

Why the Sensorimotor System Doesn't Just Support but Enables Mathematical Cognition

*IMBES 2026 Symposium: Cognitive Offloading and Mathematical
Thinking During Development*

Sept 4, 2026

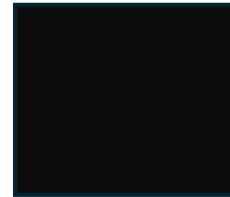
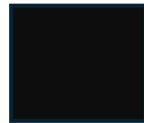
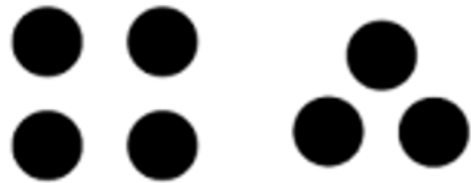
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What does it mean for mathematical cognition
to be embodied?

How does the body and nervous system enable
mathematical skills?



(Geary, Berch, & Koepke, 2014)



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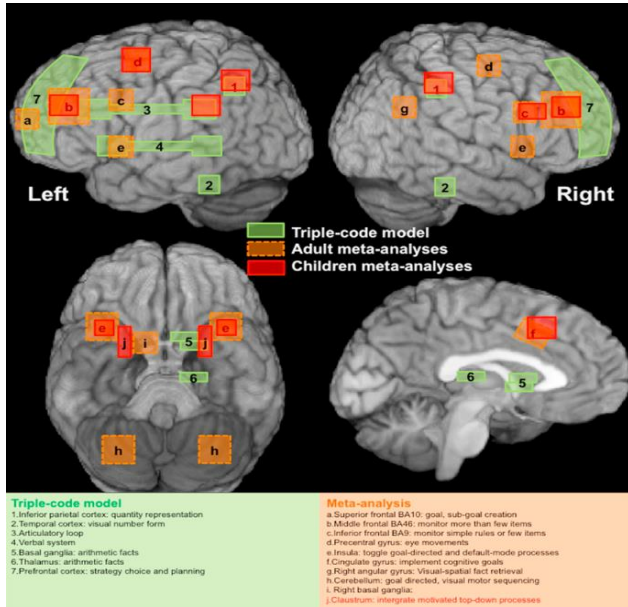
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Models in Numerical Cognition



