NACS 645 – Is visual processing modular

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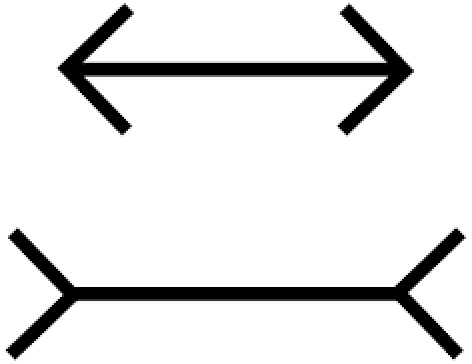
Impenetrability of the perception

Müller–Lyer illusion



Despite knowing the illusion, its effect persists on human perception. Why?

Because low-level (early visual) information operates independently from higher-level information.

Perception is impenetrable to Cognition. Low-level information is encapsulated within early visual modules.

Modularity paradigm

Fodor (1983) distinguished modular and non-modular systems. Modular systems fulfill certain properties:

1. Domain specificity
2. Mandatory operation
3. Limited central accessibility
4. Fast processing
5. Informational encapsulation
6. ‘Shallow’ outputs
7. Fixed neural architecture
8. Characteristic and specific breakdown patterns
9. Characteristic ontogenetic pace and sequencing

Modular systems are encapsulated : unaffected by other cognitive domains (cognitively impenetrable) and no information is added (non inferential).

Modularist views

Some later researchers/philosophers started drawing a border between perception and cognition.

Pylyshyn (1999) didn’t but developed from the modularist view.

- Information encapsulation is an important feature of (early) vision. Ties to cognitive impenetration
- Top-down/complex processing explained by *“local vision-specific memory embodied in early vision”*
- Hence, Phylyshyn’s vision of early visual processing is tied to modularity but not fully modularist. Additionally, there is no border drawn between perception and cognition

Fodor’s (1983) modularity

1. **Domain specificity**: A modular system processes a restricted class of inputs and problems.
2. **Mandatory operation**: Once presented with the appropriate stimulus, the system automatically engages and runs to completion without conscious control.
3. **Limited central accessibility**: The intermediate representations generated within the system are opaque to consciousness and cannot be accessed for explicit report.
4. **Fast processing**: Modular systems operate rapidly, often on the order of hundreds of milliseconds, reflecting efficiency gained from restricted informational access.
5. **Informational encapsulation**: A module’s operations draw only on its proprietary database and input signals, remaining insulated from information elsewhere in the mind.
6. **‘Shallow’ outputs**: The system produces relatively simple, general, or basic-level representations that are computationally cheap, rather than highly abstract or theoretical concepts.
7. **Fixed neural architecture**: Modular systems are implemented in dedicated and circumscribed neural circuits that can be selectively impaired without disrupting other functions.
8. **Characteristic and specific breakdown patterns**: Damage to a module produces distinctive deficits (e.g., prosopagnosia, dyslexia) without widespread cognitive collapse.
9. **Characteristic ontogenetic pace and sequencing**: Modules emerge and mature according to a species-typical developmental timetable, largely triggered rather than learned.

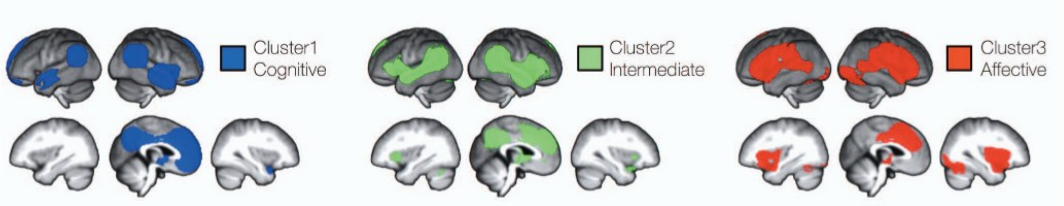
Modularity of vision

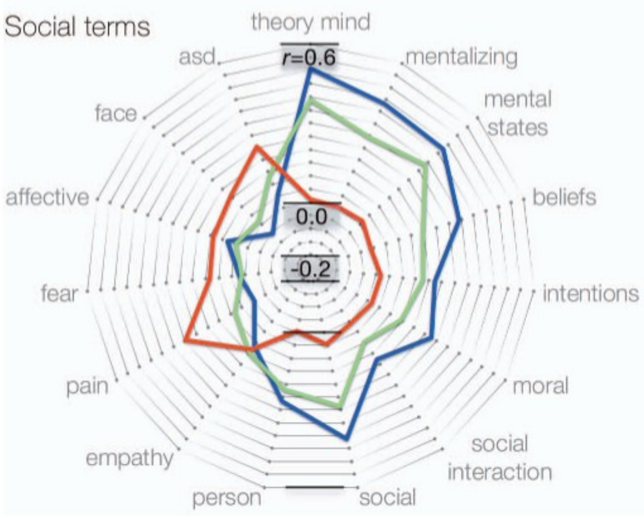
- Input systems (vision, audition, language) are modular; central systems (belief, reasoning) are not.
- Each module performs a specialized operation in a largely feedforward sequence
  Vision: retina → V1 → V2 → inferotemporal cortex
- Information processing relies only on proprietary databases + immediate sensory input (encapsulation).
  Early visual modules compute edges, shapes, depth, and pass representations forward.
- Higher cognition cannot alter early visual computations.
- Information processing is separable: fixed roles, primarily bottom-up flow.

Marr & bottom-up vision

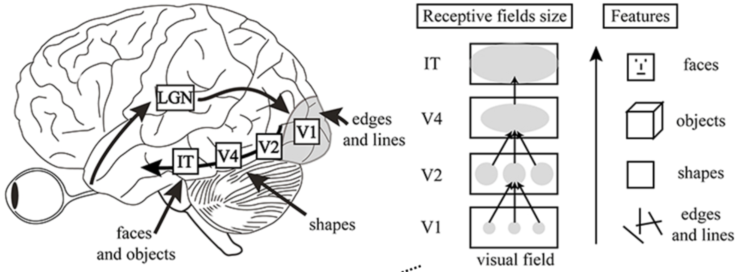
"An overall framework for visual information processing [...]:
(1) the primal sketch, [...]
(2) the 2 ½ D sketch, [...] and
(3) the 3-D model representation, whose important features are that [...] primitives of various sizes are included, arranged in a modular, hierarchical organization." (Marr, 1982)

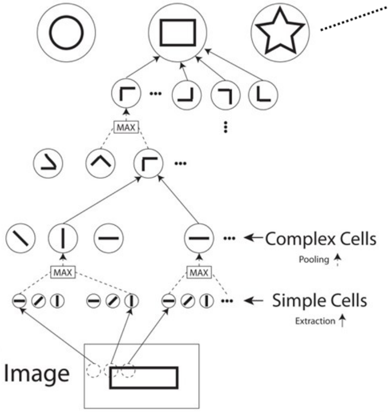
Schurz et al., 2021. *Psychological Bulletin*





