Kognitionspsychologie: Session 4
Spatial Cognition

Rui Mata, HS 2024

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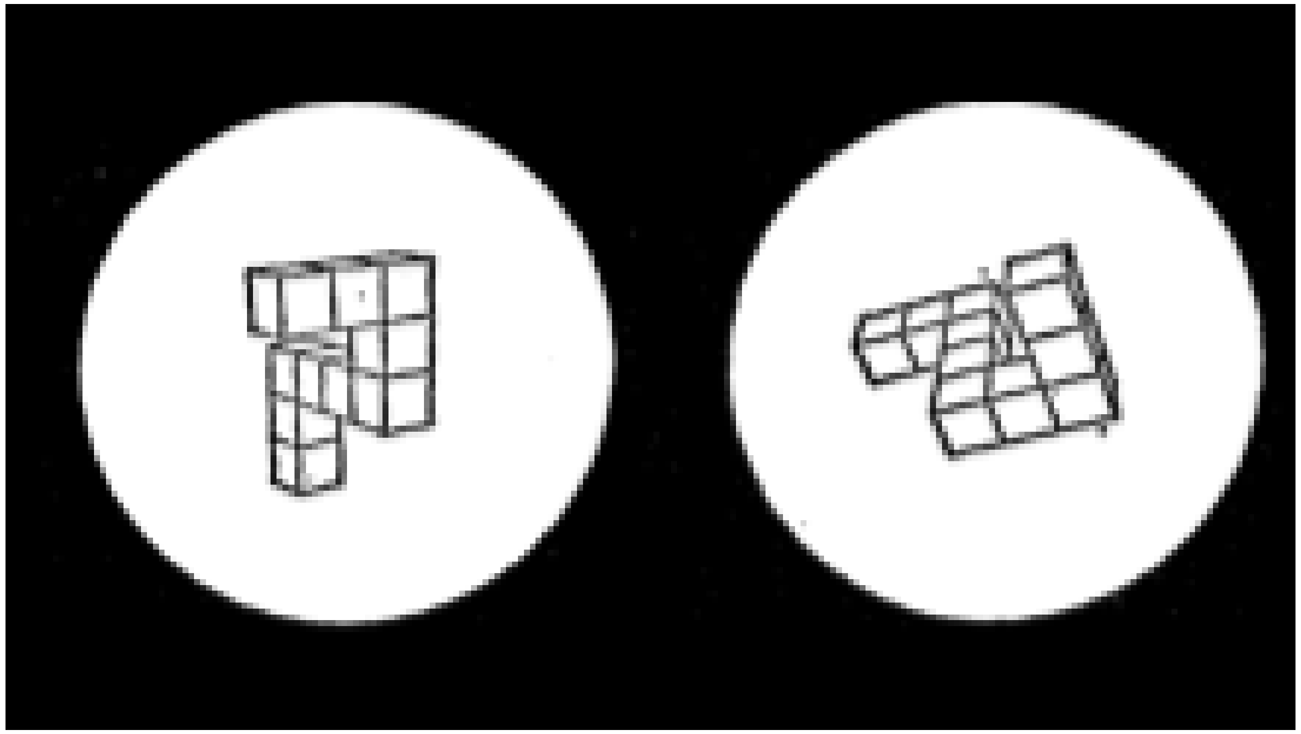
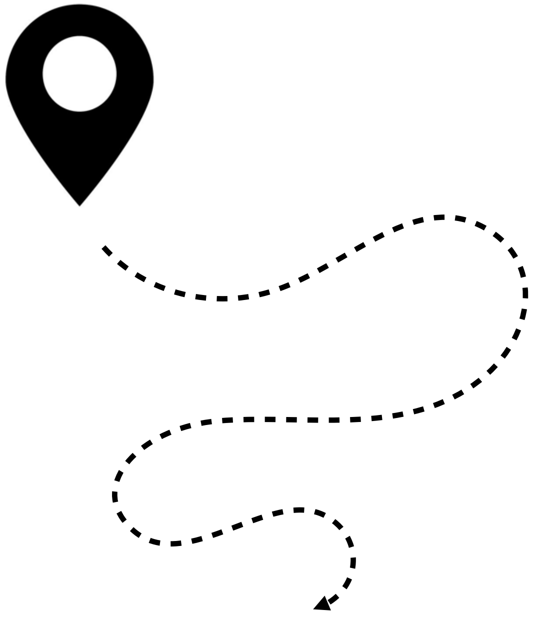
Learning Objectives

- Be able to discuss whether spatial cognition is a natural kind…
- Discuss the **adaptive significance** of spatial cognition and debate sex differences in spatial ability in light of evolutionary and socio-cultural theories
- Learn how **comparative approaches** to spatial cognition suggest that there is an important interplay between biological preparedness and cultural defaults in humans
- Learn about **developmental patterns** in the acquisition of spatial skills and cultural defaults
- Learn about **neural and computational model**(s) of spatial cognition