Quantity representation

Visual number form

Articulatory loop

Verbal system

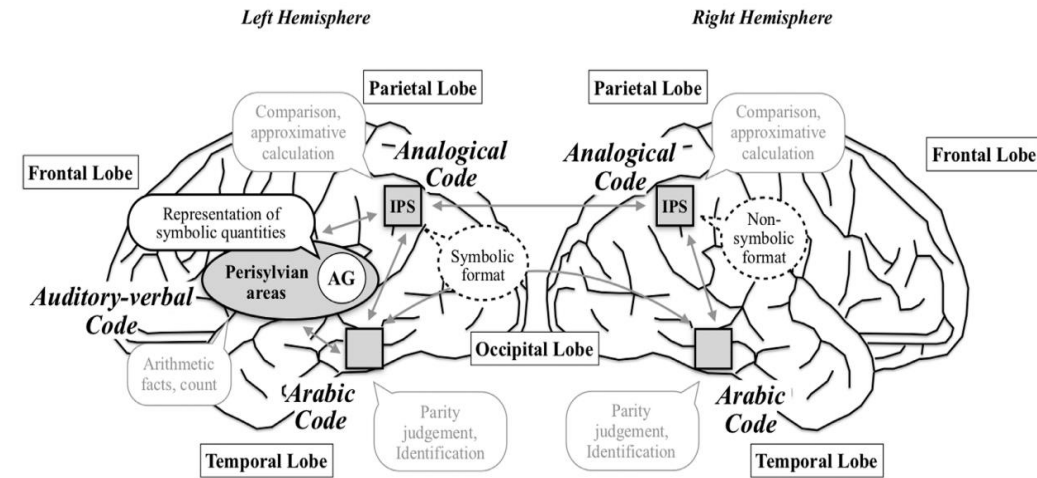
Arithmetic fact retrieval

Strategy choice and planning

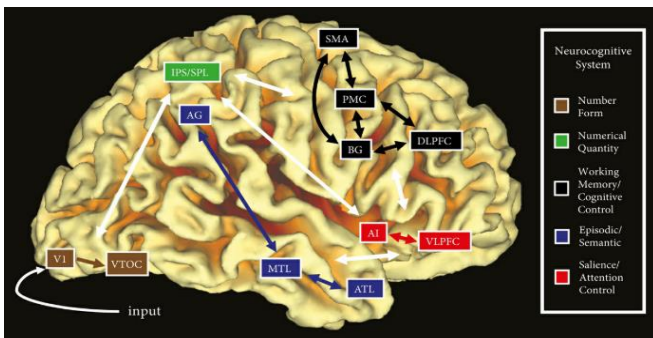
Goal, sub-goal creation

Monitor simple rules or few items

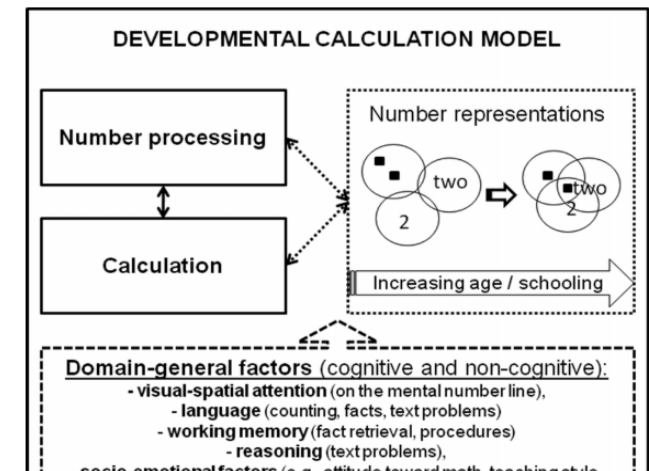
Implement cognitive goals



Faye, et al. (2019). Numerical cognition: A meta-analysis of neuroimaging, transcranial magnetic stimulation and brain-damaged patients studies.



Menon, V. (2014). Arithmetic in the Child and Adult Brain.



Kaufmann, L. (2011). Meta-analyses of developmental fMRI studies investigating typical and atypical trajectories of number processing and calculation

Cognitive Ontology

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



Brain as a physical symbol system

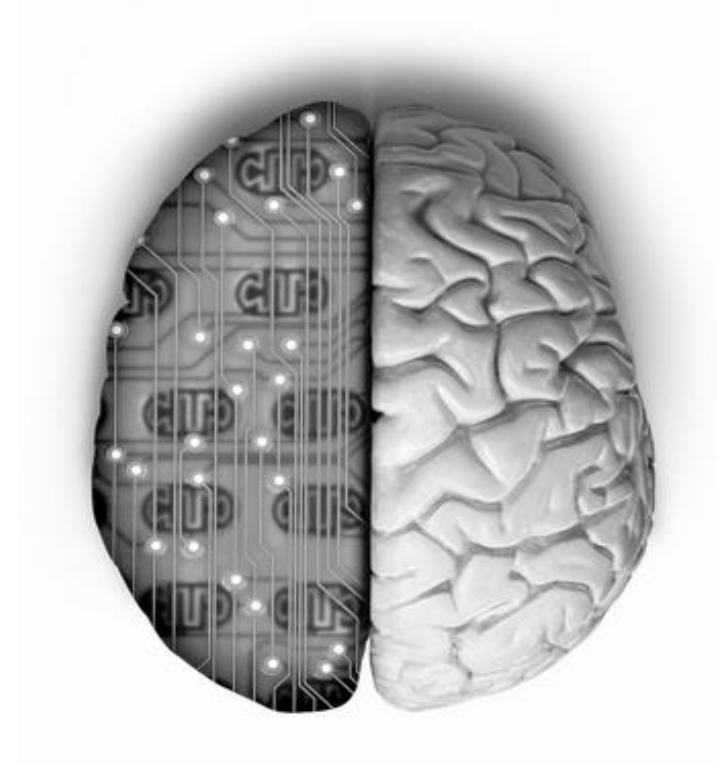
"A physical symbol system has the necessary and sufficient means for general intelligent action."

(Newell & Simon, 1976)

Computational Theory of Mind (CTM)

