Design and Analysis of Cognitive Systems

Research at Carnegie Mellon University

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Carnegie Mellon

CNBC
Center for the Neural Basis of Cognition

Design-related research at Carnegie Mellon University

College of Fine Arts

- Architecture
- Design

Humanities and Social Sciences

- Psychology
- Social and Decision Sciences

Heinz College of Public Policy

- Information Systems
- Public Policy & Management

Center for the Neural Basis of Cognition

Joint CMU/Pitt institute

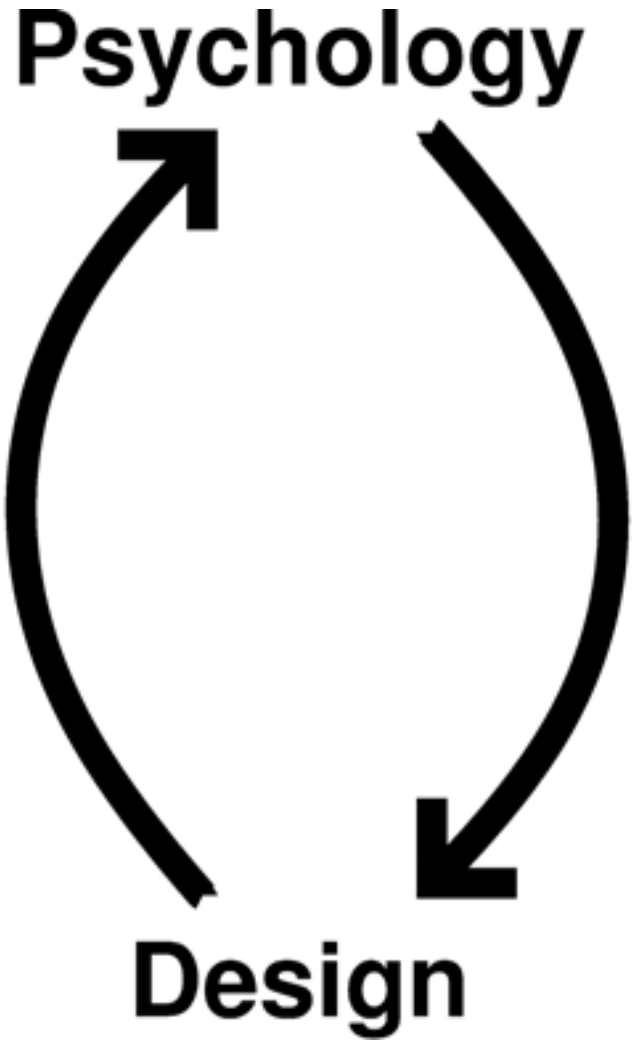
School of Computer Science

- Computer Science
- Machine Learning
- Human Computer Interaction
- Robotics
- Language Technologies
- Entertainment Technology

Carnegie Institute of Technology

- Biomedical Engineering
- Chemical Engineering
- Civic and Environmental Eng.
- Electrical and Computer Eng.
- Material Science
- Mechanical Engineering

Psychology and Design



Use design principles to inform study of cognitive processes

Provide constraints on good design

Improve design process

Department of Psychology

Cognitive Development

Basic mechanisms of learning and change across the lifespan

- Fisher, Klahr, MacWhinney, Thiessen, Rakison, Siegler

Cognitive Neuroscience

Characterization of cognitive behavior and its neural implementation

- Behrmann, Holt, Just, Plaut, Tarr, Verstynen

Cognitive Tutors / Education / Human-Computer Interaction

Computer systems for guided instruction

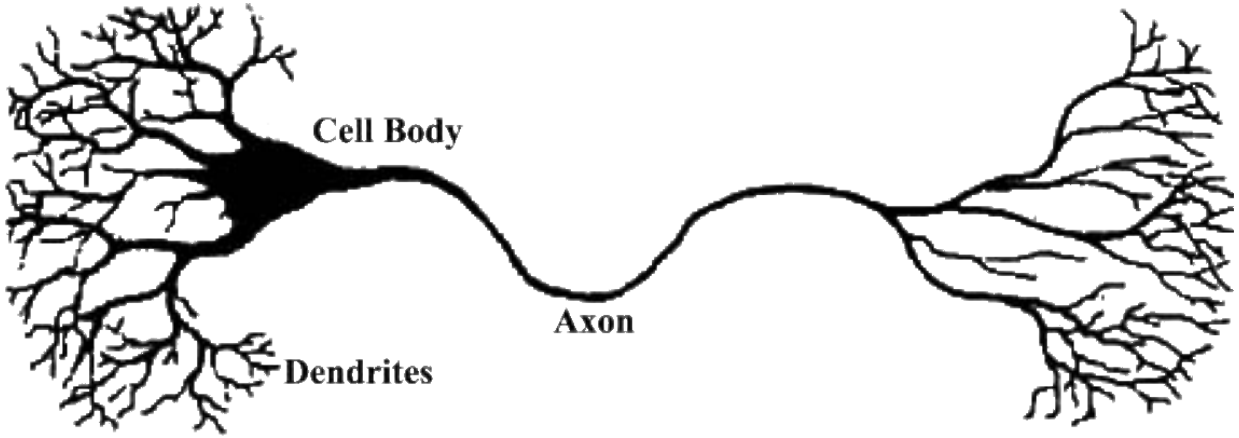
- Anderson, Klahr, Klatzky, Koedinger, Lovett, Siegler