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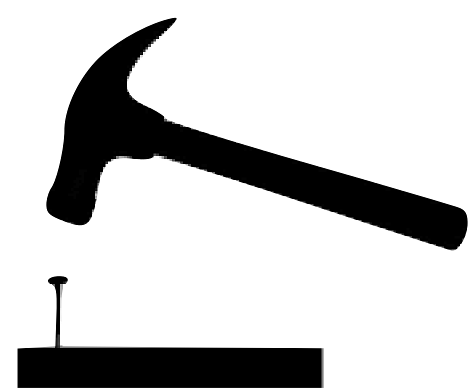
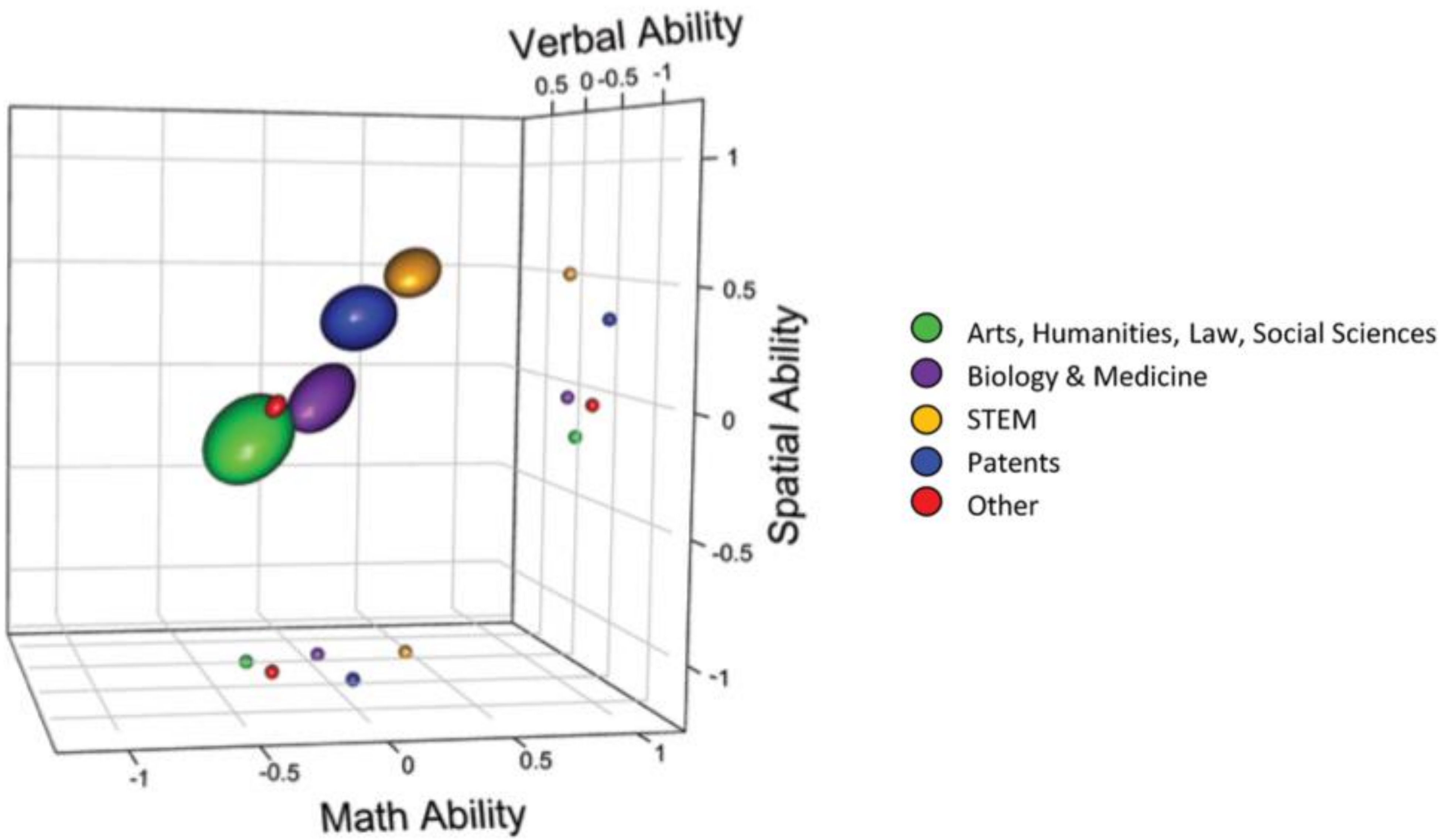
Spatial Cognition

Ontogeny	Mechanism
Phylogeny	 Adaptive Significance

The gathering of food, also known as foraging, was practised by the nomadic hunter-gatherer populations to enable them to meet their food needs. With agriculture, gathering was transformed into a systematic task: the harvest. Nonetheless, gathering food in the wild was still a useful way for the underprivileged classes to supplement their diet. Later, as standards of living increased in the industrial era, gathering food in the wild turned into a leisure activity.

© André Houot, mise en couleurs Jocelyne Charrance / Musée cantonal d'archéologie et d'histoire, Lausanne ; Musées cantonaux, Sion et Musée d'art - Picking blueberries, Mesolithic

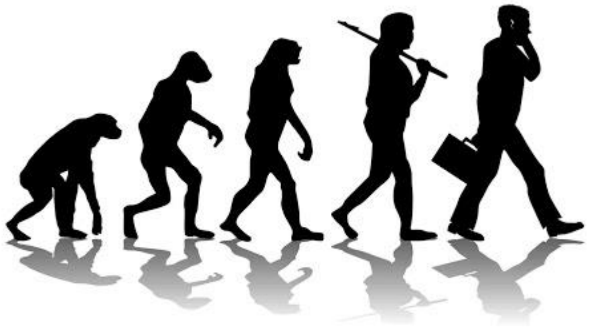
Spatial ability is important for technical innovation!



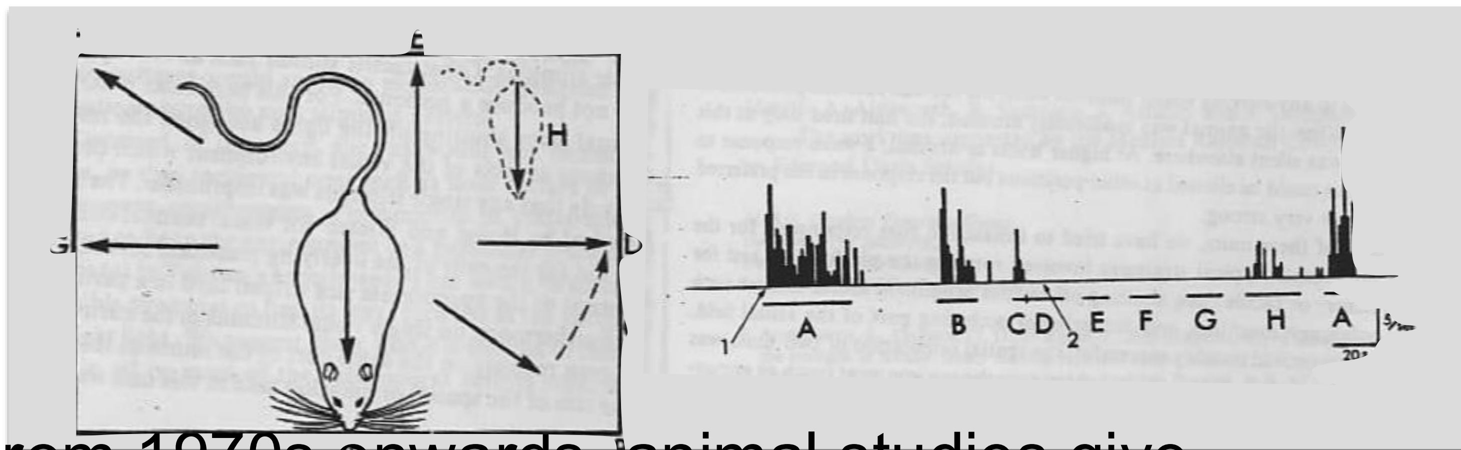
Spatial ability is correlated with performance in STEM (science, technology, engineering, mathematics)

Kell, H. J, Lubinski, D., Benbow, C. P., & Steiger, J H. (2013). Creativity and Technical Innovation. *Psychological Science, 24*(9), 1831–1836. http://doi.org/10.1177/0956797613478615

Spatial Cognition

Ontogeny	Mechanism
 Phyıogeny	Adaptive Significance

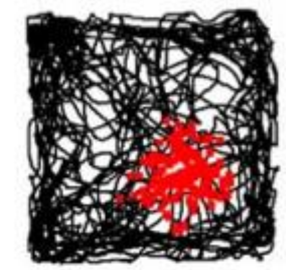
Navigation



"From 1970s onwards, animal studies give neurobiological support to the idea of a cognitive map. For example, O'Keefe and Dostrovsky (1971) discovered place cells in the rodent hippocampus, which fire as a function of the spatial position of the animal. Since, other cells (not only in hippocampus) have been identified that provide a spatial positioning system, involving both the representation of external space and the position/direction of the animal (see figures on the right). Now it is believed that the **hippocampus** provides the neural instantiation of a spatial map, an Euclidean coordinate system that allows landmarks to be encoded in terms of their allocentric locations (location of objects in space relative to other objects)."

