

Going beyond the cognitivist framing in understanding bodily foundations of mathematical cognition

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March 21, 2024

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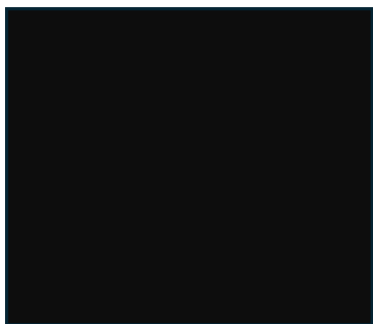
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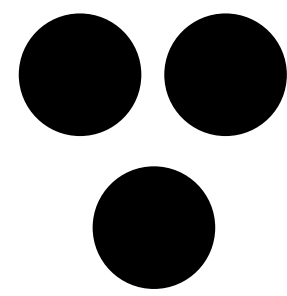
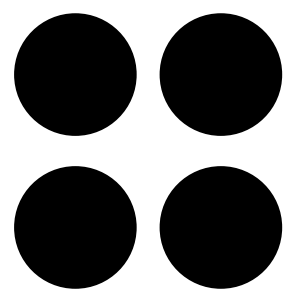
What does it mean for mathematical
cognition to be embodied?

How should we change the way we study
numerical cognition based on what we know about
embodiment?

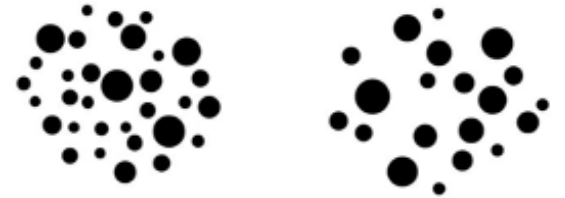
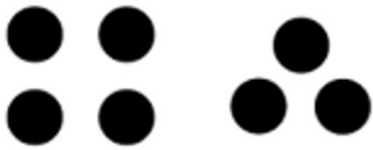
Numerical Cognition

- Sociocultural, developmental, cognitive, and biological aspects of mathematical abilities
- Case studies with patients (Henschen, 1919)
- Mathematical insights, learning/teaching, introspection (Hadamard, 1945; Thorndike, 1922)
- Cognitive revolution; Computational Theory of Mind (CTM) (McCulloch, 1961; Newell & Simon, 1976; Marr, 1982)
- Emergence of cognitive neuroscience
- Embodied and situated cognition, ecological psychology (Gibson , 1979; Varela, Thompson, & Rosch, 1991)
- Brain as a dynamic and complex system; network science (Buzsáki, 2010; Sporns, 2011)









(Geary, Berch, & Koepke, 2014)