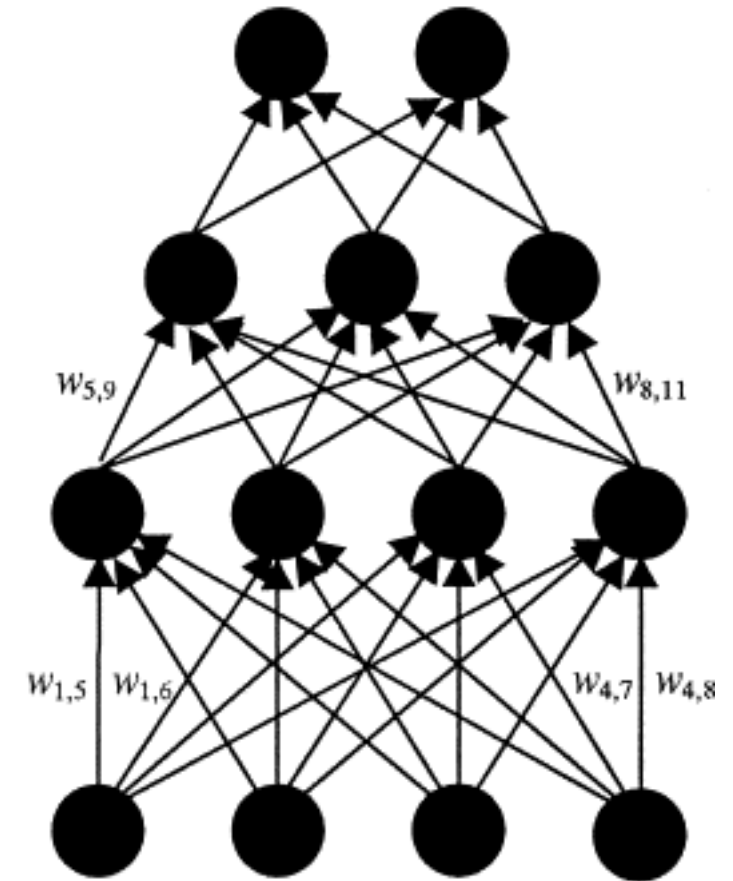
Functional modules in the brain

(Neumann, 1958)



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.





Embodiment of Numerical Cognition

- Mathematical skills enabled by sensorimotor and behavioral control systems
- The special case of hands/fingers & mathematics



How does the sensorimotor system, the body and the body's interactions with the environment enable 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?

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)

Behaviors emerging from the **continuous interaction among the brain, the body, and the environment**, rather than being produced by the brain alone.



Photo by Angelo Cordeschi

Evolution of behavioral control in vertebrates

From reacting to stimuli → representing and selecting actions in context

Cognition as action-oriented control systems and their representations of affordances and future possibilities.

Early Chordates

- Exploit nearby resources
- Explore when resources are poor
- Escape threats

Vertebrates

- Optic tectum maps space
- Approach vs. escape
- Action selection becomes targeted

Mammals

- Neocortex expands
- Basal ganglia select behavioral systems
- Cerebellum supports prediction

Primates

- Fronto-parietal action maps
- Objects represented by what they afford
- Prefrontal cortex supports future options

Cisek, P. (2022). Evolution of behavioural control from chordates to primates. *Philosophical Transactions of the Royal Society B*.

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) ;
general magnitude system (Walsh, 2003)



An Action-Specific Account of Perception

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

Magnitude Processing: Sensorimotor Origins

- 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)



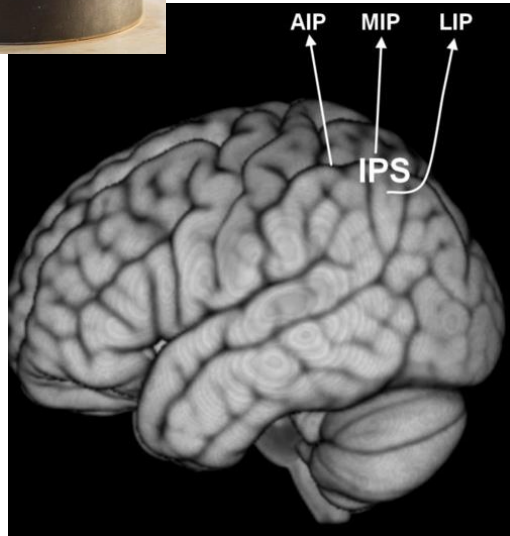
SNARC effect (Dehaene, 1993)

Distance effect (Moyer and Landauer, 1967)

Size-congruity effect (Henik & Tzelgov, 1982)

A shared magnitude system
(Walsh, 2003), grounded in the
sensorimotor system (Kadosh &
Walsh, 2009)

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)