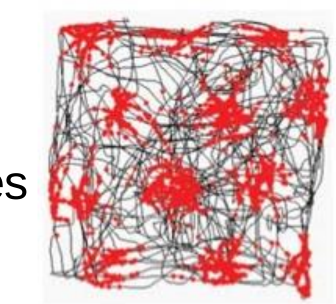
Place Cells

A type of pyramidal neuron within the hippocampus that becomes active when the animal enters a particular place in the environment; this place is known as the place field.



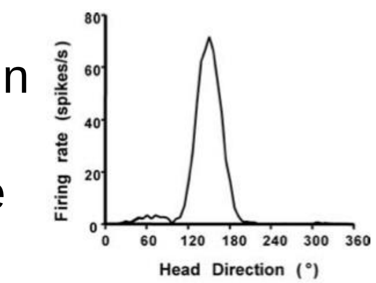
Grid Cells

A type of neuron that becomes active when the animal is in particular places that form a set of small clusters, with such clusters forming the vertices of a grid of equilateral triangles.



Head Direction Cells

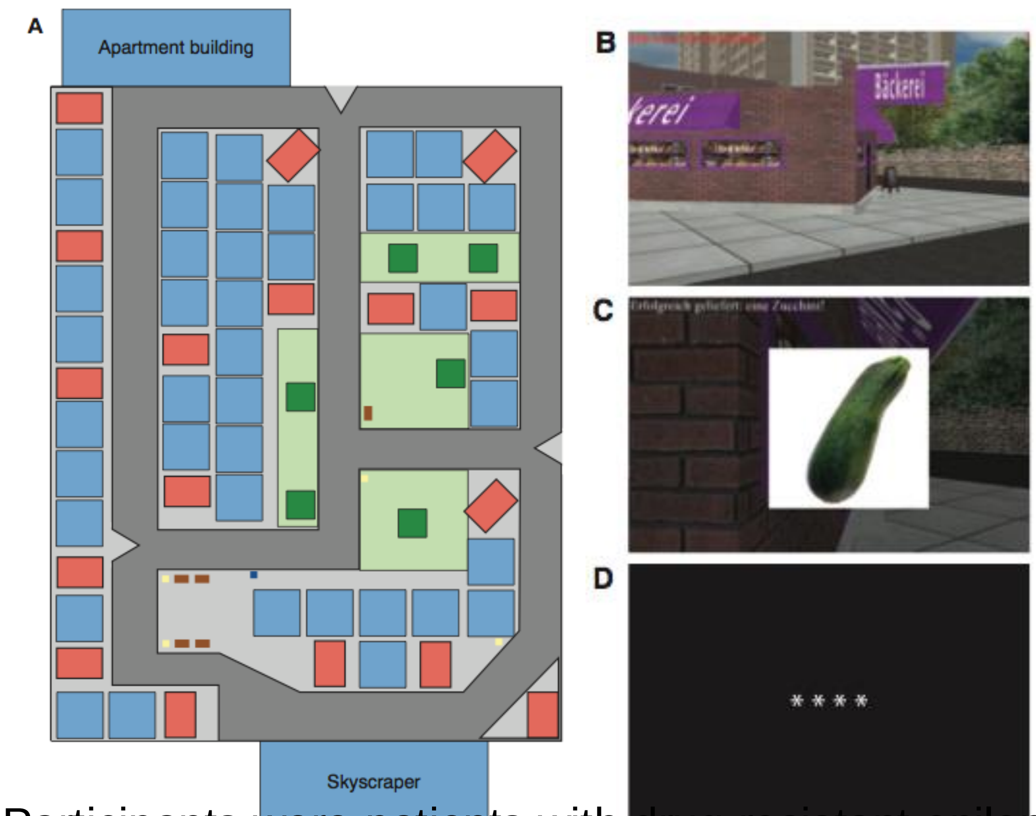
A type of neuron present in the brains of many mammals, which increase their firing rates above baseline levels only when the animal's head points in a specific direction.

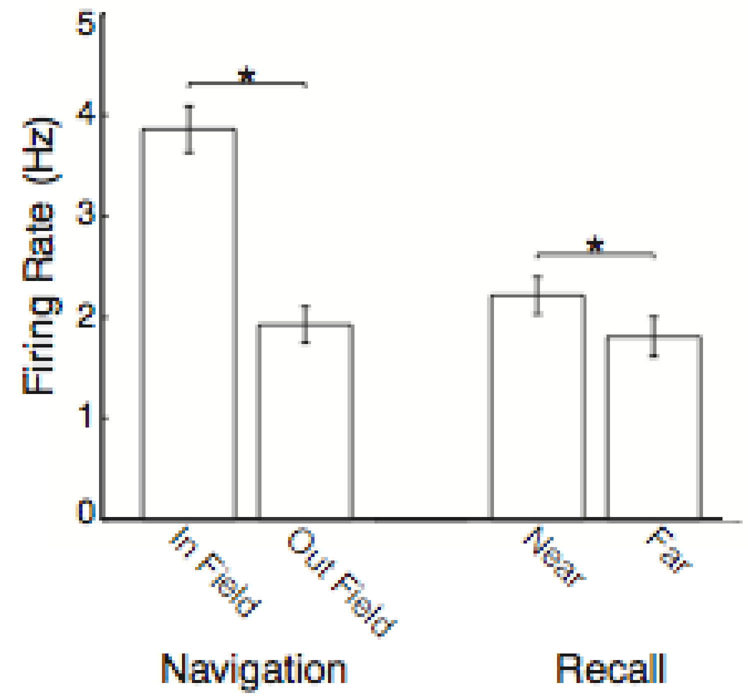


Burgess, N. (2008). Spatial cognition and the brain. *Annals of the New York Academy of Sciences, 1124*, 77-97.

Navigation

Delivery Game





Place-responsive cell activity during navigation and recall."In Field" indicates the average place-responsive cell firing rate when navigating within a cell's place field, whereas "Out Field" indicates the average place-responsive cell firing rate at locations outside of a place field (Right) Recall. "Near" indicates cell firing rate in the time period from 1.5 s before to 1 s after recall onset of items that were initially presented in or close to the center of a place field. In contrast, "Far" represents the average place-responsive cell firing rate in the same time window for recall of items that were initially presented far from the center of a place field.

Participants were patients with drug-resistant epilepsy who were implanted with depth electrodes to localize the focus of their seizures and to map cognitive function in surrounding healthy tissue. Participants played a delivery game in which they delivered 13 items at a time. After all items were delivered, they had to recall all items.(A) Overhead map of the virtual environment. Red rectangles, store locations; blue squares, locations of non-store buildings; green areas, grass and trees; small dark blue, brown, and yellow boxes; mailboxes, benches, and street lights. (B) An example storefront that a participant might encounter. (C) The presentation of an item (a zucchini) upon arrival at the target store (bakery). (D) The initiation of the recall period, as indicated by a black screen with asterisks.