Computational Modeling

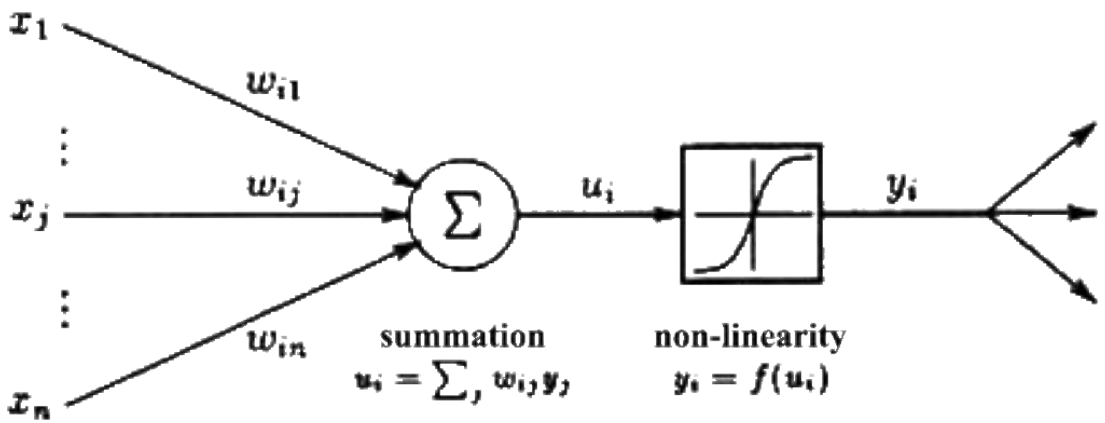
Simulation of psychological and neural mechanisms of cognitive behavior

- Anderson, Kemp, Plaut, Reder

Computational modeling with artificial neural networks

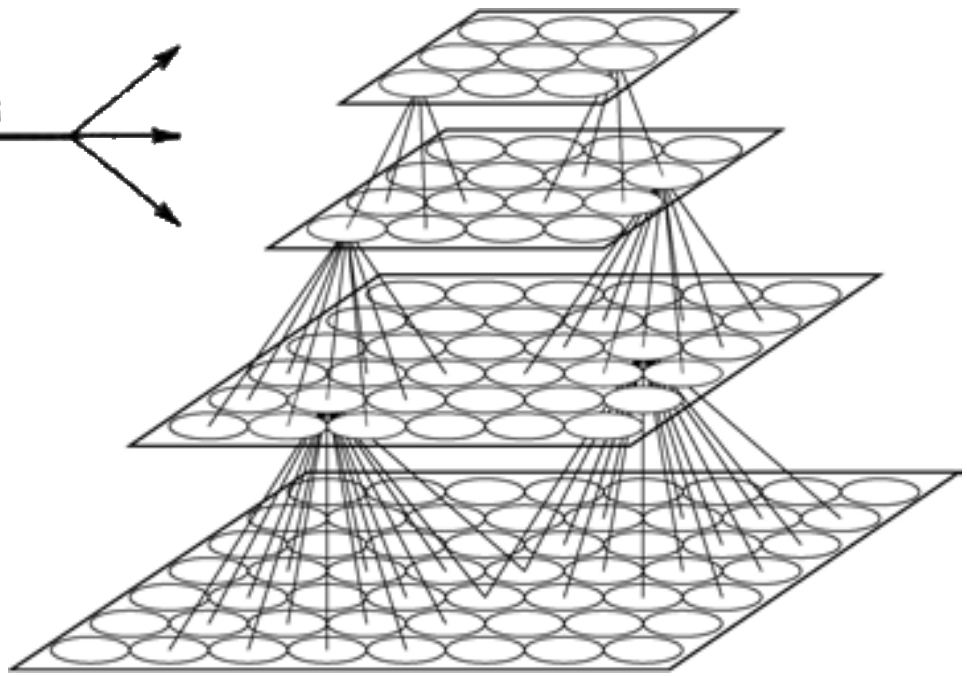


(a)



(b)