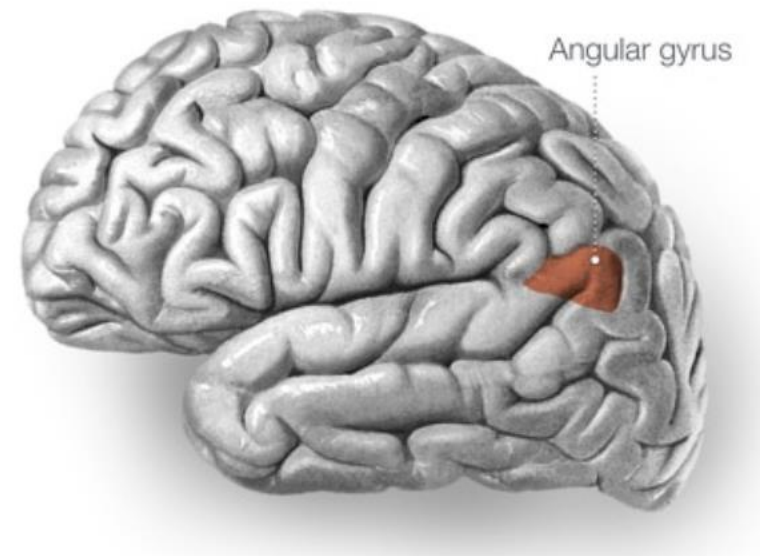
IPS as one of the most functionally flexible regions in the cortex (Yeo et al., 2015)

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

Case 2: *Verbal Encoding 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); for semantic memory and representation (Bonner et al., 2013)
- The “**cortical language network**” might be bogus (Aliko et al., 2023)
- Language processing is multimodal and action based (Muraki et al., 2023)

IPS vs. Angular Gyrus : Two heteromodal integration areas

Intraparietal sulcus (IPS)

Integration for action and affordances

- Visual + somatosensory + motor information
- Where is it? How can I act on it?
- Supports reaching, grasping, and spatial attention
- Strongly linked to action affordances

“What can I do with this?”

Angular gyrus (AG)

Integration for meaning

- Visual + language + memory information
- What does it mean? How does it relate to what I know?
- Supports semantic/conceptual processing

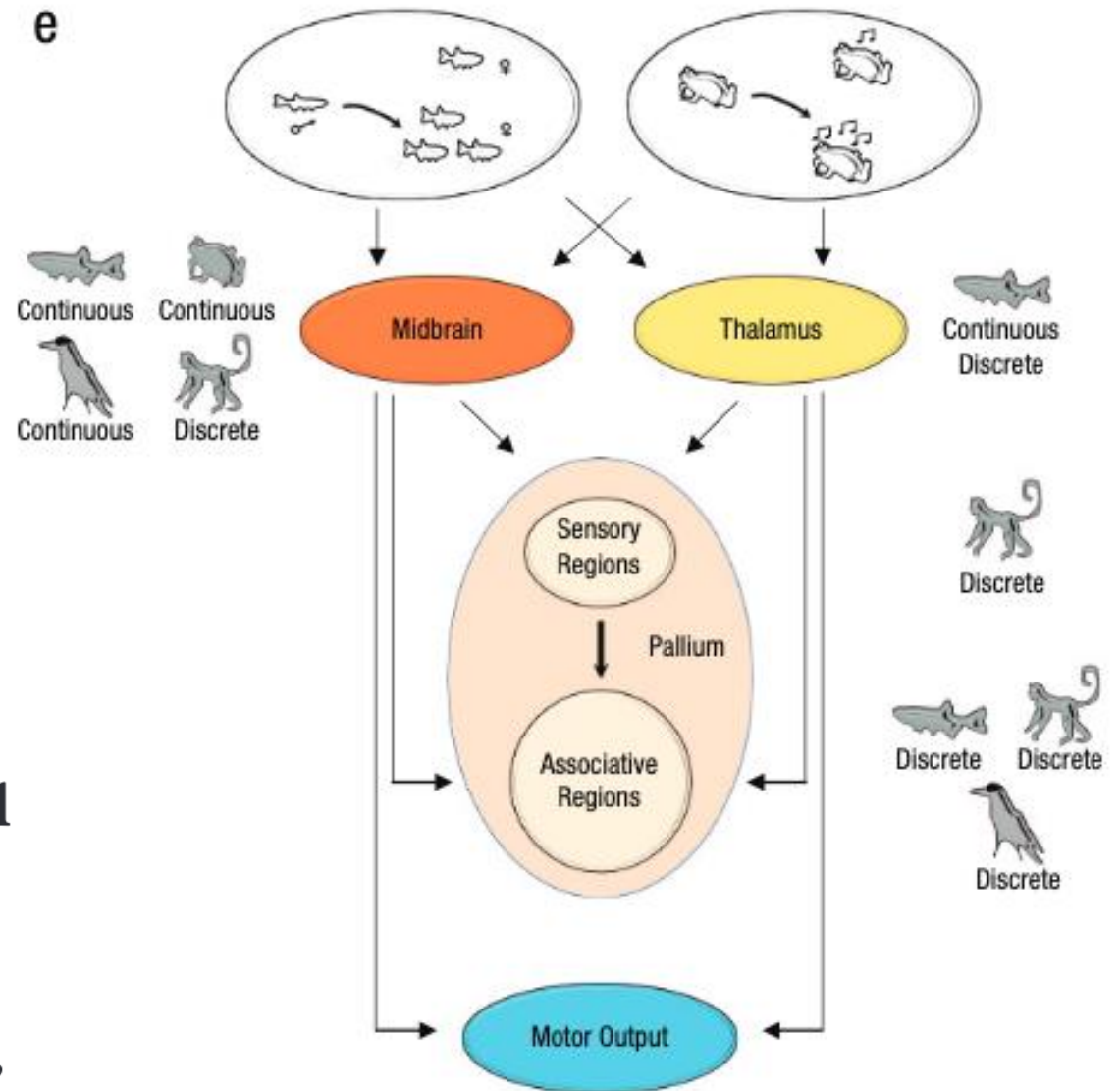
“What does this mean?”