Herzog, Clarke, 2014. *Front. Comput. Neurosci*





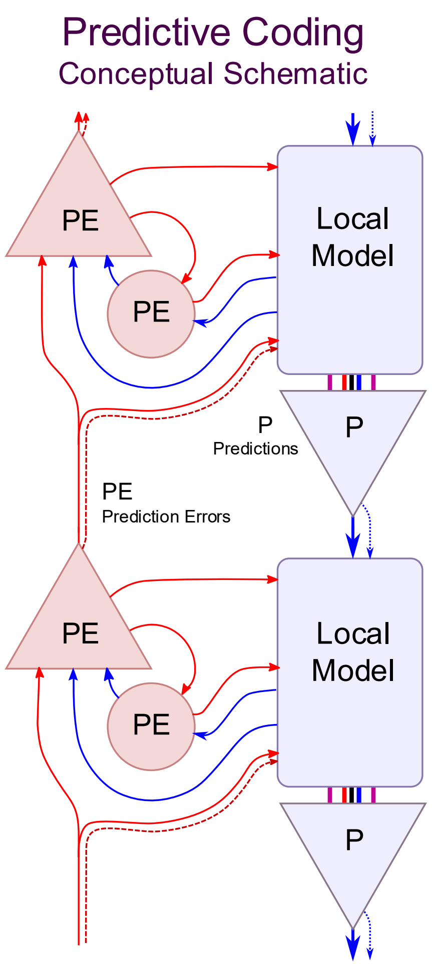
de Ladurantaye, Rouat & Vanden-Abeele, 2012. *Visual Cortex: Current Status and Perspectives*

"There is some irony in this because Marr's emphasis on vision as a bottom-up process heavily influenced opponents of the idea that perception is cognitively penetrable" (Lupyan, 2015)

Predictive coding paradigm

- Initially a model of sensory system
- Brain as a hierarchical prediction machine:
  - Higher levels generate expectations about what lower levels should sense;
  - Lower levels return only prediction errors (mismatch expected-actual input).
- Perception is an ongoing cycle of prediction and correction
  Each level predicts the one below and updates based on its error signals

Jan C. Hardenbergh for *Wikipedia*
Created from Rao & Ballard, 1999, and ulterior literature



Predictive Coding compares data coming from the senses against expectations coming from the brain. When they do not match, Prediction Errors (PE) are generated.

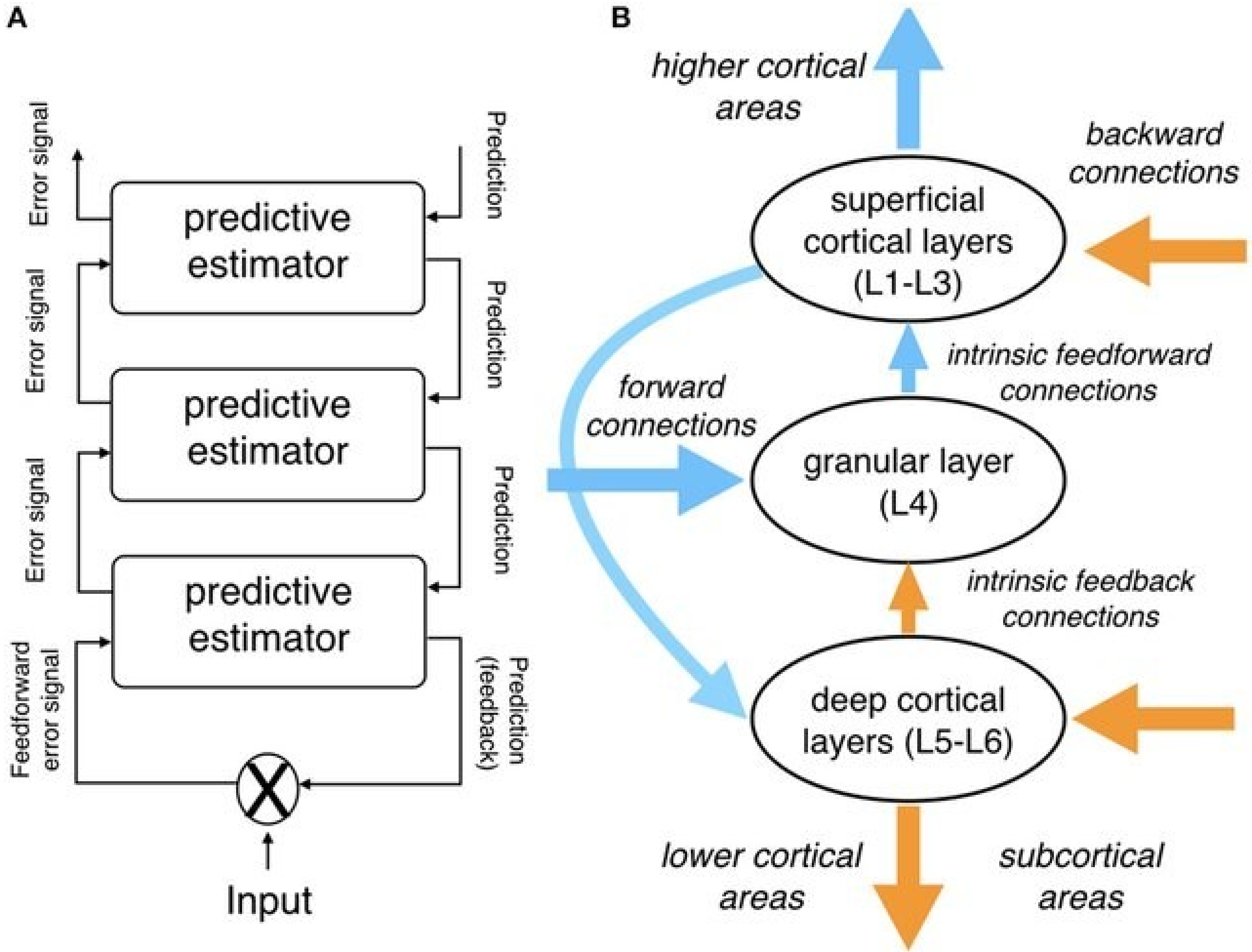
Predictions (P) are generated by models constructed from prior experience with the world. Precision expectations flow with the predictions (dotted blue line).

Prediction Error Neurons include excitatory neurons (triangle) and inhibitory neurons (circle). A precision metric of the error is in included in the signal (dotted line).