Large networks of interacting neuron-like processing elements

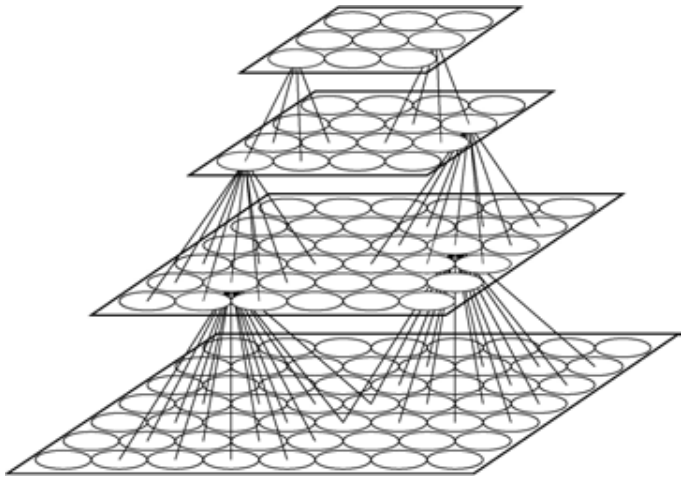


- **Processing:** massively parallel constraint satisfaction
- **Learning:** Adjust connections based on performance feedback

Computational principles as "design" constraints: Cooperation and competition among neural representations

Representations are hierarchically organized

The representation of information at each level, as a pattern of neural activity, **cooperates** with (i.e., mutually activates and reinforces) the representations of consistent information at lower and higher levels.



Cooperation depends on available connectivity

Connectivity is strongly constrained to minimize axon length (total volume); cooperating representations **need to be close** to each other.

Inconsistent representations compete

Representations of inconsistent information **compete** with each other to become active, and to become stronger through learning.

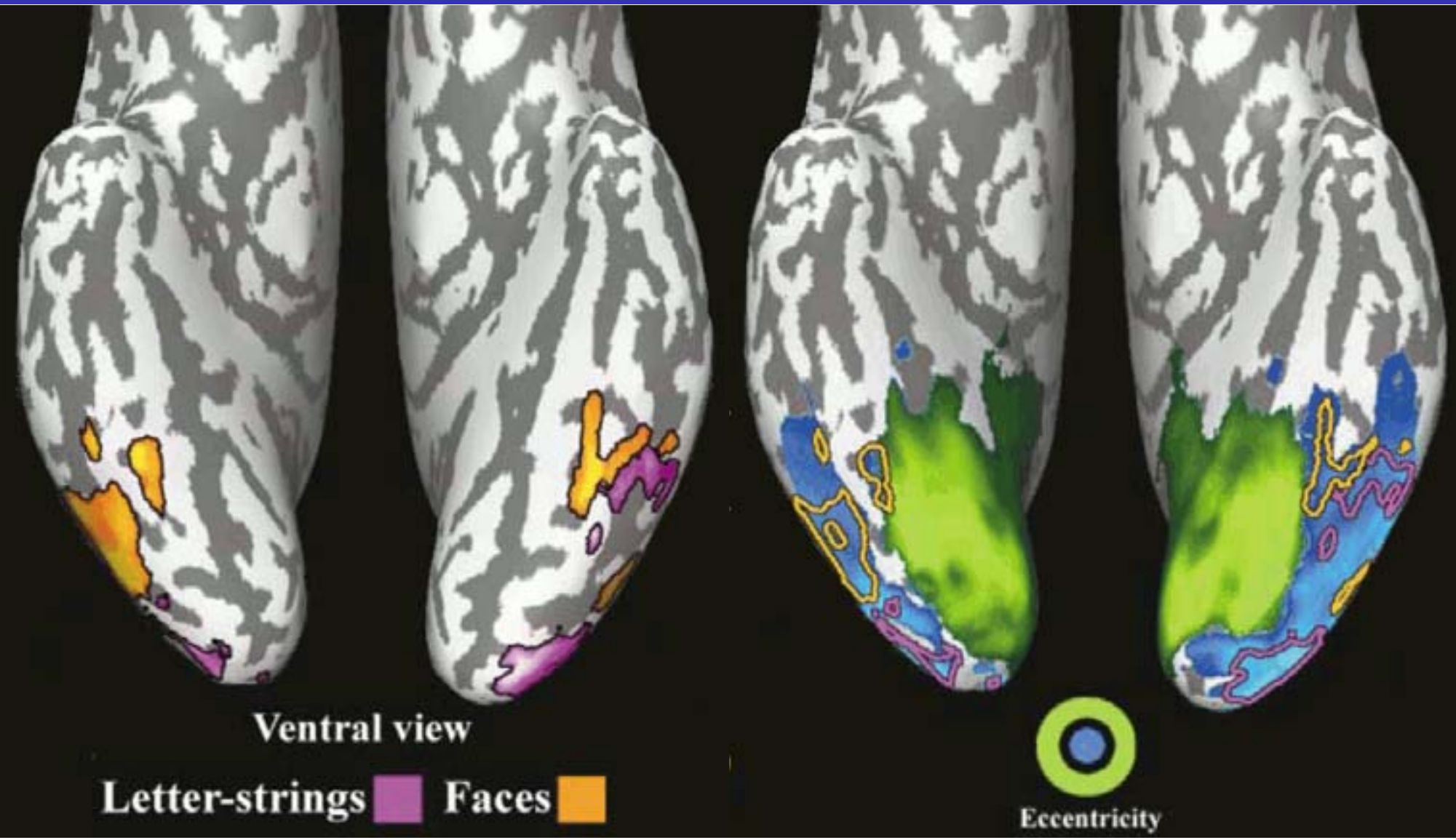
Example: Interdependence of face and word processing

- As visual objects, faces and words are unrelated
- However, both face and word recognition place extensive demands on **high-acuity visual information** from central vision.