Miller et al. identified place-responsive cells in the hippocampus that were active during virtual navigation and subsequent recall of navigation-related memories without actual navigation. Neuronal firing during the retrieval of each memory was similar to the activity that represented the locations in the environment where the memory was initially encoded.

Miller, J. F., Neufang, M., Solway, A., Brandt, A., Trippel, M., Mader, I., …, & Schulze-Bonhage, A. (2013) Neural activity in human hippocampal formation reveals the spatial context of retrieved memories. *Science, 342*, 1111-1114.

Navigation

Figure 1 Neuroimaging studies reveal a network of brain regions involved in spatial navigation. Neurosynth[149] (http://www.neurosynth.org/) was used to perform an automated meta-analysis of 64 studies of human navigation, revealing common activation across these studies in the hippocampus (Hipp), as well as parahippocampal, retrosplenial and entorhinal cortices, among other regions (map thresholded at $P < 0.01$, corrected for false discovery rate). This navigational network overlaps with three regions (PPA, RSC, OPA) that respond strongly during viewing of scenes and buildings, which were defined in a large group of participants ($n = 42$) using standard methods[150]. Only the right-hemisphere inflated cortical surface is shown, though similar regions are also found in the left hemisphere.

Hipp = hippocampus; PPA = parahippocampal place area; RSC = retrosplenial complex; OPA = occipital place area

Epstein, R. A., Patai, E. Z., Julian, J. B., & Spiers, H. J. (2017). The cognitive map in humans: spatial navigation and beyond. Nature Neuroscience, 20(11), 1504–1513. http://doi.org/10.1038/nn.4656

Object representation: Two Visual Pathways

Object discrimination

Landmark discrimination

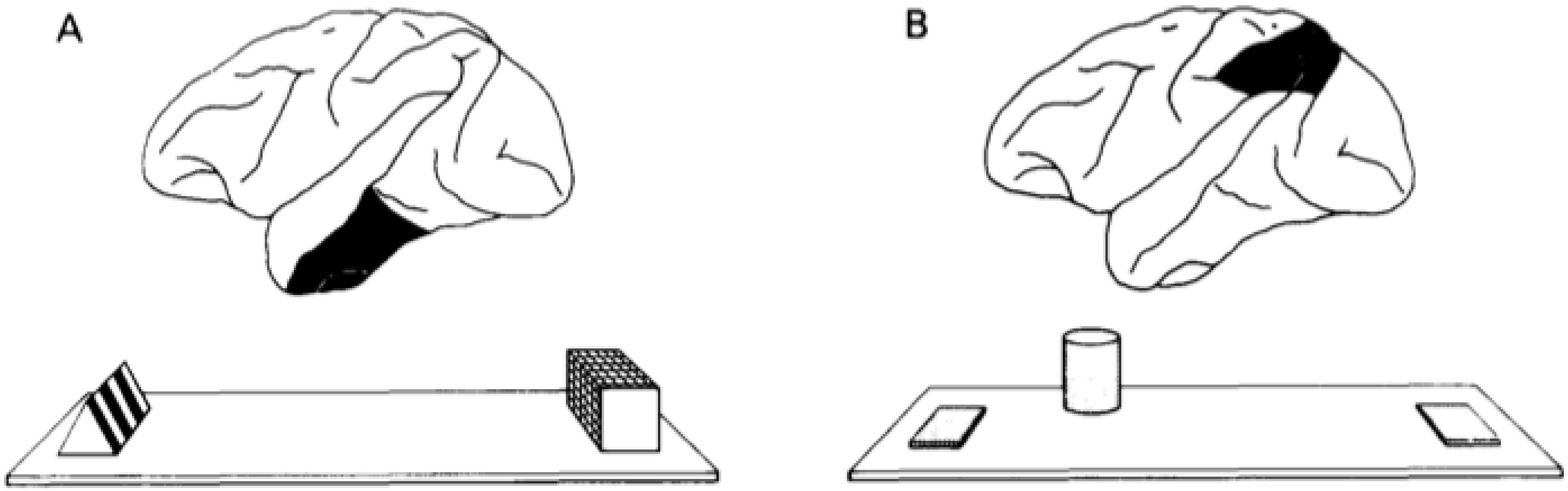
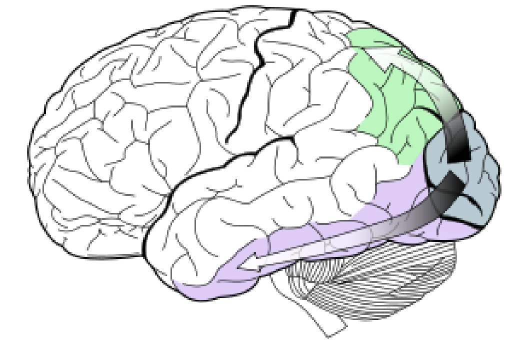


Fig. 2. Behavioral tasks sensitive to cortical visual lesions in monkeys. (A) Object discrimination. Bilateral removal of area TE in inferior temporal cortex produces severe impairment on object discrimination. A simple version of such a discrimination is a one-trial object-recognition task based on the principle of non-matching to sample, in which monkeys are first familiarized with one object of a pair in a central location (familiarization trial not shown) and are then rewarded in the choice test for selecting the unfamiliar object. (B) Landmark discrimination. Bilateral removal of posterior parietal cortex produces severe impairment on landmark discrimination. On this task, monkeys are rewarded for choosing the covered foodwell closer to a tall cylinder, the 'landmark', which is positioned randomly from trial to trial closer to the left cover or closer to the right cover, the two covers being otherwise identical.

"Evidence is reviewed indicating that striate cortex in the monkey is the source of two multisynaptic corticocortical pathways. One courses ventrally, interconnecting the striate, prestriate, and inferior temporal areas, and enables the visual identification of objects. The other runs dorsally, interconnecting the striate, prestriate, and inferior parietal areas, and allows instead the visual location of objects. How the information carried in these two separate pathways is reintegrated has become an important question for future research."

Mishkin, M. , Ungerleider, L. G., & Macko, K. A. (1983). Object vision and spatial vision: Two cortical pathways. *Trends in Neurosciences, 6*, 414-417.