Bornkessel-Schlesewsky & Schlesewsky, 2019, *Frontiers in Psychology*

Corollaries of predictive coding hypothesis

- The brain continuously performs hypothesis testing: it infers causes of input and revises its model when errors appear (active inference)
- Neural architecture is hierarchical/layered (low → mid → high)
- Information flows top-down and bottom-up (continuous feedback loops)
- Priors, expectations, task demands determine how strongly predictions constrain early processing
- Attention and uncertainty weight which signals dominate: precise prediction errors override priors, while imprecise ones are down-weighted
- Prediction errors drive inference and learning



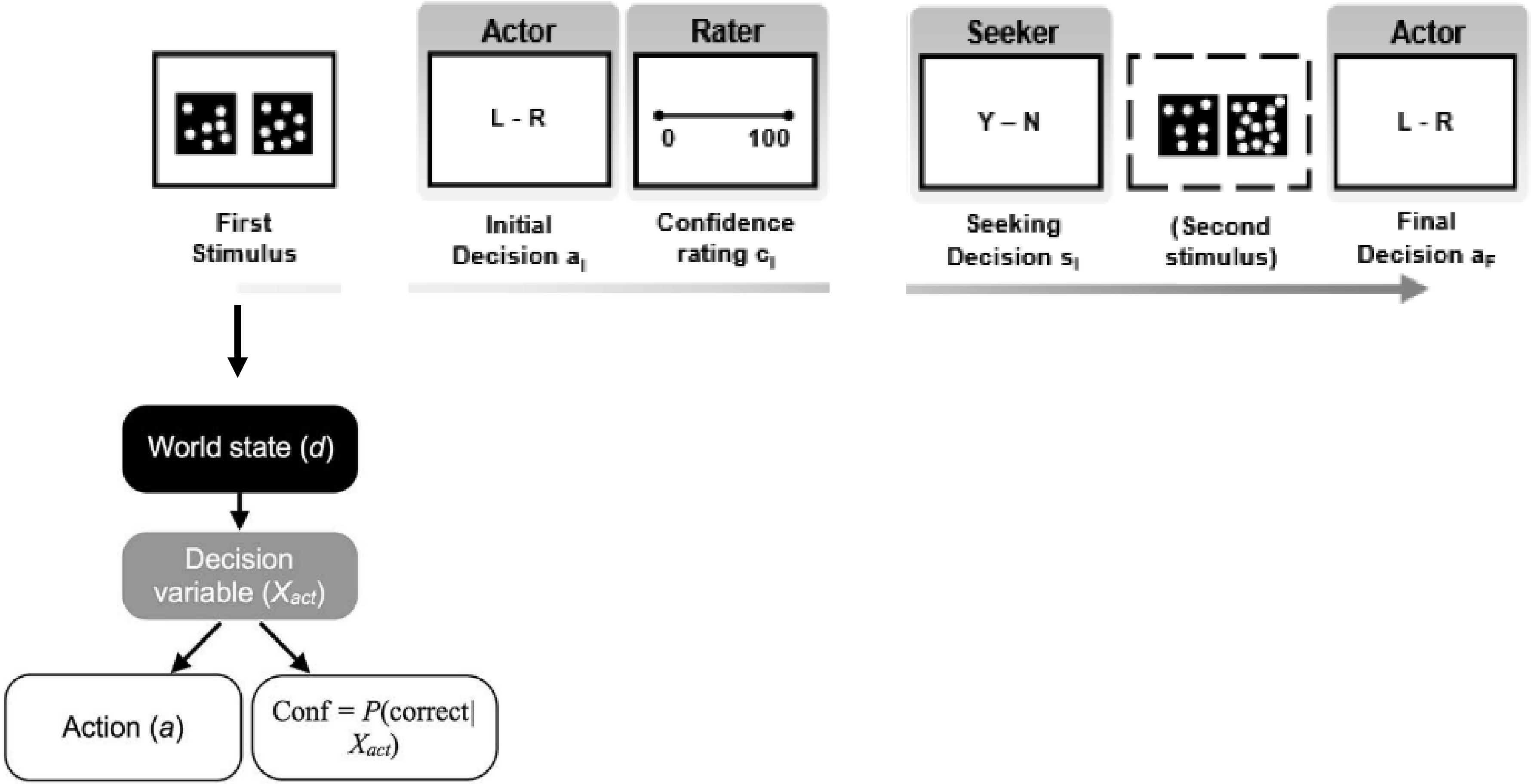
The predictive brain

Predictive coding is member of a wider set of theories that follow the Bayesian brain hypothesis:

- Predictive coding (Sensory coding and perception)
- Bayesian inference (Brain holds probabilistic beliefs about the true state)
- Free energy principle (Minimizing surprise to maintaining adaptive states)
- Active inference (Perception-action)

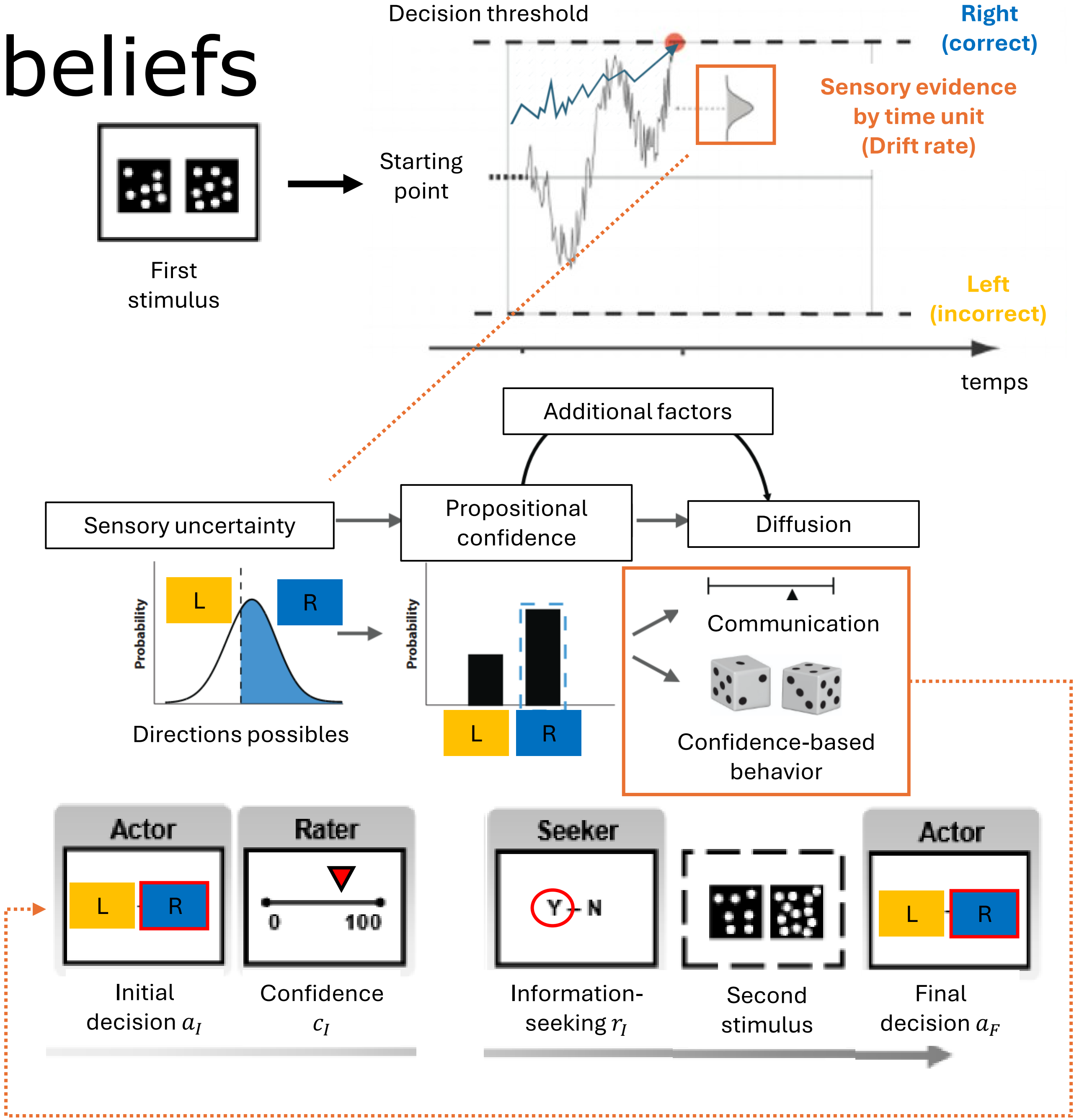
- Tentatives to unify predictive coding, active inference and approximate Bayesian inference