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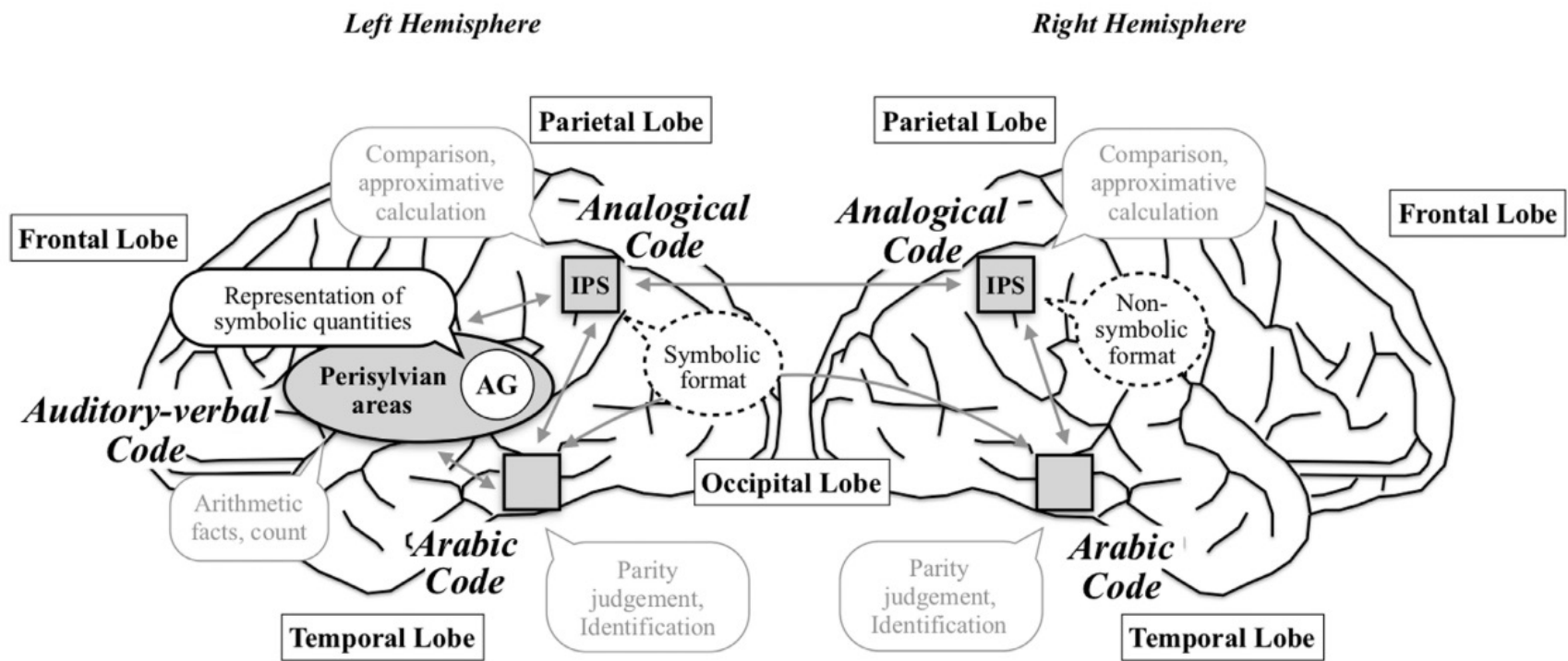
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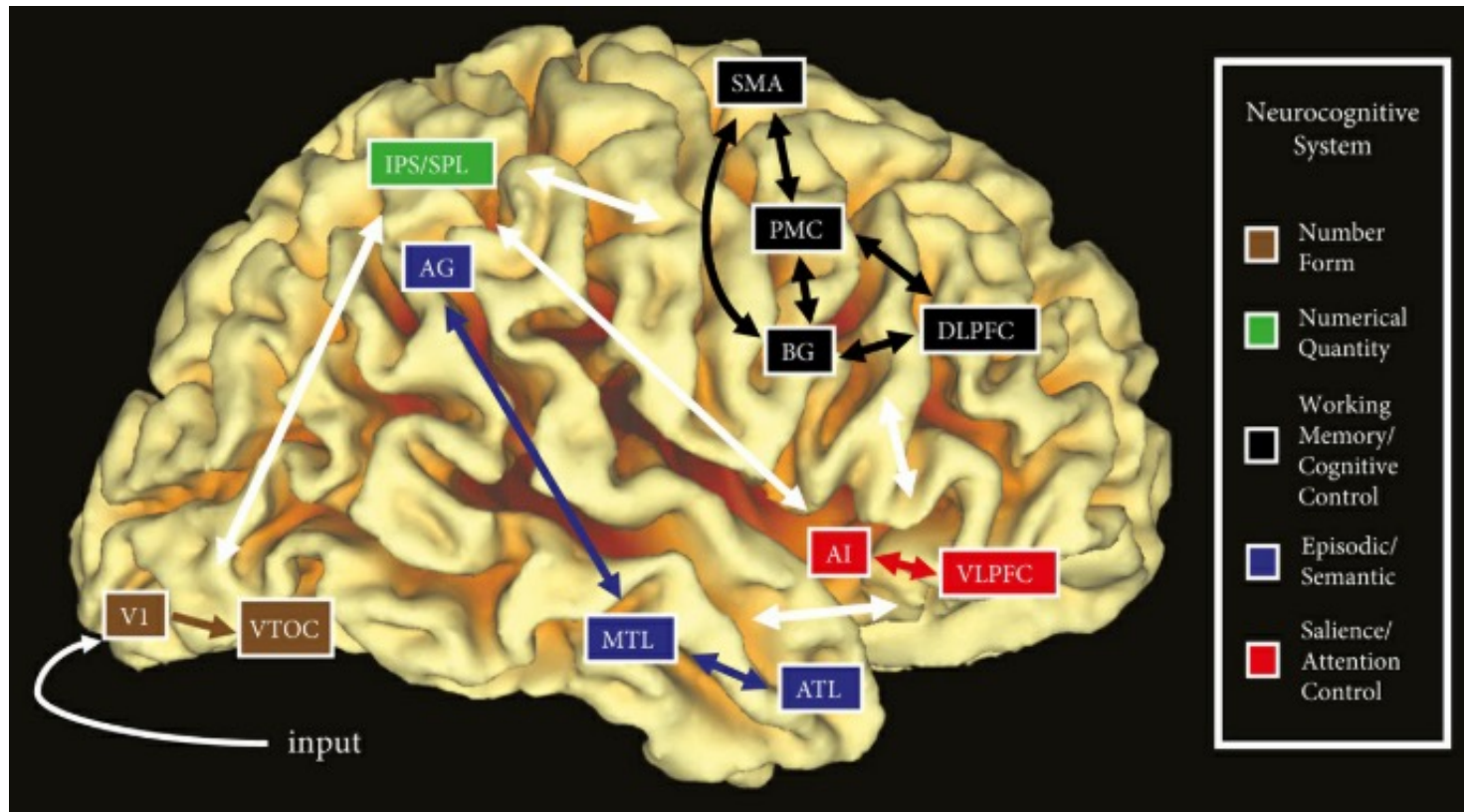
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Faye, A., Jacquin-Courtois, S., Reynaud, E., Lesourd, M., Besnard, J., & Osiurak, F. (2019). Numerical cognition: A meta-analysis of neuroimaging, transcranial magnetic stimulation and brain-damaged patients studies. *NeuroImage: Clinical*