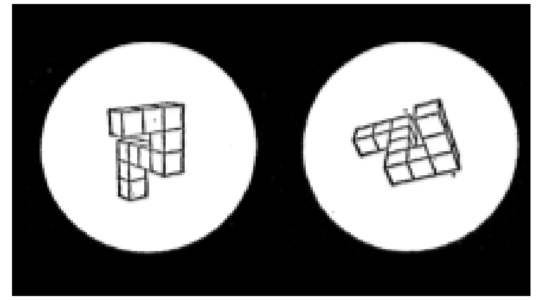
Ventral System/Stream

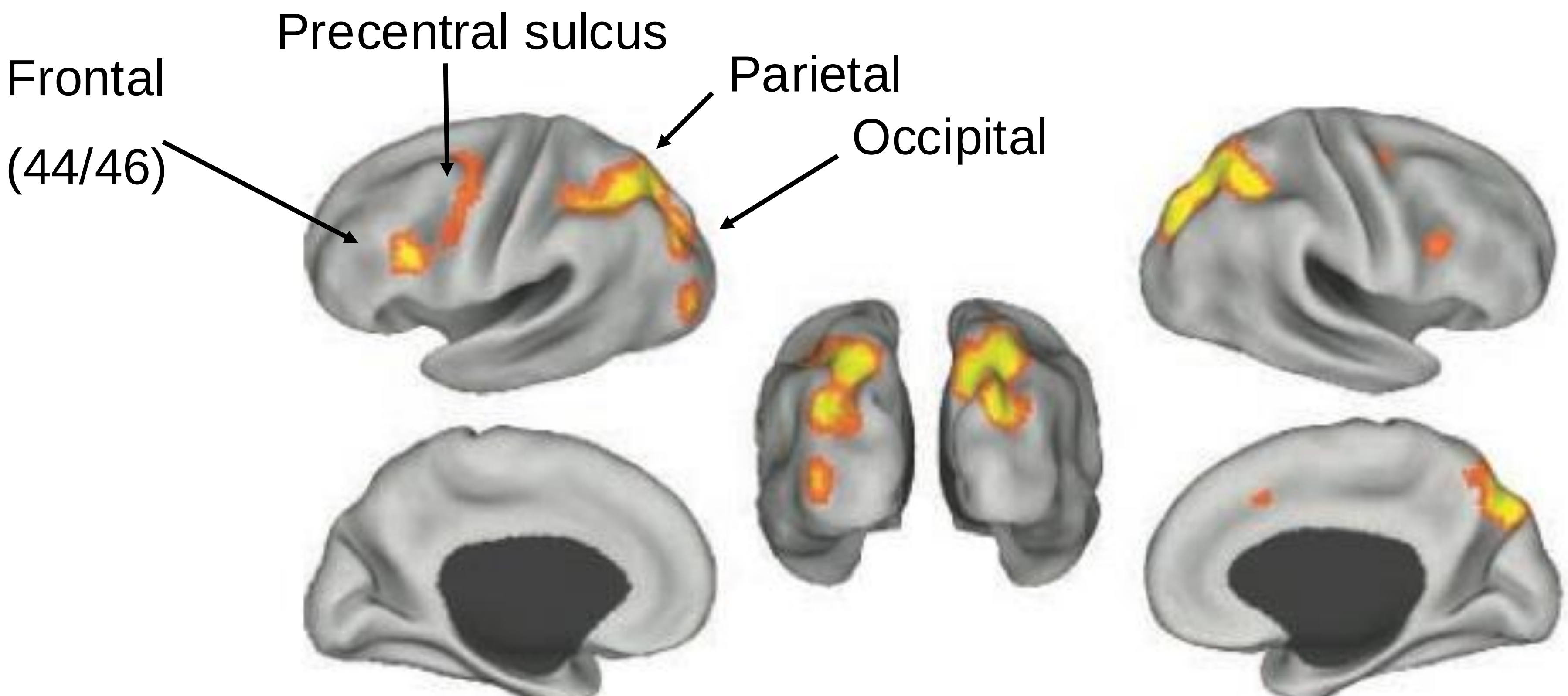
Leads from V1 to the inferior temporal cortex: "what" pathway, associated with recognition and object representation.

Dorsal System/Stream

Lead from V1 to the posterior parietal cortex: "where" pathway, associated with movement and the representation of location of objects, particularly when actions are involved.

Object representation and manipulation





Meta-analysis of neuroimaging studies of **mental rotation**. The panel shows the regions that responded above chance in mental rotation task comparisons across all studies. Brighter colors indicate stronger responses.

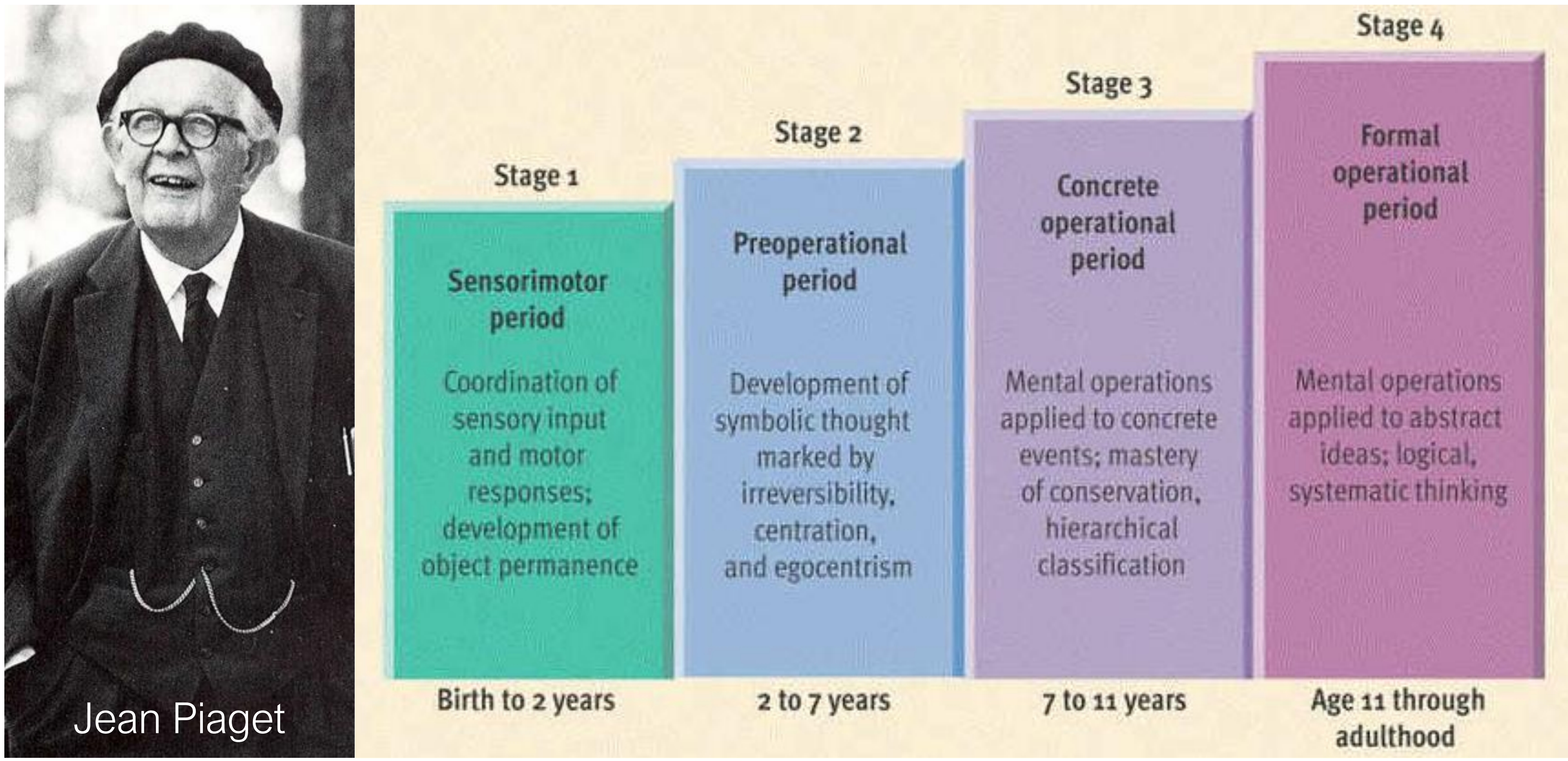
“The present meta-analysis allows for two strong conclusions regarding the neural substrate of mental rotation. First, the posterior parietal cortex (as well as regions extending down into the superior posterior occipital cortex) is consistently activated during mental rotation across a range of tasks (…). This region is therefore a good candidate for implementing the transformation-specific computations required to carry out mental rotation tasks. (…) Second, motor areas in the posterior frontal cortex are clearly activated during many mental rotation paradigms.