Beliefs during decisions about percepts



Fleming and Daw, 2017. *Psychological Review;* Schulz et al., 2021. *Psychological Review*

Propositional beliefs



Modularity vs Predictive coding: qualitative difference

« *If a mismatch between bottom-up sensory data and top-down predictions is more effectively resolved at a higher level, then conflicts can be resolved at these higher levels leaving lower-level representations less affected. No one needs to "decide" where the influence of a higher-level state should terminate.* ***This is an emergent property of a hierarchical predictive system****, examples of simply performing computations that reduce global prediction error, much as water finds the shortest path downhill.* » (Lupyan, 2015)

Modularity

- Information flow fixed by architecture
- Higher-level effects occur only where explicitly wired
- Encapsulation defines boundaries of influence

Predictive Processing

- Influence emerges from prediction-error minimization
- No module "decides" where influence stops
- Global error reduction dictates how priors and errors interact

NACS 645 – Is face processing modular

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Modularity of mind

Originates from Simon (1962?). Fodor (1983) distinguished modular and non-modular systems. Modular systems fulfill certain properties:

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Bornkessel-Schlesewsky & Schlesewsky, 2019, *Frontiers in Psychology*

Predictive coding

- Brain as a hierarchical prediction machine
  Hi-levels: prediction; Lo-levels: PE
- Continuous hypothesis testing:
  it infers causes of input and revises its model when errors appear (active inference)
- Neural architecture is hierarchical/layered (low → mid → high)
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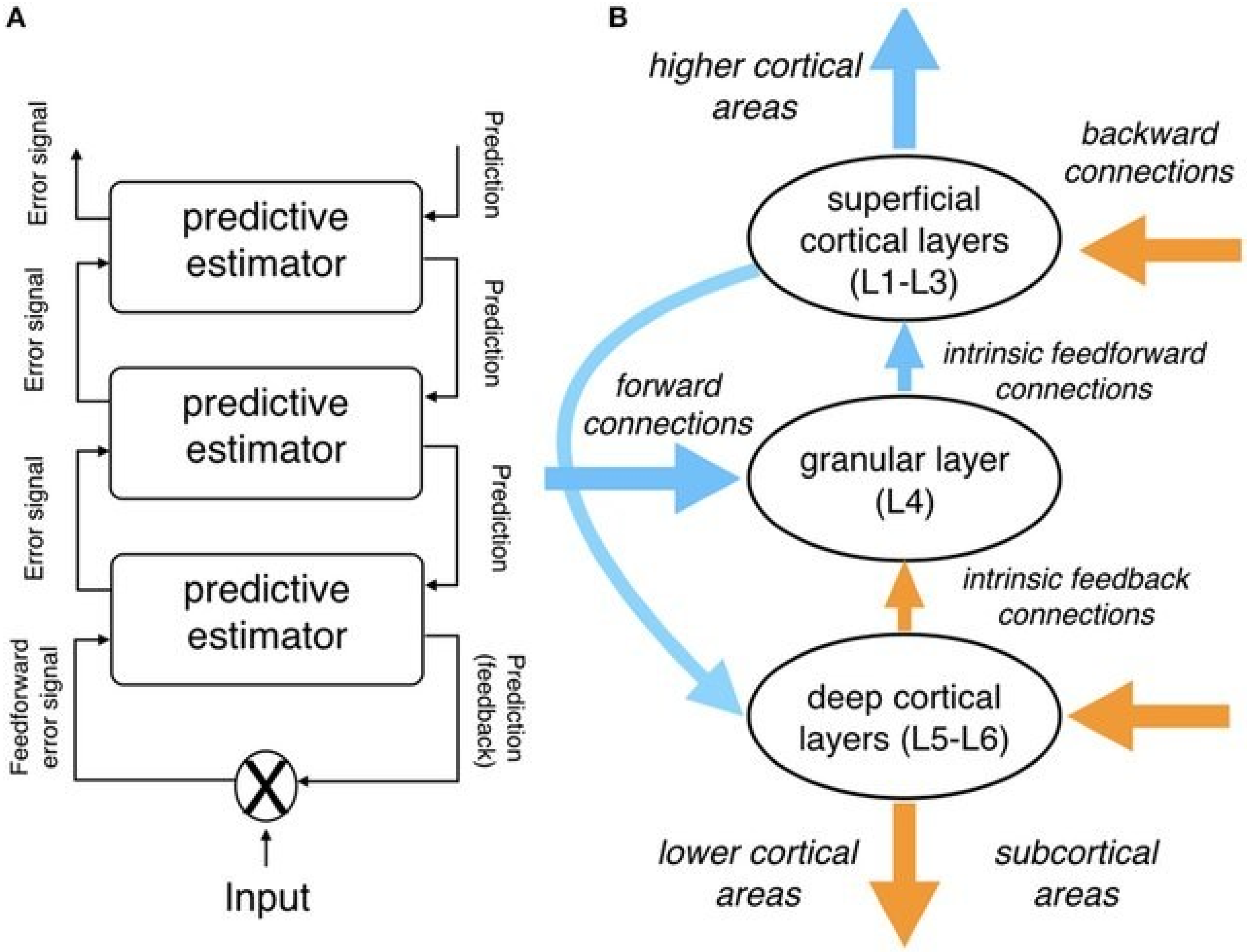
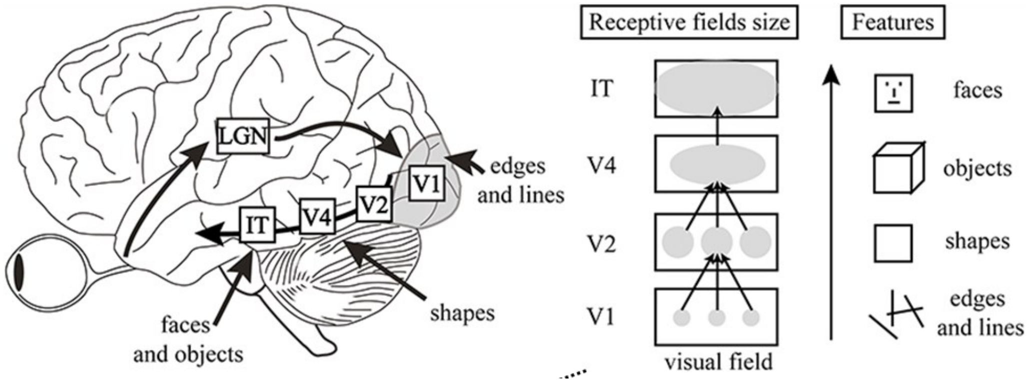