- Due to spatial constraints on the neural organization of visual information, central visual information is **in a particular place** in each hemisphere of the brain.
- Both face and word representations need to be near central visual information to cooperate with it, but they compete with each other.
- As a result, words are stronger in the left-hemisphere (to cooperate with language) and faces are stronger in the right-hemisphere, but they are **mixed in both hemispheres** and therefore influence each other.

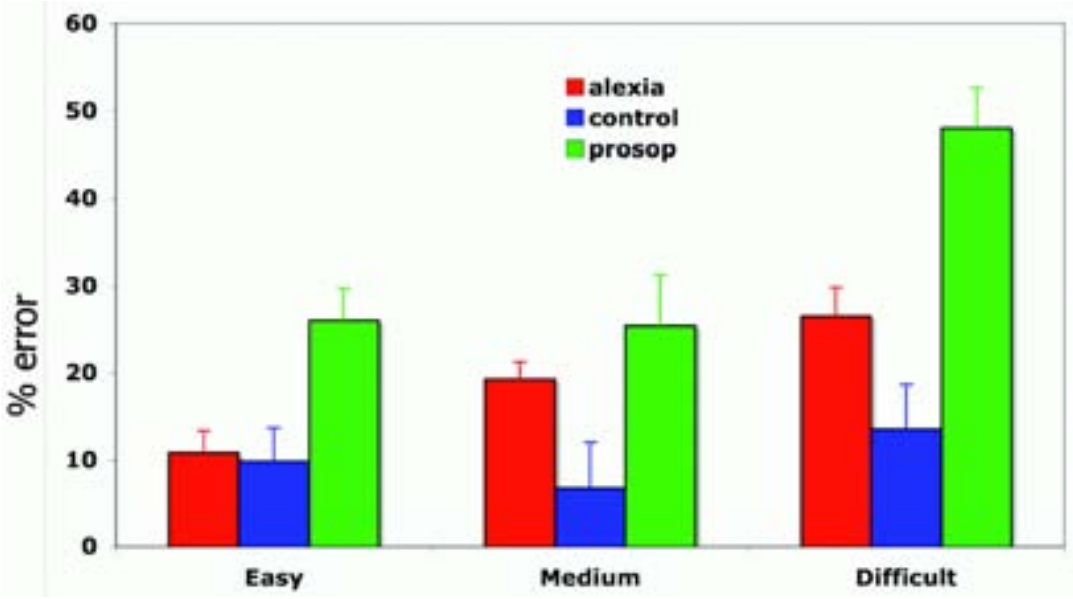
Plaut & Behrmann (2011, *Cog. Neuropsych.*)

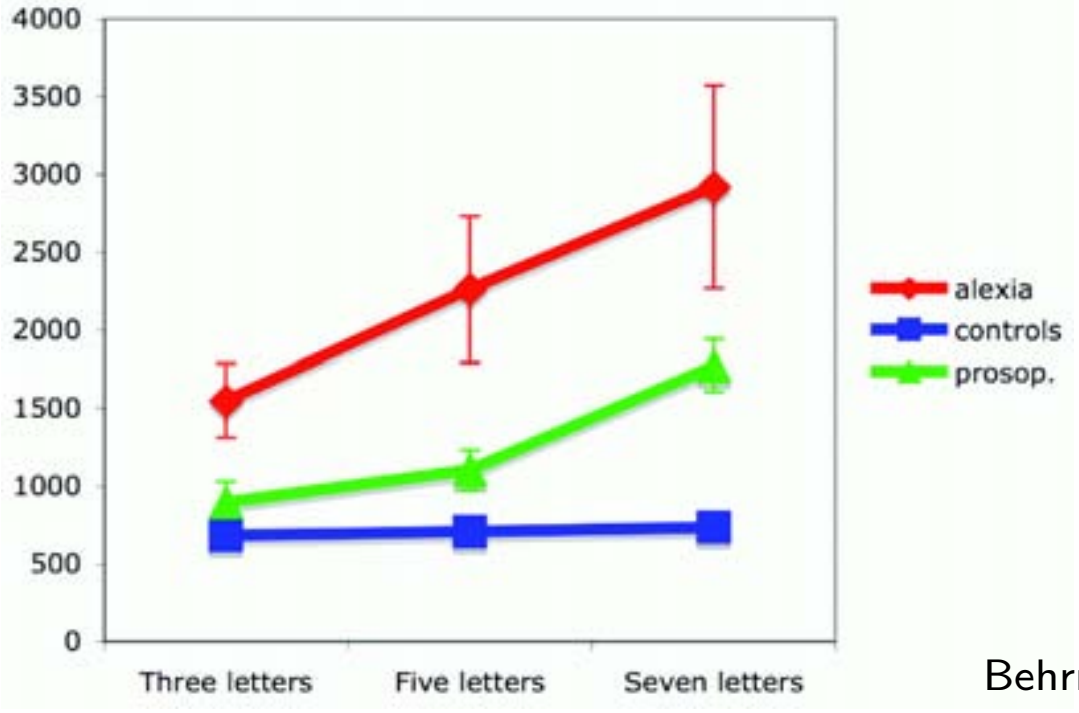
Face and word representations are near central visual information