Zacks, J. M. (2008). Neuroimaging studies of mental rotation: A meta-analysis and review. *Journal of Cognitive Neuroscience, 20*, 1-19.

Spatial Cognition

Ontogeny 	Mechanism
Phylogeny	Adaptive Significance

The Development of Spatial Cognition



Egocentric (self to object)

Represents the location of objects in space relative to the body axes of the self

Allocentric (object to object)

Represents the location of objects in space relative to other objects.

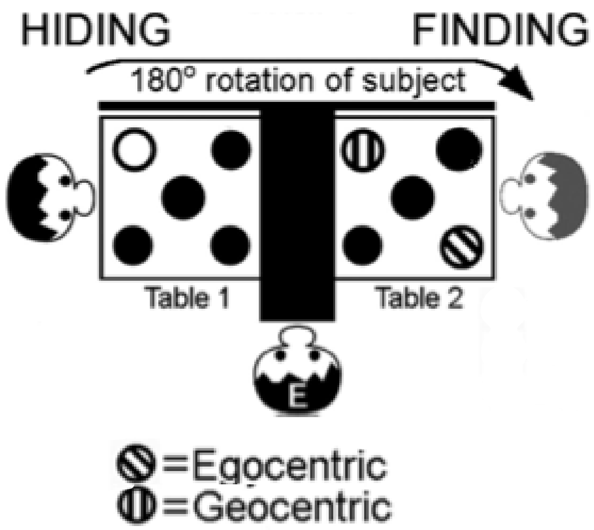
Geocentric (object to world)

Represents the location of objects in space relative to absolute coordinates (e.g., north, south)

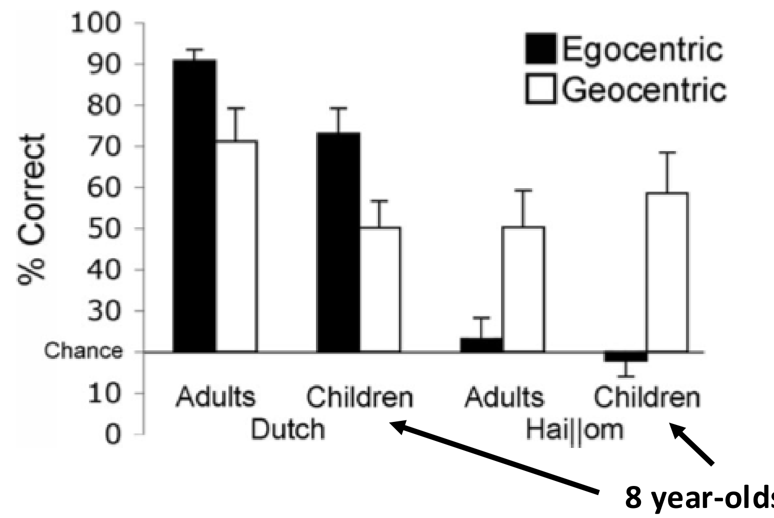
Piaget believed that spatial cognition in young children is fundamentally egocentric and only later does it become allocentric (i.e., less self-centered) – this is spatial cognition seen from the lens of general cognitive development…

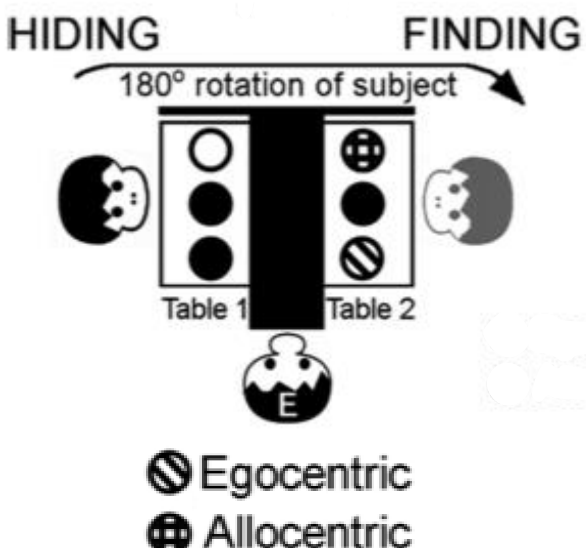
Piaget, J. (1967). *A Child's Conception of Space*. Norton Edition.

Developmental approaches

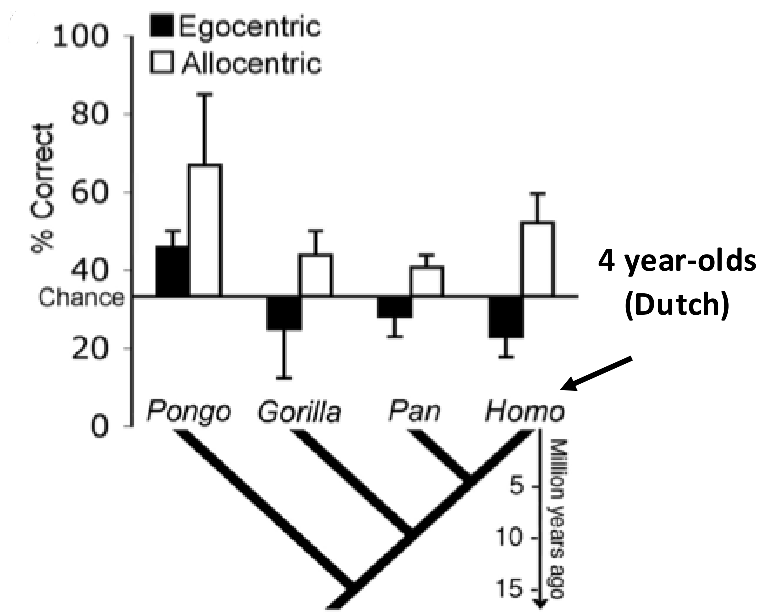


Dutch and Hai//om participants watched while a target was hidden. Then participants moved to the other table and indicated where they thought a second target might be hidden.