Functional Modularity (cog. psyc.)

Herzog, Clarke, 2014. *Front. Comput. Neurosci*



The brain is hierarchically modular, with modules and non-modules.

Modules are defined by:

- **Fodor (1983):** cognitive impenetrability, information encapsulation, innate modules

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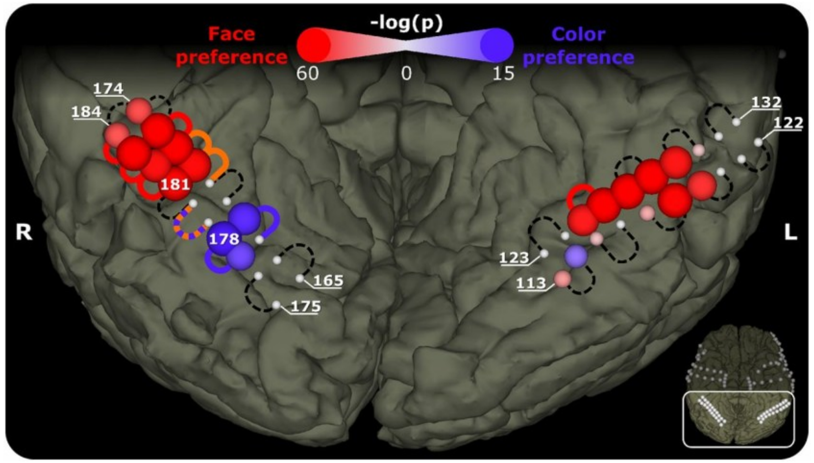

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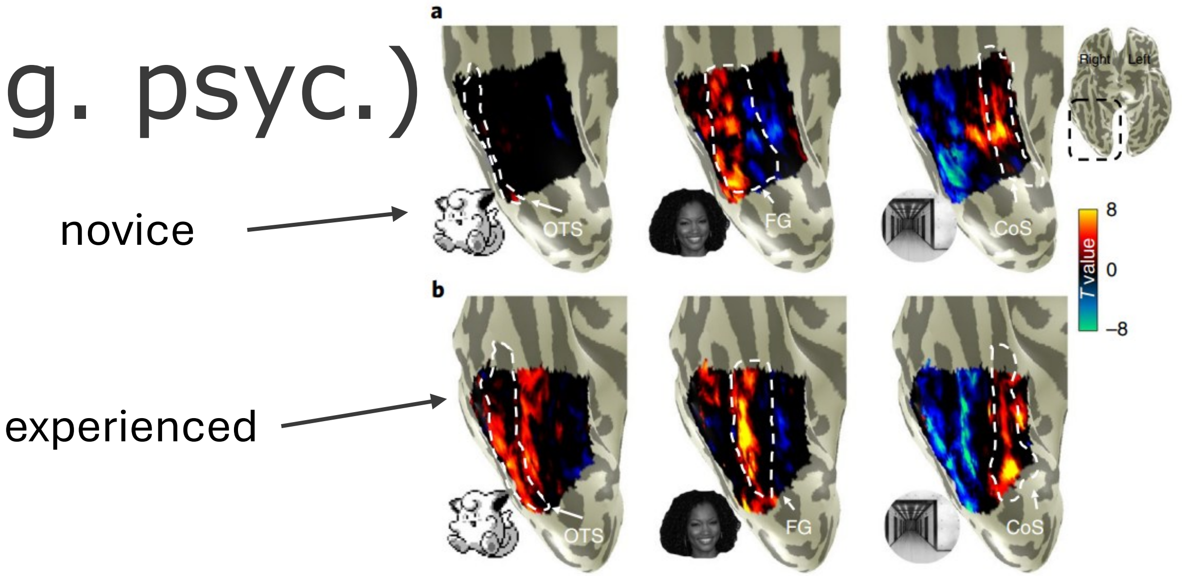

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Modules are defined in terms of (cognitive-cortical) functions – most debates regard domain-specificity, penetrability, encapsulation, innateness

Topological Modularity (network theory)

The brain is hierarchically modular, with modules and sub-modules.

Modules are defined in terms of topology. They are network communities in a connectome.

Topological Modularity (network theory)