Hasson, Levy, Behrmann, Hendler & Malach (2002, *Neuron*)

Unilateral brain damage affects both faces and words





Face processing

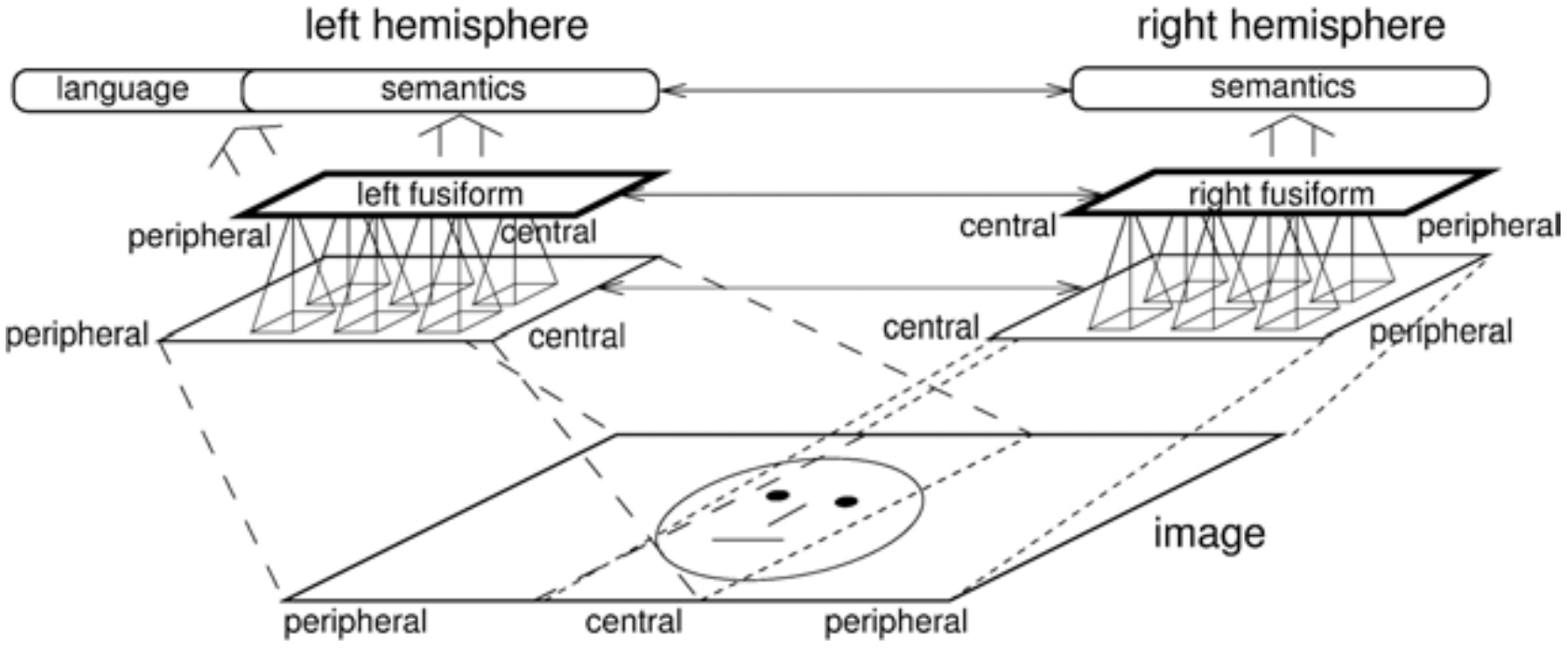
- Patients with prosopagnosia are severly impaired
- Patients with alexia (severe impairment on words) are also mildly impaired on faces

