13} & 0 \\ a_{21} & a_{22} & 0 & a_{24} \\ a_{31} & 0 & a_{33} & a_{34} \\ 0 & a_{42} & a_{43} & a_{44} \end{bmatrix} + u_3 \begin{bmatrix} 0 & \textcircled{$b_{12}^{(3)}$} & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \textcircled{$b_{34}^{(3)}$} \\ 0 & 0 & 0 & 0 \end{bmatrix} \right\} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 & c_{12} & 0 \\ c_{21} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix}$$

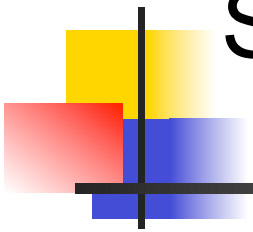
Fig. 3. A simple bilinear extension of the linear dynamic system shown in Fig. 1. This is an example for a concrete implementation of the neural state equation of DCM for fMRI. Note the role of the bilinear terms which model context-dependent (additive) changes of the strengths of the connections from the right to the left hemisphere (circled elements in the B matrix)

Stephan on systems analysis and causality (K. Stephan 2004)



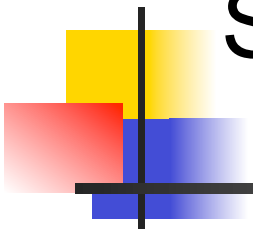
- Such a model provides a causal description of how system dynamics result from system structure, because
- (1) it describes when and how external inputs enter the system
- (2) how the state changes induced by these inputs evolve in time depending on the system's structure
  - Structure is given by the connectivity pattern and all other time-invariant properties of system elements

System evolution and causality



- This is certainly causal in one sense
  - The evolution of a system is a causal process
  - The system model shows how the state of a system at $t + n$ is fixed by its state at t together with its structure and exogenous inputs
- But does it allow us to see the causal progression of information processing?
  - What is it about the inputs that determines how the system evolves?

System evolution and causality

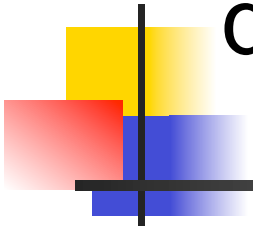


- The model tells us how effective connectivity is modulated by certain inputs
- But what we want to know is why this occurs?
- Why do the demands imposed by the task change the dependencies between stations in the network?

Dynamic causal modeling (DCM)

- Two components
- 1) A neural model with more or less the form of the second (bilinear) system model.
- 2) A biophysical forward model of the transformation from neural activity to BOLD response
- (Friston, Stephan et al.)

Does DCM answer the *why* question?

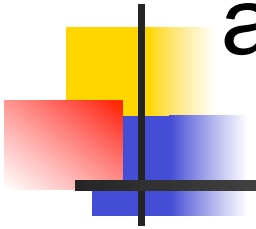


- Not really – it pushes it one step back
- DCM gives us a way of dealing with the fact that the BOLD response is an indirect measure of neural activity
- But it does not tell us why particular tasks exploit certain patterns of connectivity rather than others
- And the causal parameters are derived from anatomical data. . .

A challenge for philosophy and theoretical cognitive science

- To clarify what exactly we are looking for in a causal model of a task-dependent brain network
  - • A theoretical account of information flow as a causal process
  - • A theoretical account of what would count as a causal explanation in this area
  - • A theoretical account of the nodes in brain networks that allows them to be the sorts of thing that can stand in causal relations
    - . . . The third question

Three key questions for philosophy and theoretical cognitive science



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Functional brain networks

- Two principles governing research into functional brain networks
- Anatomical segregation (ie. possibility of identifying specialized neurons and neural populations)
- Functional integration (ie. the idea that cognitive processing requires coordinated activity of a distributed network of different areas)

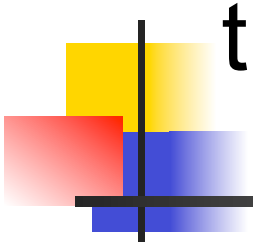
Functional brain networks

- It is generally assumed that functional brain networks are specialized for certain tasks
- In a minimal sense, therefore, these functional networks are modular
  - Degree of domain-specificity
- But do they exhibit any other defining features of (Fodor?) modularity?

Two anomalies

- The idea that functional brain networks are informationally encapsulated seems to be in tension with global connectedness at the anatomical level
- E.g. “cross-talk” between the dorsal and central information-processing streams
- Data from fMRI do not obviously corroborate the classical model of modular processing in terms of information flowing through a series of encapsulated modules
-

The challenge for philosophy and theoretical cognitive science



- To develop a model of modular information-processing that does justice to

- Anatomical segregation
- Functional integration
- Global connectedness
- Causal nature of information flow
- The causal efficacy of individual brain areas
-