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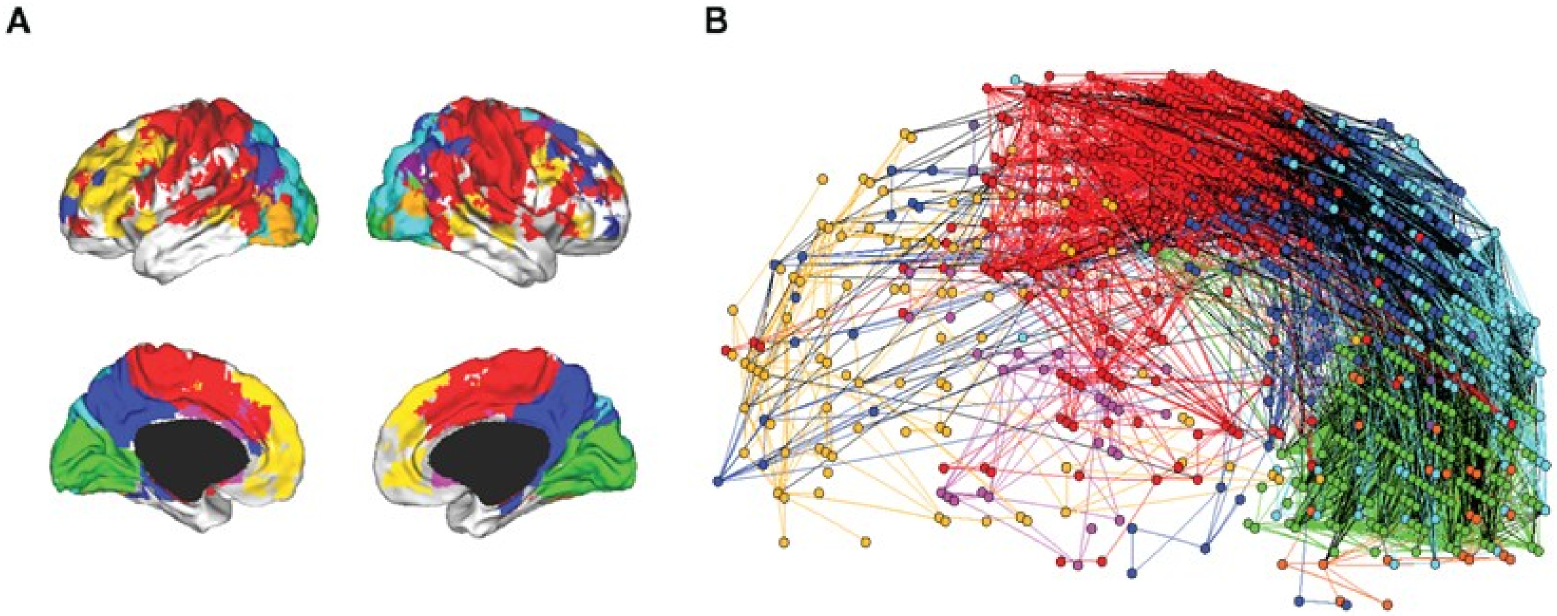

Meunier, Lambiotte et Bullmore, 2010.
Frontiers in Neuroscience

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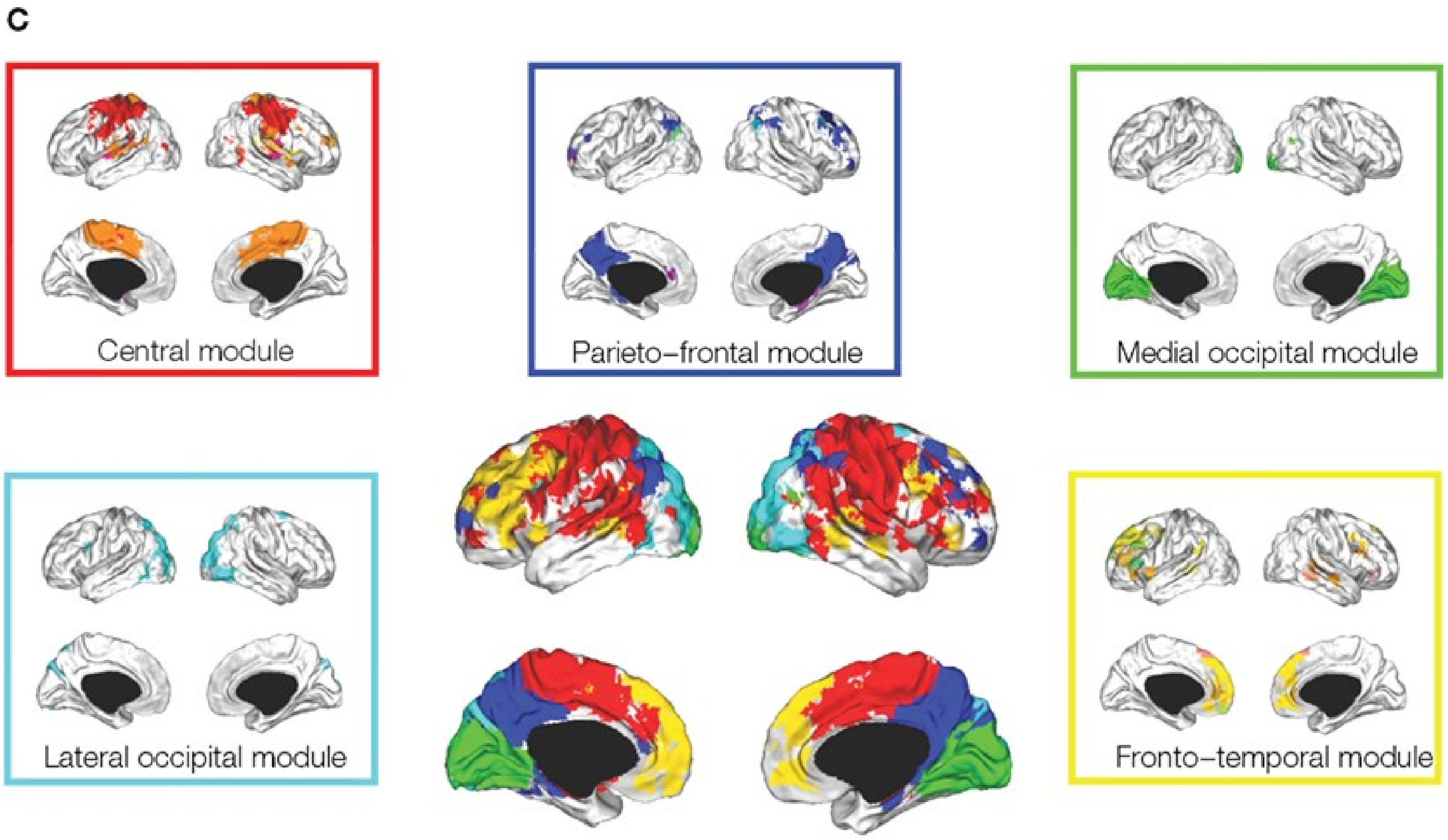
Topological Modularity: Early networks