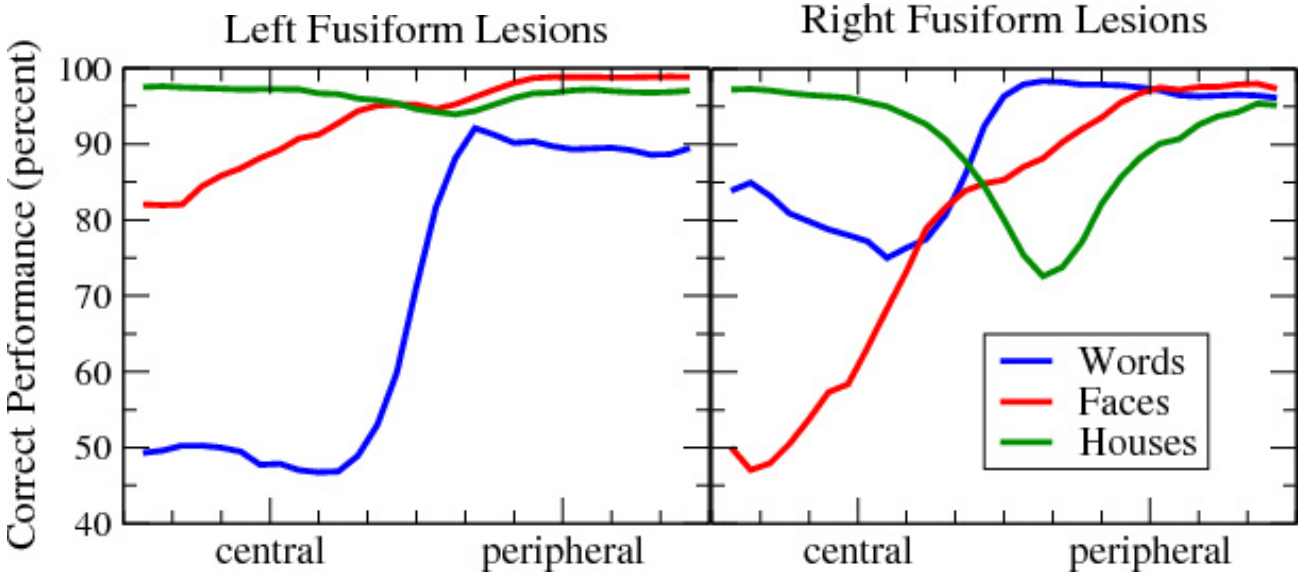
Word processing

- Patients with alexia are severly impaired
- Patients with prosopagnosia are also mildly impaired on words

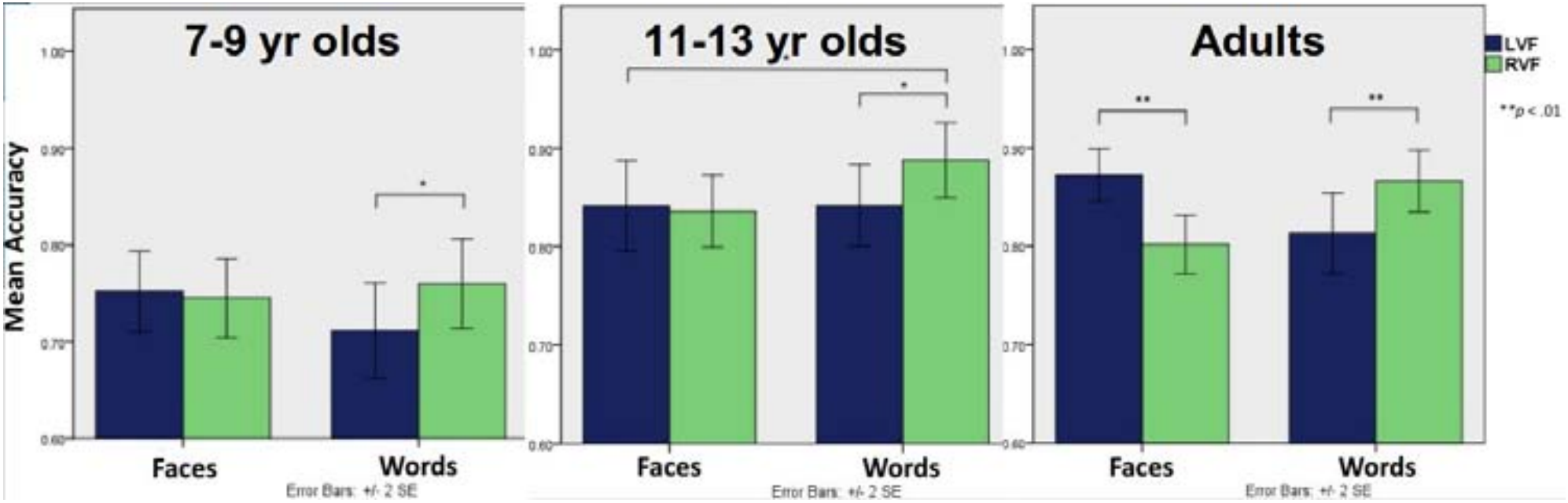
Behrmann & Plaut (2012, *Cereb. Cortex*)