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**

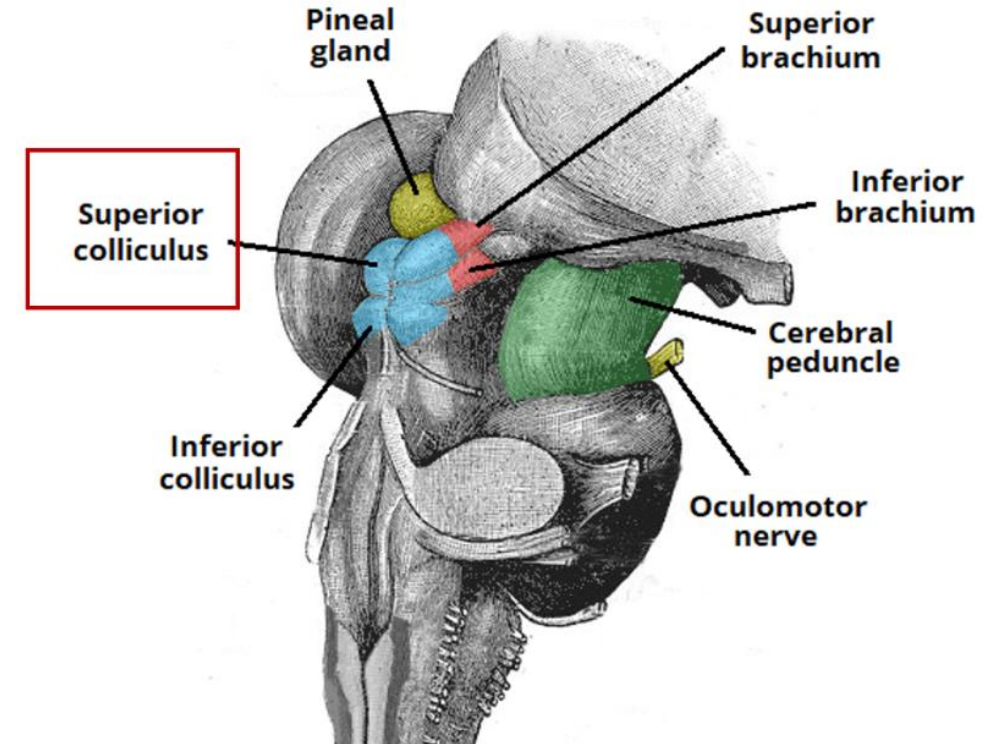
Centre for Mind/Brain Science (CIMEC), University of Trento



Superior Colliculus: An Early System for Representing Magnitude

Magnitude-sensitive midbrain systems are evolutionarily ancient and can guide behavior before cortical pathways are fully developed.

- Midbrain neurons can represent stimulus magnitude—such as visual size—and use it to guide behavior.
- The superior colliculus connects with more anterior brain regions earlier in development than the thalamus–cortex pathway.
- This early pathway is already functional in newborns: 2-day-old infants can discriminate discrete visual quantities.
- Magnitude coding is not limited to vision: similar midbrain mechanisms can represent the number of **sounds/calls** and trigger behavior when a threshold is reached.



Superior colliculus (optic tectum):
interfaces sensory information with action and
can encode stimulus magnitude.

“vertebrate neuroarchitecture does not respect the boundaries of standard mental terms”

Pessoa, L., Medina, L., & Desfilis, E. (2022). **Refocusing neuroscience: Moving away from mental categories and towards complex behaviours.** *Philosophical Transactions of the Royal Society B: Biological Sciences*

Thank you!

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A new ontology for numerical cognition: Integrating evolutionary, embodied, and data informatics approaches

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