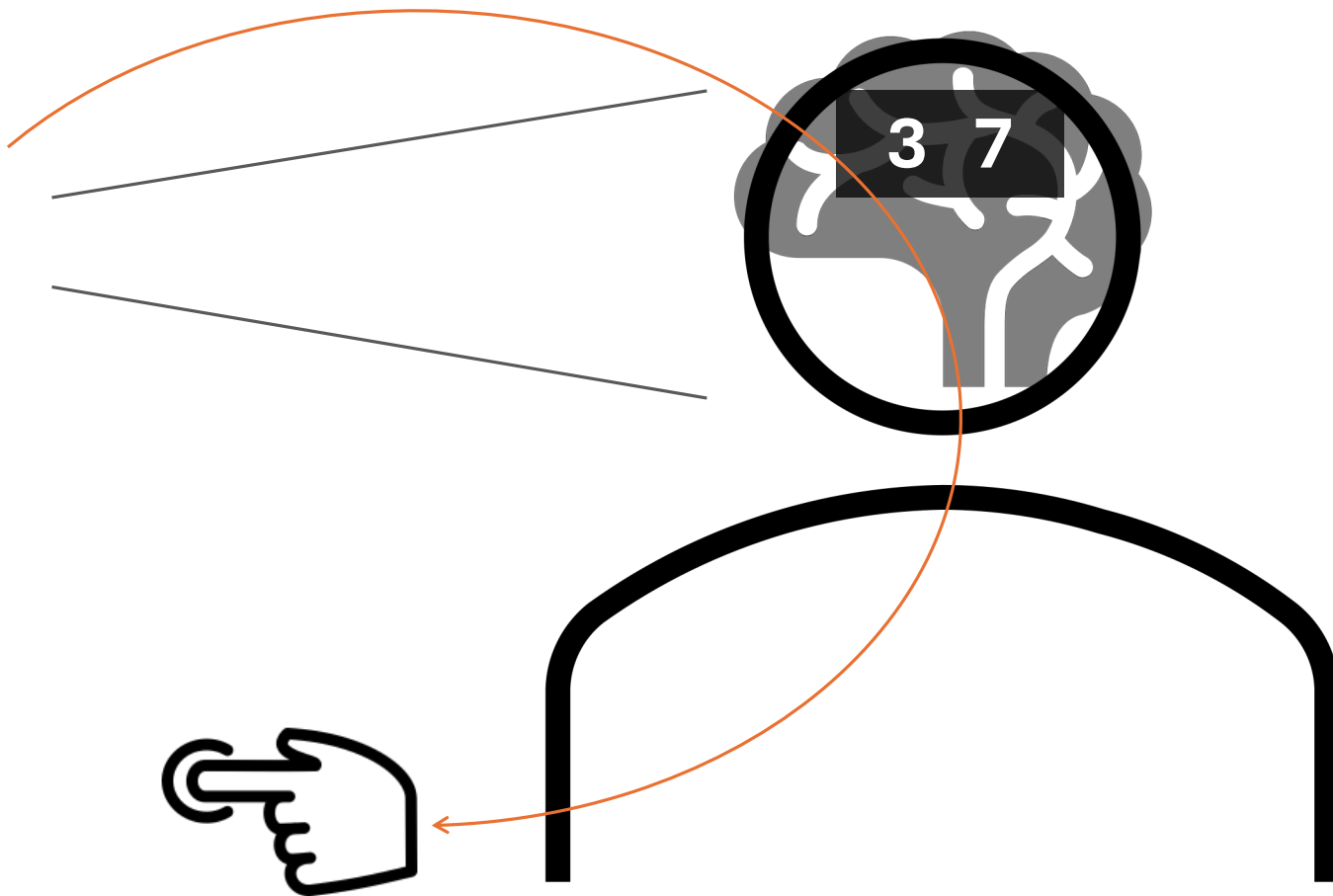
Number form
 Numerical quantity
 Working memory
 Cognitive control
 Episodic/semantic
 Salience/attention
 control

Schematic circuit diagram of basic neurocognitive processes involved in arithmetic.

Menon, V. (2014). Arithmetic in the Child and Adult Brain. In R. Cohen Kadosh & A. Dowker (Eds.), *The Oxford Handbook of Mathematical Cognition (Vol. 1)*. Oxford University Press.

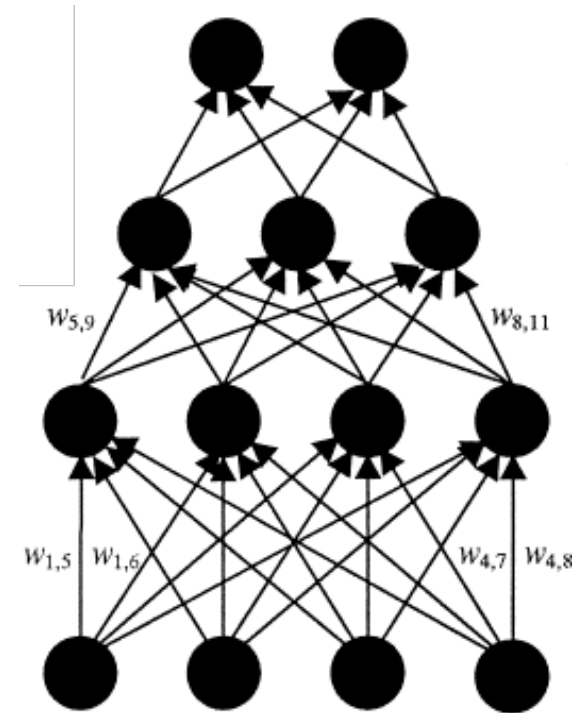
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An interconnected set of logical units can realize different numerical operations

McCulloch (1961). What is a number, that a man may know it, and a man, that he may know a number.



Brain as a physical symbol system

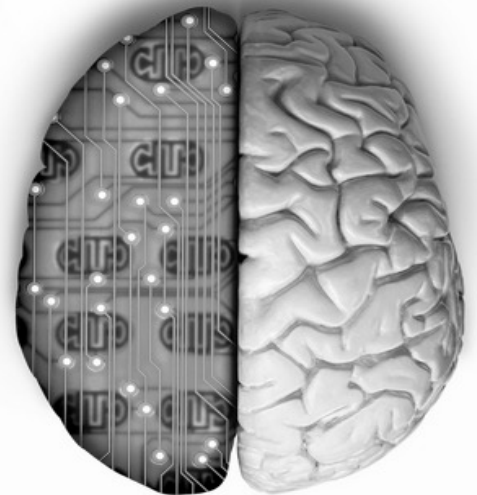
"A physical symbol system has the necessary and sufficient means for general intelligent action."