Similar but simpler setup was used to compare human children and non-human primates..



Hai//om

A group of hunter–gatherers living in the savanna of northern Namibia. Striking features include a unique kinship and naming system, frequent storytelling and an absolute (geocentric) linguistic system for spatial relations.

Cladistics

from the Greek, klados, branch, is an approach to biological classification in which organisms are grouped together based on whether or not they have one or more shared unique characteristics that come from the group's last common ancestor and are not present in more distant ancestors. Members of the same group are thought to share a common history and be more closely related

The results suggest that human spatial relational learning varies cross-culturally (Dutch vs. Hai//om). In addition, they suggest a similar default relational processing through all great ape genera: All genera, including 4-year-old humans preferred allocentric to egocentric processing of spatial relations. Perhaps an inherited bias toward allocentric coding is overridden by cultural preferences (Dutch 8-year-olds already show preference for egocentric spatial coding)…

Haun, D.B.M.. Rapold, C.J., Call, J., Janzen, G, & Levinson, S.C. (2006). Cognitive cladistics and cultural override in human spatial cognition. Proceedings of the National Academy of Sciences, 103, 17568-17573.

Males outperform females on most spatial ability tasks

Domain	Effect size	Comment	Reference
Navigation	0.36	male>female	Nazareth, A., Huang, X., Voyer, D., & Newcombe, N. (2019). A meta-analysis of sex differences in human navigation skills, 1–26. http://doi.org/10.3758/s13423-019-01633-6
Mental rotation	0.39	male>female	Lauer, J. E., Yhang, E., & Lourenco, S. F. (2019). The development of gender differences in spatial reasoning: A meta-analytic review. *Psychological Bulletin*, *145*(6), 537–565. http://doi.org/10.1037/bul0000191
Mental rotation	0.56	male>female	
Spatial perception	0.44	male>female	Voyer, D., Voyer, S., & Bryden, M. P. (1995). Magnitude of sex differences in spatial abilities: A meta-analysis and consideration of critical variables. *Psychological Bulletin*, *117*(2), 250–270. http://doi.org/10.1037/0033-2909.117.2.250
Spatial visualization	0.19	male>female	
Visual-spatial working memory	0.16	male>female	Voyer, D., Voyer, S. D., & Saint-Aubin, J. (2017). Sex differences in visual-spatial working memory: A meta-analysis, 1–28. http://doi.org/10.3758/s13423-016-1085-7
Object location	0.27	female>male	Voyer, D., Postma, A., Brake, B., & Imperato-McGinley, J. (2007). Gender differences in object location memory: A meta-analysis. *Psychonomic Bulletin & Review*, *14*(1), 23–38. http://doi.org/10.3758/BF03194024

Males outperform females on most spatial ability tasks **but** differences increase with age…

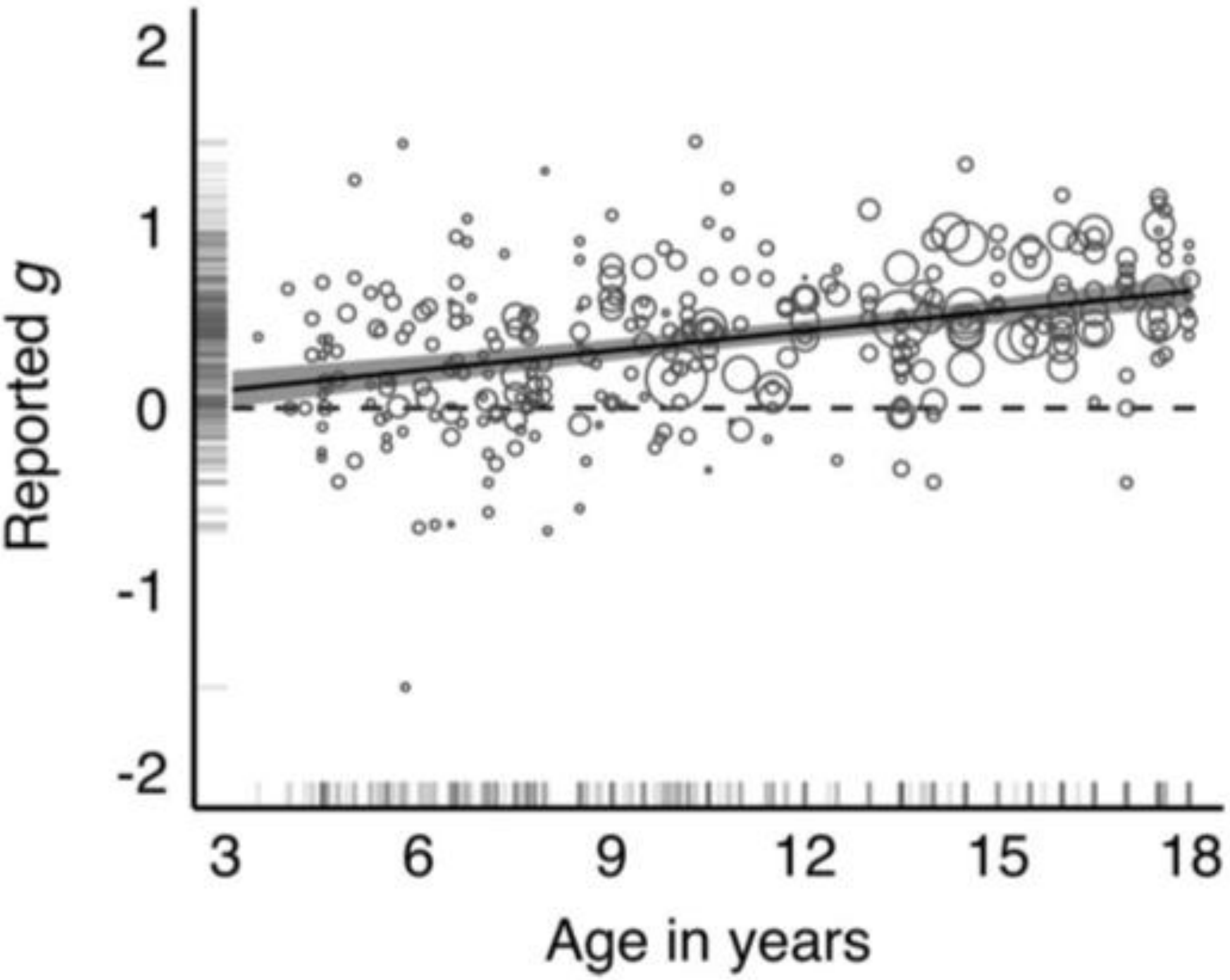
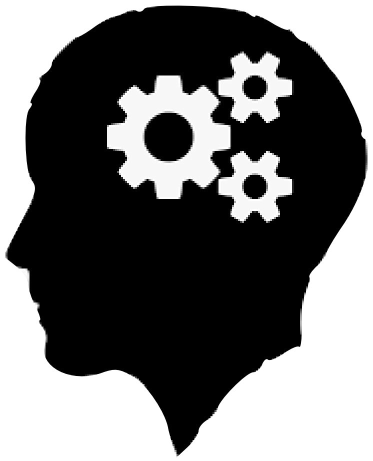


Figure 3. Bubble plot depicting the relation between mean sample age and reported gender differences in mental rotation performance with marginal rug plots that illustrate the distributions of age and effect size. Effect sizes greater than 0 indicate a male advantage in performance, whereas effect sizes less than 0 indicate a female advantage. Marker sizes are proportional to the meta-analytic weight of the corresponding effect size. The solid line denotes the metaregression line for a model with age as the only predictor; the shaded area represents its 95% confidence interval.