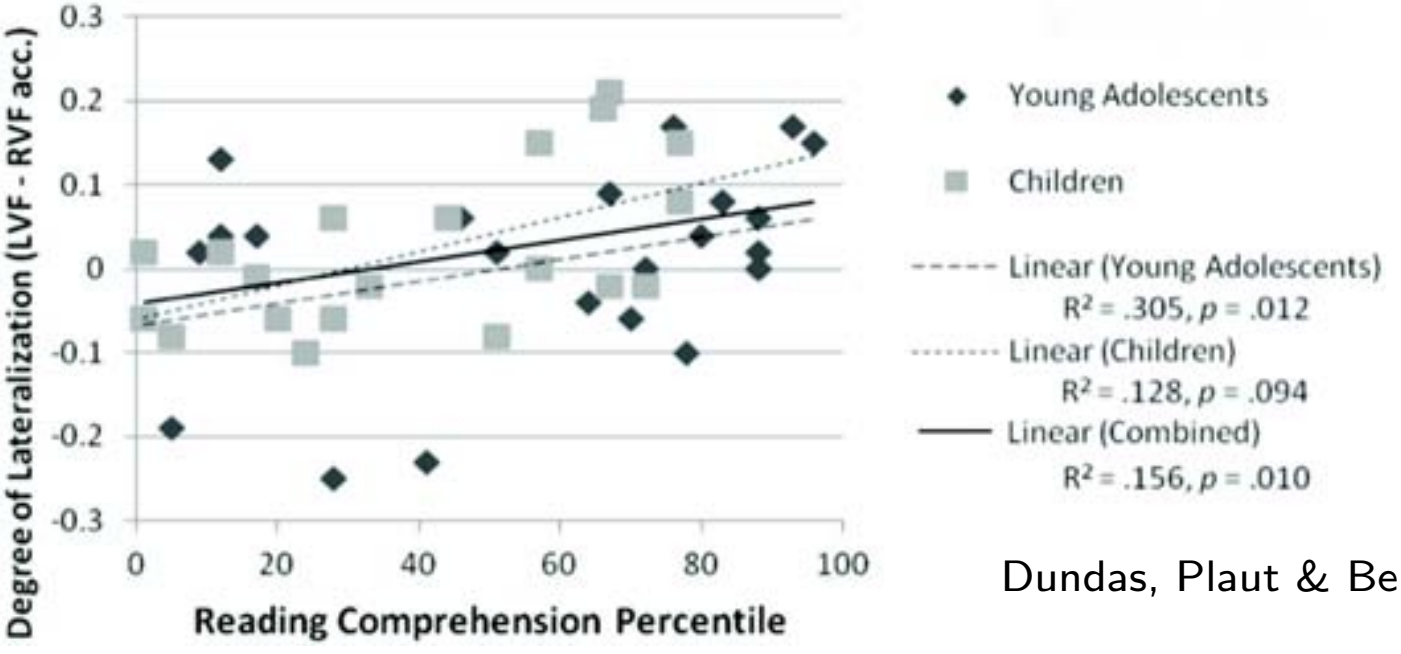
Simulation of effects of damage on faces and words





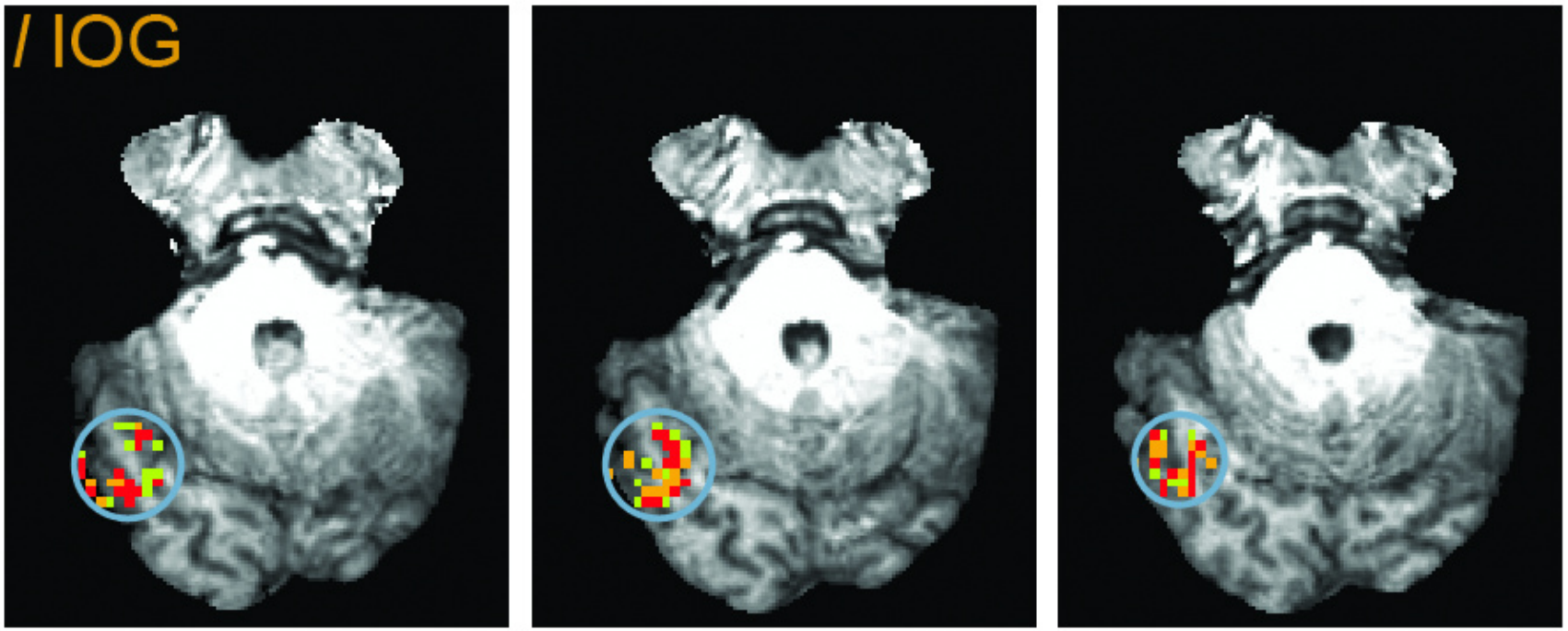
Development of word lateralization drives face lateralization