(Newell & Simon, 1976)

Computational Theory of Mind (CTM)

Functional modules in the brain

(Neumann, 1958)





Fingers and numbers

Finger tapping (Soylu & Newman, 2016)

Finger gnosis (Soylu et al., 2018, 2019)

Finger counting habits (Newman & Soyulu, 2014)

Finger numeral configurations (Soylu et al., 2019;
Salehzadeh et al. 2023ab)

Finger math review (Soylu et al., 2018)



What are the biological systems that support mathematical skills?

How did our number skills evolve?

How do number skills relate to other abilities?

How can we apply our understanding of EC in experimental research?

A set of cognitive processes and their interrelationships (Hastings et al., 2014)



How do we define the processes in our new ontology?

Cognitive skills like reading and mathematics are products of both **biological and cultural evolution** (Geary, 2007; O'Shaughnessy et al., 2021)

Bodily interactions structure the **sensorimotor system** to provide semantic content for number processing (Abrahamson, 2021; Lindemann & Fischer, 2015)

It is the **networks** that carry out cognitive functions and not individual regions (Pessoa, 2022; Najafi et al., 2016)

Neural Reuse

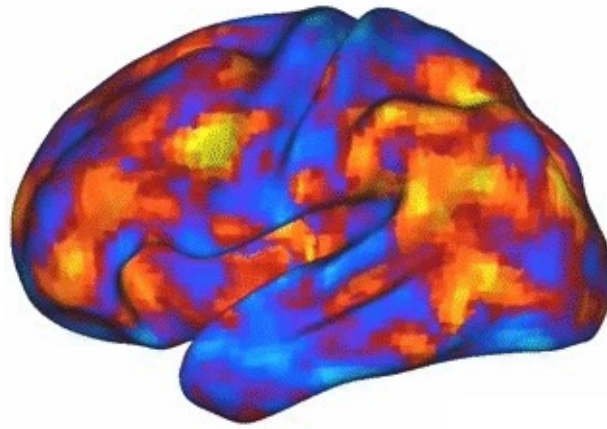


Anderson, M. L. (2014). *After Phrenology: Neural Reuse and the Interactive Brain*. MIT Press.
Gould, S. J., & Vrba, E. S. (1982). Exaptation—A Missing Term in the Science of Form. *Paleobiology*

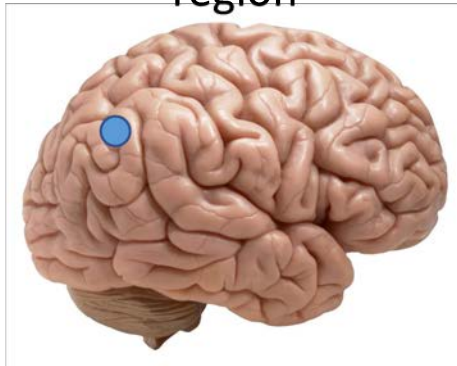
Dynamic brain-body-environment assemblies (Beer, 2008)



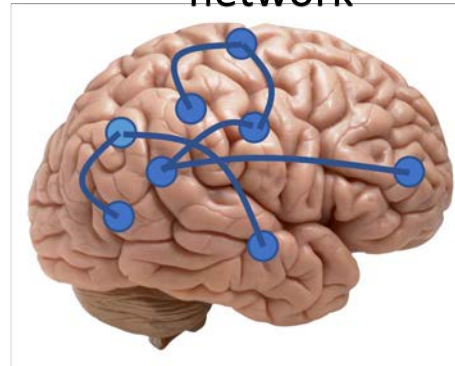
Photo by Angelo Cordeschi



region



network



Case1: *Magnitude Processing*

- the ability to estimate, represent, and process magnitudes across multiple modalities (mainly visual, but also auditory, olfactory, etc.)
- precursor for numerical magnitude representation (Cohen Kadosh et al., 2008; Dormal et al., 2012; Moyer & Landauer, 1967)



An Action-Specific Account of Perception

Humans perceive the
environment based on their
ability to act in it
(Gibson, 1979)

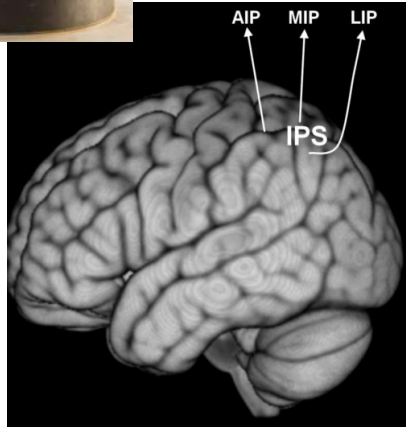
Magnitude Processing

- objects positioned to be easier to grasp are estimated to be closer (Linkenauger et al., 2009),
- graspable object sizes are judged relative to the hand size (Linkenauger et al., 2013), and
- object sizes are perceived relative to the body size (van der Hoort et al., 2011).

Other effects with slope, volume, weight, time, distance, and other factors (Philbeck & Witt, 2015 for a review)



(Andres et al., 2008; Badets et al. 2007)



Is IPS a magnitude processing module?