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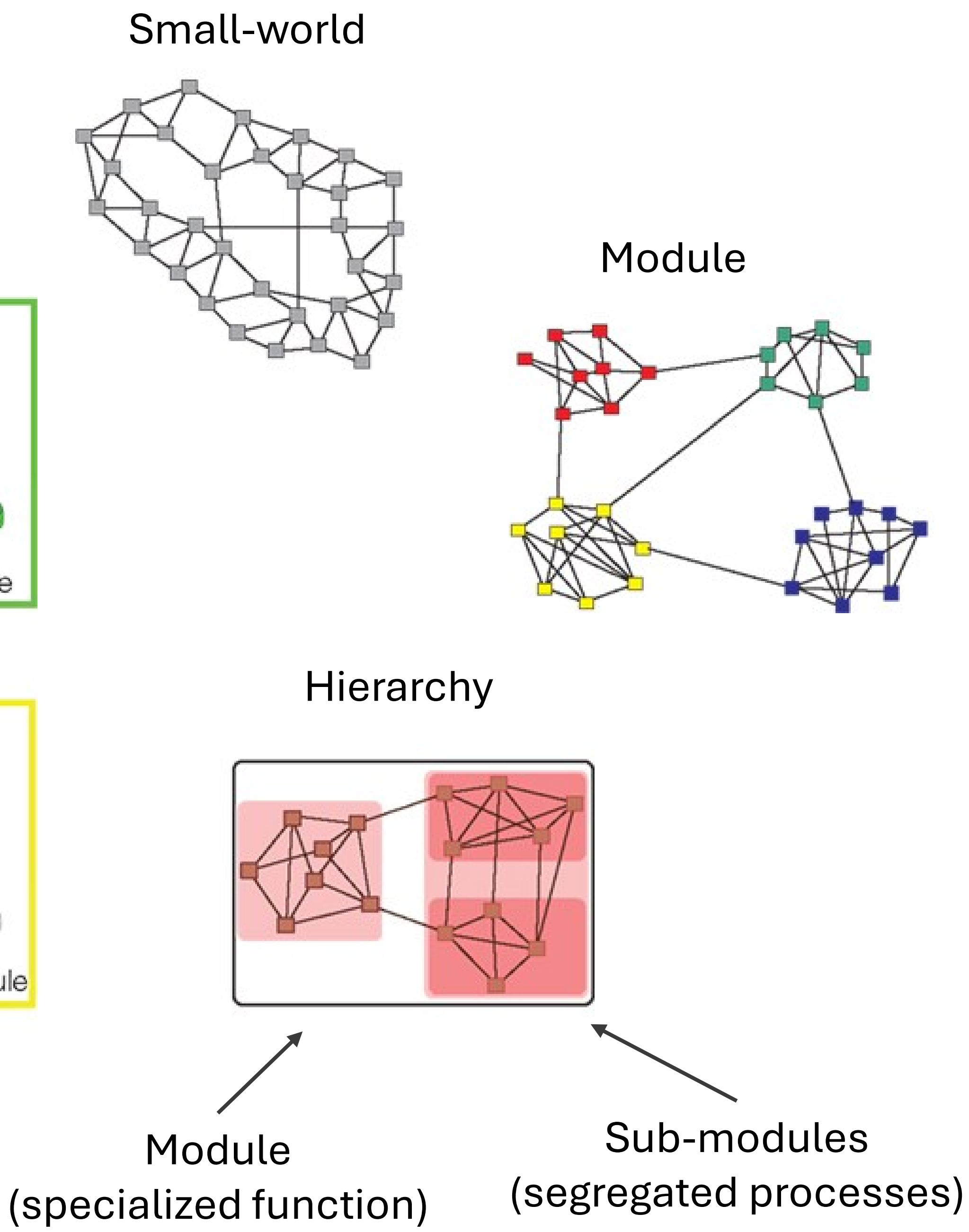
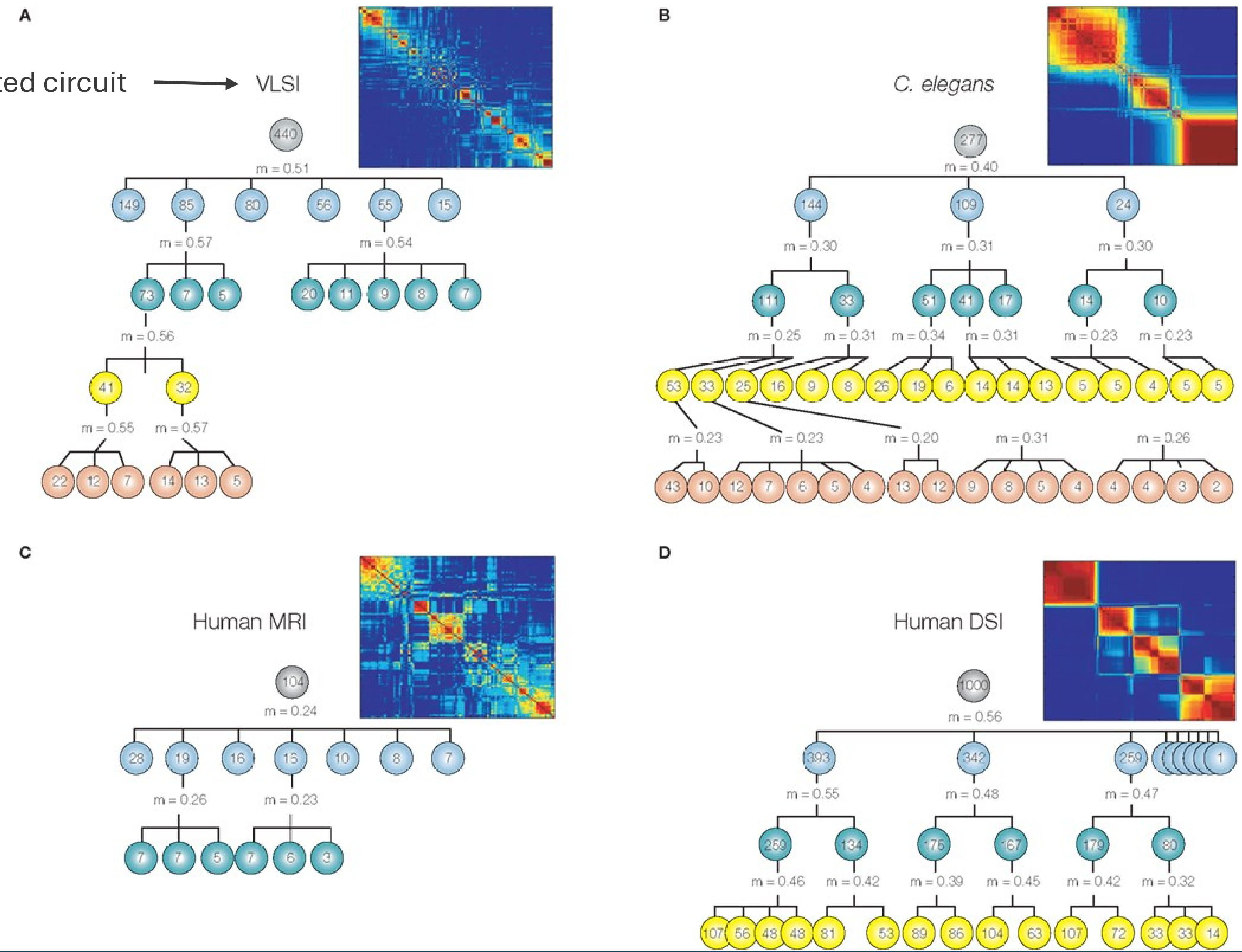