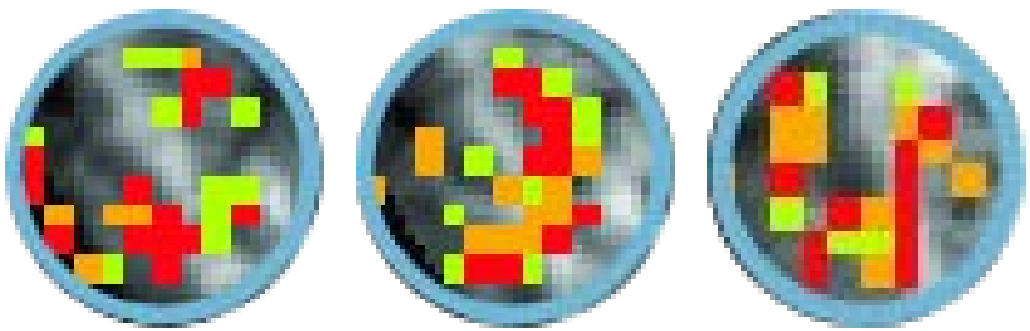


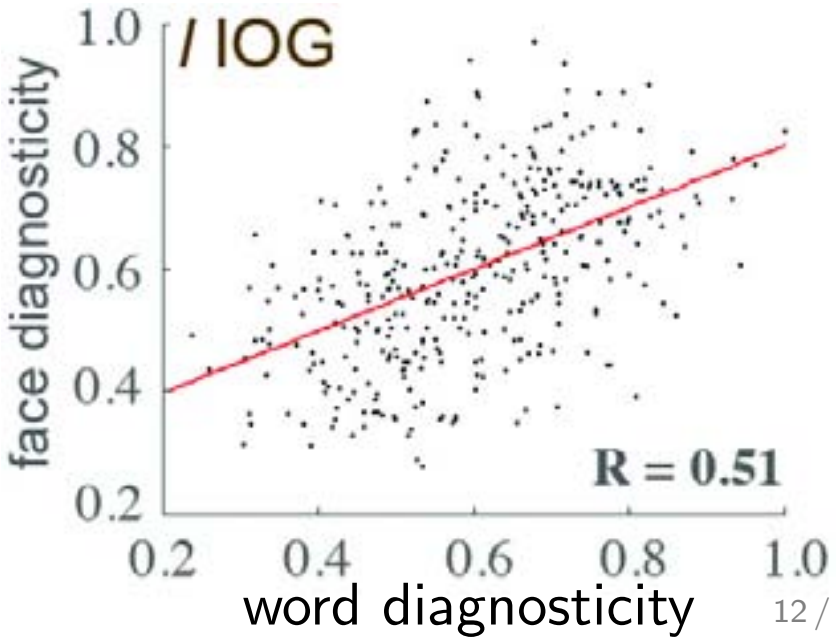


Dundas, Plaut & Behrmann (2012, *JEP:Gen.*)

Same brain areas differentiate both faces and words







Nestor, Behrmann & Plaut (2011, *PNAS*)
Nestor, Plaut & Behrmann (2012, *Cereb. Cortex.*)

Summary and conclusions

- Cognitive processing (and the corresponding brain organization) can be understood as the consequences of a **design process** of achieving certain functionality subject to structural constraints.
- The interaction of functional and structural constraints can give rise to unexpected consequences—such as the interdependence of face and word processing in the brain.
- Computational modeling can play a crucial role in exploring the implications of hypothesized constraints for the resulting structure and function of the system.