Integration of multimodal information for proprioception and object-oriented actions (Grefkes & Fink, 2005)

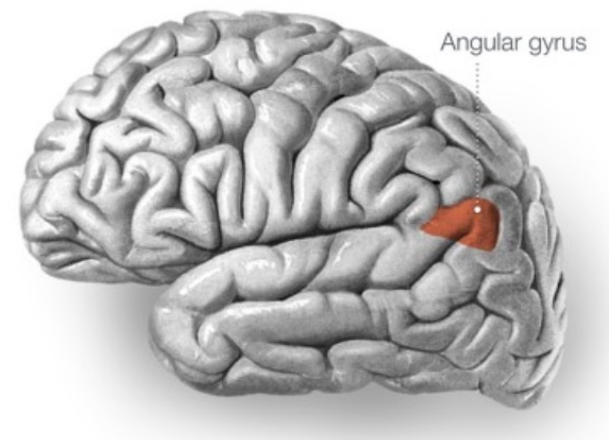
AIP encoding graspable features of objects, PIP experiential knowledge of action (Mruczek et al., 2013; Tunik et al., 2008)

IPS as one of the most functionally flexible regions in the cortex (Yeo et al., 2015)

A region integrating visual, tactile, and motor modalities in the service of many different perceptuomotor and cognitive functions (Uddin et al., 2010)

Case2: *Verbal Coding of Numbers*

- Fact retrieval vs. calculation activates AG (Dehaene et al., 2003; Delazer et al., 2003; Grabner et al., 2009)
 - AG is part of the perisylvian language network
- => AG is responsible for verbal coding of numbers



Is AG a *verbal area*?

- Many different functions: semantic processing, conceptual integration, spatial coordination, memory retrieval, the default mode network, spatial cognition, theory-of-mind ... (Igelström & Graziano, 2017; Seghier, 2012)
- Heteromodal integration: a highly connected, central hub (Binder et al., 2009)
- Integration of multiple modalities for semantic memory and representation (Bonner et al., 2013)
- The “cortical language network” might be bogus (Aliko et al., 2023)
- Language processing is action based (Muraki et al., 2023)

A New Ontology

- Evolutionary approaches in elucidating how the brain facilitate *contextual behaviors* (Cisek, 2022)
- Seeking foundational primitive sensorimotor operations and networks (Anderson, 2014)
- New experimental approaches, with contextualized and authentic tasks
- Use of large-scale data and data analytics approaches

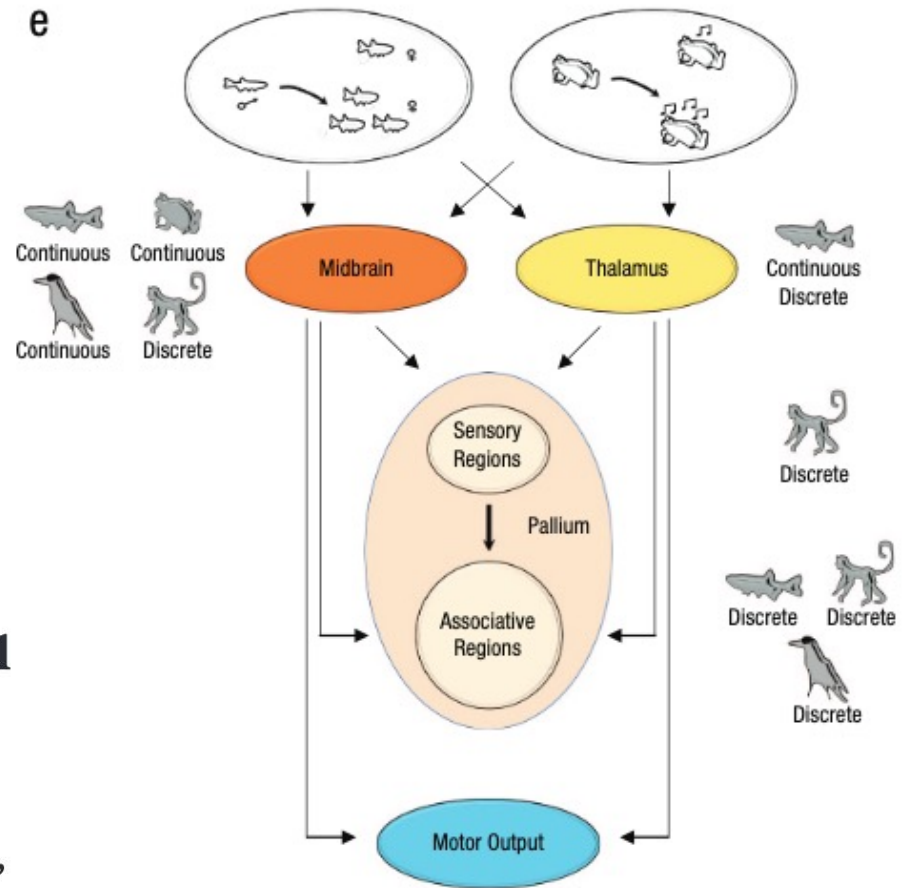
Example:

A sensorimotor model
of magnitude
processing, across
vertebrates

Magnitudes for Nervous Systems: Theoretical Issues and Experimental Evidence

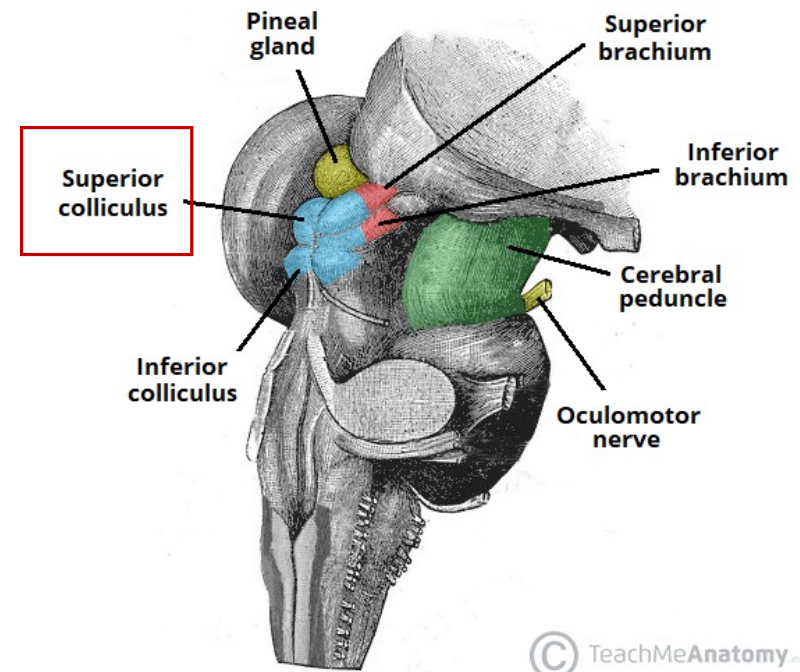
Giorgio Vallortigara , Elena Lorenzi, Andrea Messina,
and Matilde Perrino

Centre for Mind/Brain Science (CIMEC), University of Trento



Vallortigara et al. (2022)

A midbrain (subpallial) role in magnitude representation is suggested by the involvement of the optic tectum (superior colliculus in mammals) in size discrimination (see Fig. 1). The optic tectum, situated toward the back of the midbrain, plays a central role in interfacing sensory stimuli and behavioral motor patterns. In animals ranging from amphibians to pigeons, size selectivity emerges from neurons in the optic tectum that modulate their responses in accordance with the size of the stimulus (small or large; Preuss et al., 2014).



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2020). In humans, the pathway that connects the superior colliculus with more anterior brain regions develops earlier than the pathway that connects the thalamus with the cortex, and 2-day-old human newborns, who have mainly the former pathway in use, are capable of discriminating discrete visual quantities (Izard et al., 2009).

The midbrain seems to be responsive to magnitude even in other sensory modalities. Rose (2018) found that in the torus semicircularis, a midbrain structure involved in sound perception, some neurons are selective to specific calls crucial for female toads' reproductive choice: Interval-counting neurons spike ("fire") when the number of calls reaches a certain threshold.

babbling...looking for sensorimotor primitives...babbling

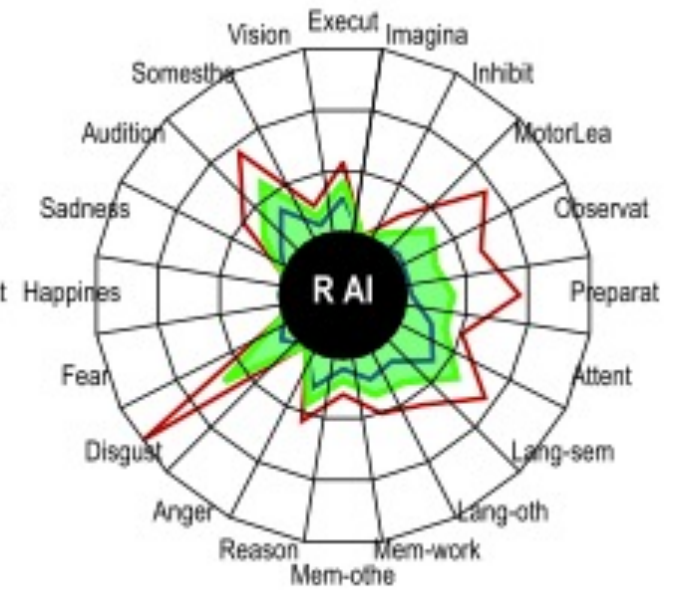
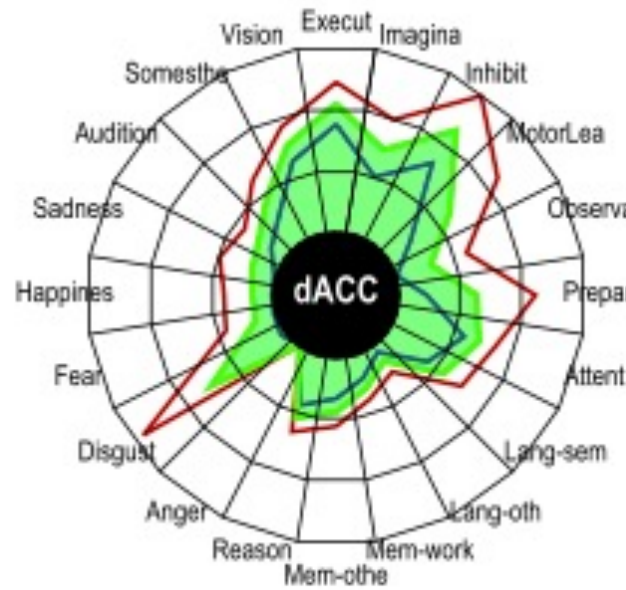
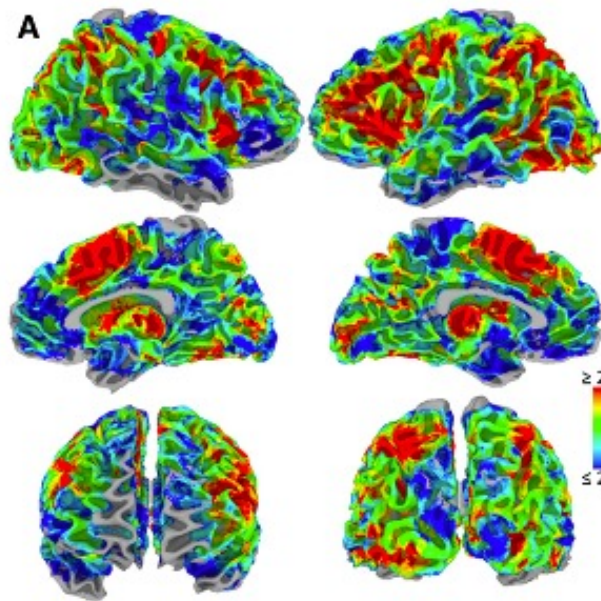
- Are there sensorimotor building-block processes that support different numerical abilities? (Anderson, 2014)
- If so, how can we isolate these processes and understand their function?