Topological Modularity:
A property of information-processing systems

Meunier, Lambiotte et Bullmore, 2010. *Frontiers in Neuroscience*

Integrated circuit →



← Diffusion spectrum imaging

« Many systems have the **fractal** property of hierarchical modularity, multi-scale modularity or *russian doll* modularity »

Topological Modularity:
Recent networks

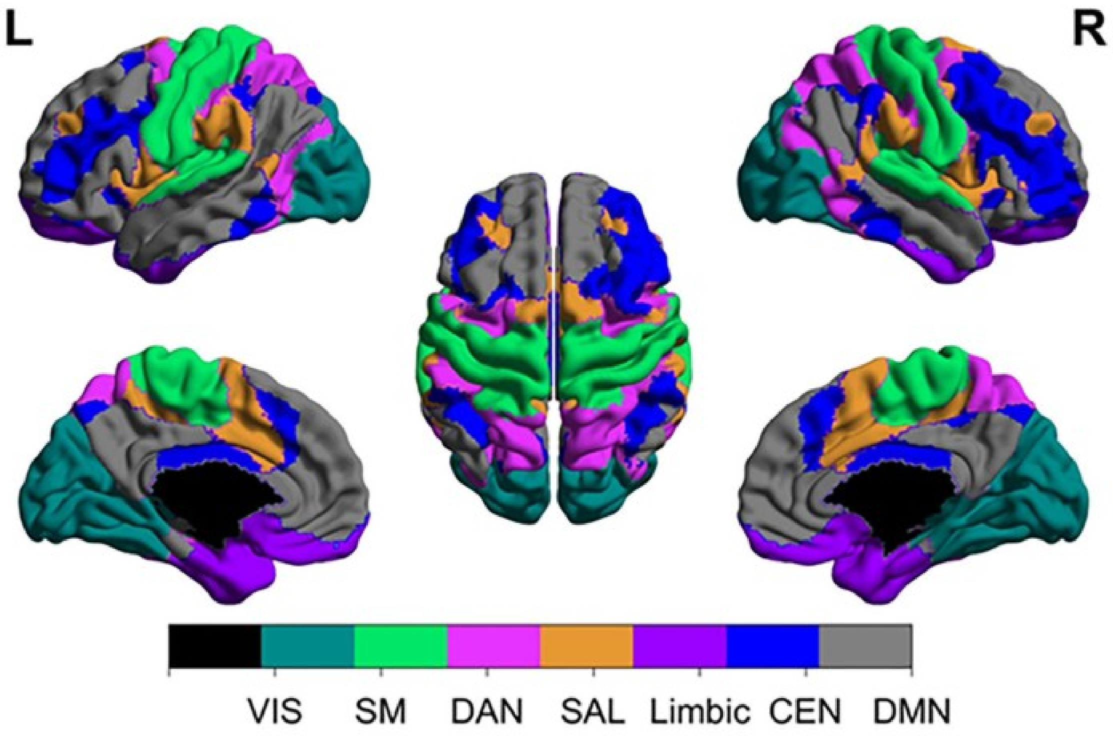


FIGURE 1
Anatomical topographies of canonical large-scale networks. Networks were generated from those reported in Schaefer et al. (2018) (available at: https://github.com/ThomasYeoLab/CBIG/tree/master/stable_projects/brain_parcellation/Schaefer2018_LocalGlobal) with updated terminology. VIS, visual; SM, somatomotor; DAN, dorsal attention network; SAL, salience; CEN, central executive network; DMN, default mode network.

Boerger et al., 2023.
Frontiers in Human Neuroscience

"In recent years, a paradigm shift in neuroscience has been occurring from "***localizationism***," or the idea that the brain is organized into separately functioning modules, toward "***connectomics***," or the idea that interconnected nodes form networks as the underlying substrates of behavior and thought."

Topological Modularity: Modularity of anatomy and functions

Meunier, Lambiotte et Bullmore, 2010. *Frontiers in Neuroscience*
Seguin, Sporns et Zalesky, 2023. *Nature reviews neuroscience*

Cognitive modularity

- Modularity is a property of brain regions
  - Mind organized into **modules**: specialized systems for processing certain inputs (vision, language)
  - Modules defined by: **domain specificity** (operate only on certain inputs), **encapsulation** (insulated from other knowledge), **automaticity** (mandatory operations), relatively **fixed neural architecture**
  - *Psychological-level* definition: modules are computational "boxes" in the mind

Network modularity **(predictive coding -compatible)**

- Modularity is a property of networks that optimizes information communication
  - A module is a cluster of brain regions with **dense internal connectivity, sparse external connectivity and recursivity**
  - Brain networks are **hierarchically modular**: large modules (e.g., visual network) subdivided into smaller submodules (ventral vs. dorsal visual pathways) subdivided into smaller submodules
  - Modularity provides **computational advantages**: efficiency, robustness, balance between segregation (specialization) and integration (coordination)
  - Modules forward information **with dedicated paths and diffusion processes** to achieve *optimal signalling delay*

Meunier, Lambiotte et Bullmore, 2010. *Frontiers in Neuroscience*

Why are brain networks expected to be modular?

- **Small-world design:** Favors high clustering within modules supports **locally segregated processing** (e.g., visual motion detection) at low wiring cost, while short path lengths **enable global integration** for generic functions (e.g., working memory)

- **Rich non-linear dynamic behaviors**: Modularity supports **fast intra-modular and slower inter-modular processes**; neural activity can remain **locally encapsulated**; **neural activity is balanced**: *activity doesn't die, doesn't spread network-wise*; **redundancy of signal; flexibility and stability** by allowing modules and submodules **reconfiguration**

- **Origins**: Modular networks arise naturally when structure and dynamics co-evolve. Connections between regions that tend to synchronize are reinforced; weak or unsynchronized links are pruned. Specialized submodules can be reused

Meunier, Lambiotte et Bullmore, 2010. *Frontiers in Neuroscience*

End quote

“In the psychological literature, the central principle of phrenology or faculty psychology has been that mental function can be somehow sub-divided into part-functions or mental modules (Fodor, 1983).

Modular processes, like color vision, have been described as automatic, effortless, informationally encapsulated, and anatomically localized (Zeki and Bartels, 1998).

More consciously effortful tasks, like working memory, have been proposed to demand access to a more globally integrated processing system – a workspace of synchronized neurons oscillating coherently over large physical distances across the whole brain (Varela et al., 2001; Buzsáki and Draguhn, 2004).

In short, there are strong prior reasons to believe that brain networks are formed and function as modular systems.”