Soylu, F. (in review). A New Ontology for Neuroimaging in Numerical Cognition: Integrating Evolutionary, Embodied, and Data Informatics Approaches

Emerging Methods

Data analytics methods (e.g., machine learning) allowing capture of deeper patterns in neuroscience data (Salehzadeh et al., 2023a, 2023b)

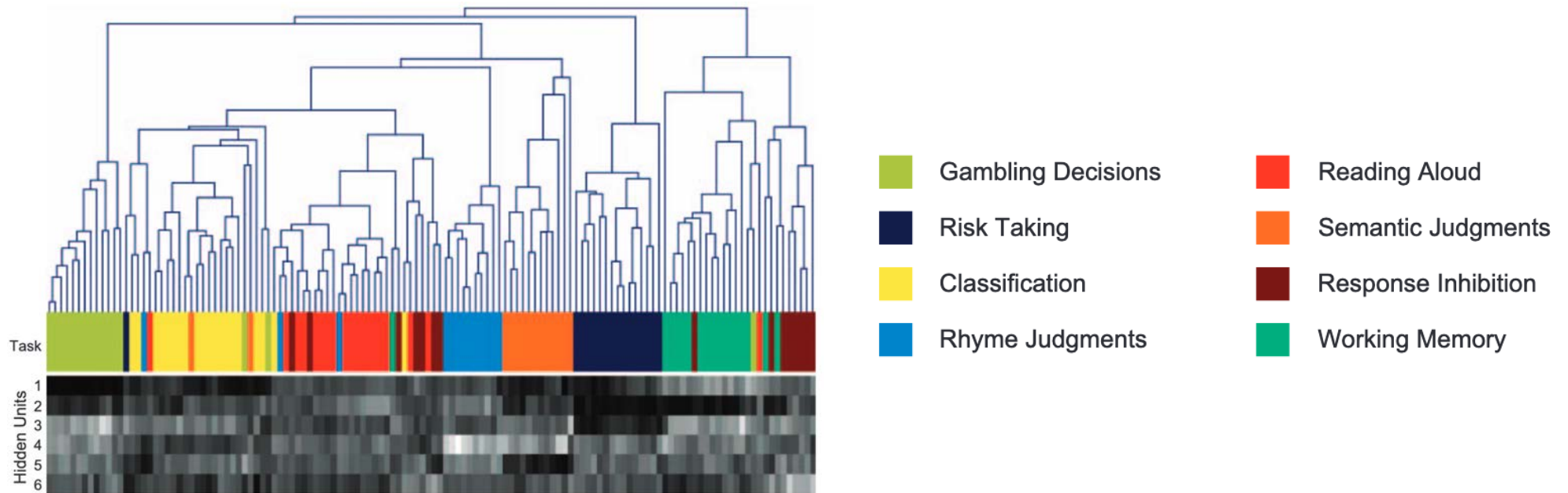
Embodied & evolutionary approaches guiding analysis and interpretation of data



Functional Diversity

Anderson, M. L., Kinnison, J., & Pessoa, L. (2013).
Describing functional diversity of brain regions and brain
networks. *NeuroImage*

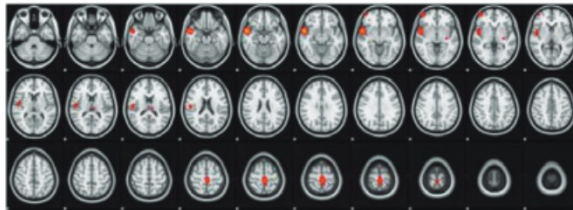
Machine Learning Methods



Poldrack, R. A., Halchenko, Y. O., & Hanson, S. J. (2009). Decoding the Large-Scale Structure of Brain Function by Classifying Mental States Across Individuals. *Psychological Science*

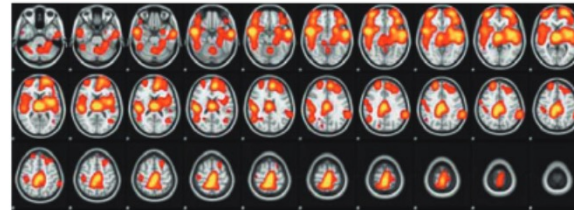
Dimension 1

audition
language
positiveemotion
semantics
workingmemory
phonology
responseinhibition
speech



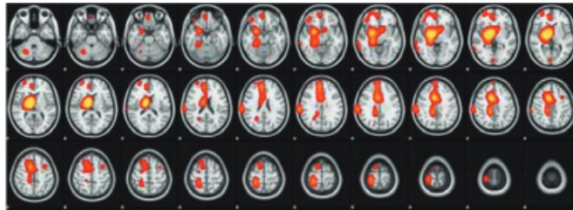
Dimension 2

language
orthography
phonology
responseinhibition
semantics
speech
actionexecution
audition
decisionmaking
emotion
implicitmemory
memory
numericalprocessing
reasoning
reward
spatialprocessing
vision
workingmemory



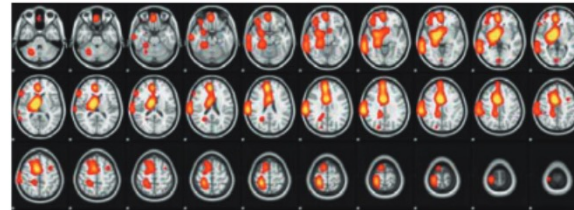
Dimension 3

decisionmaking
memory
actionexecution
audition
calibration
emotion
implicitmemory
language
numericalprocessing
orthography
phonology
positiveemotion
reasoning
responseinhibition
reward
semantics
spatialprocessing
speech
vision
workingmemory

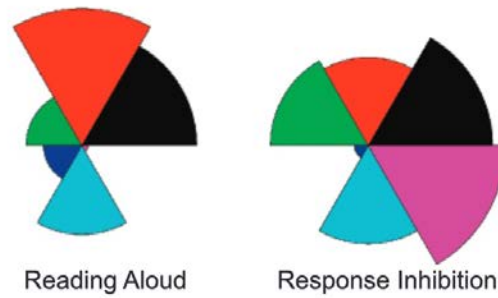


Dimension 4

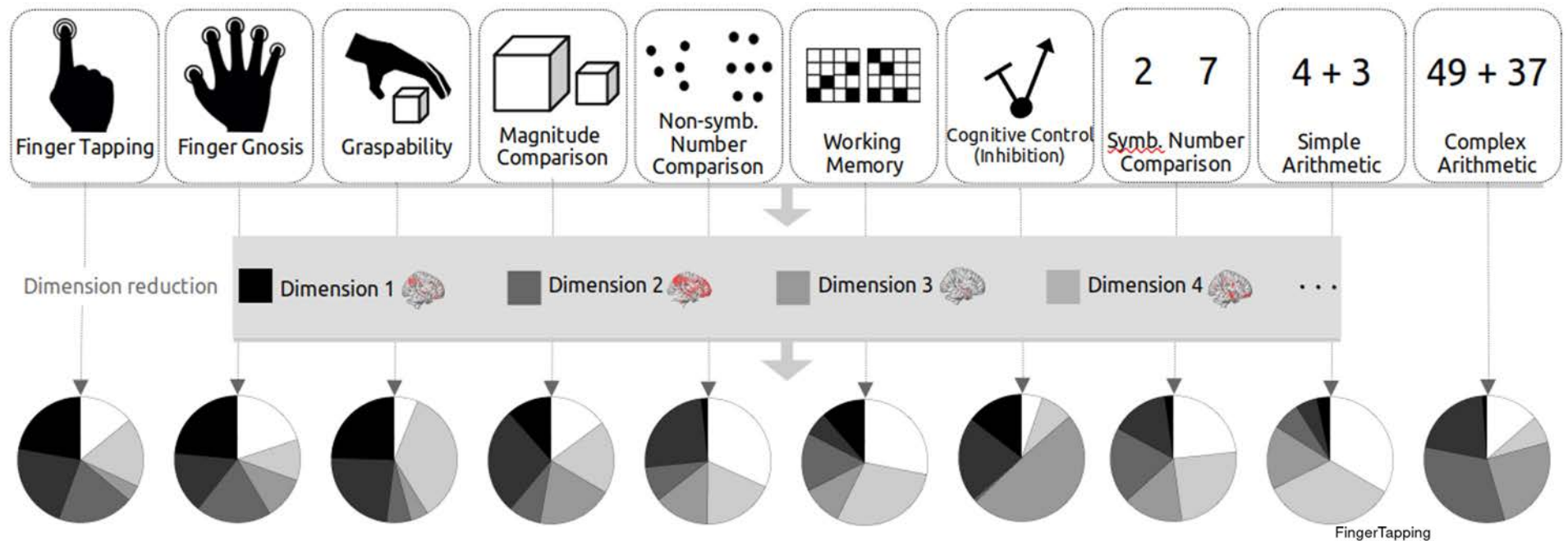
actionexecution
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language
numericalprocessing
workingmemory



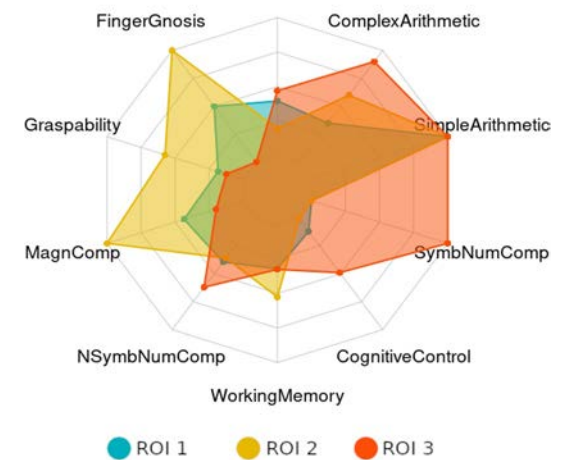
(Poldrack et al., 2009).



(Poldrack et al., 2009).



Uncharted territories



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