These findings speak for a role of experience and training - potentially brought about by cultural roles and expectations (but do not exclude the possibility of biologically determined interests and maturation)

Lauer, J. E., Yhang, E., & Lourenco, S. F. (2019). The development of gender differences in spatial reasoning: A meta-analytic review. Psychological Bulletin, 145(6), 537–565. http://doi.org/10.1037/bul0000191

Spatial Cognition

Ontogeny	Mechanism 
Phylogeny	Adaptive Significance

(…) spatial cognition is not a natural kind. Humans act in two distinct ways in the spatial world: We navigate, and we manipulate objects. The two modes have different evolutionary roots, and distinct neural bases, albeit with some interconnections.

Newcombe, N. S. (2019). Three Kinds of Spatial Cognition. In Stevens' Handbook of Experimental Psychology and Cognitive Neuroscience, J. T. Wixted (Ed.). doi:10.1002/9781119170174.epcn315

Temporo-parietal model of spatial memory and imagery

Egocentric (self to object)

Represents the location of objects in space relative to the body axes of the self

Allocentric (object to object)

Represents the location of objects in space relative to other objects.

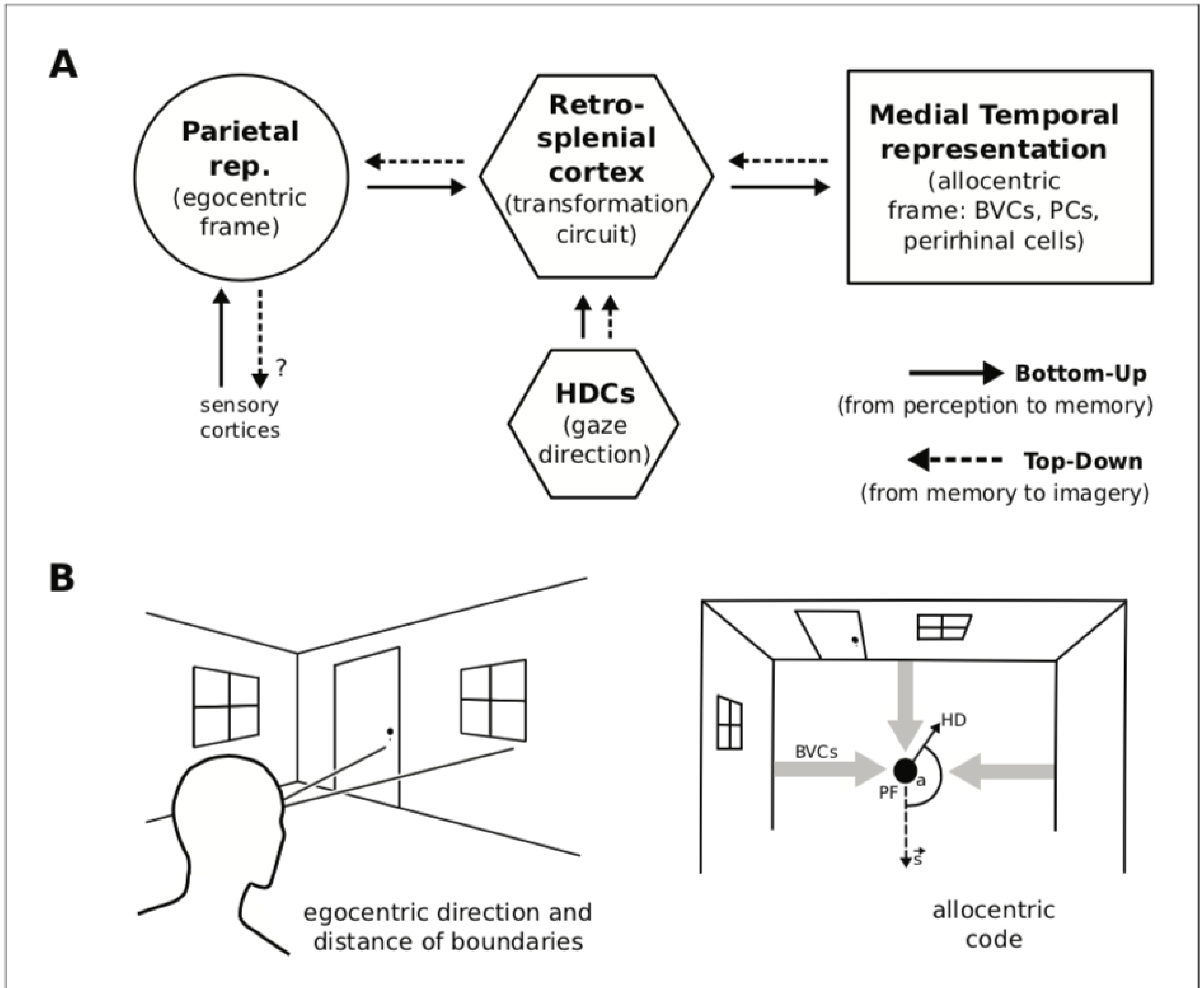


Figure 1. (A) Processed sensory inputs reach parietal areas and support an egocentric representation of the local environment (in a head-centered frame of reference). Retrosplenial cortex uses current head or gaze direction to perform the transformation from egocentric to allocentric coding. At a given location, environmental layout is represented as an allocentric code by activity in a set of boundary vector cells (BVCs), the place cells (PCs) corresponding to the location, and perirhinal neurons representing boundary identities (in a familiar environment, all these representations are associated via Hebbian learning to form an attractor network). Black arrows indicate the flow of information during perception and memory encoding (bottom-up). Dotted arrows indicate the reverse flow of information, reconstructing the parietal representation from view-point invariant memory (imagery, top-down). (B) Illustration of the egocentric (left panel) and allocentric frame of reference (right panel), where the vector s indicates South (an arbitrary reference direction) and the angle a is coded for by head direction cells, which modulate the transformation circuit. This allows BVCs and PCs to code for location within a given environmental layout irrespective of the agent's head direction (HD). The place field (PF, black circle) of an example PC is shown together with possible BVC inputs driving the PC (broad grey arrows).

Bicanski, A., & Burgess, N. (2018). A neural-level model of spatial memory and imagery. *Elife*, *7*. http://doi.org/10.7554/eLife.33752

Temporo-parietal model of spatial memory and imagery

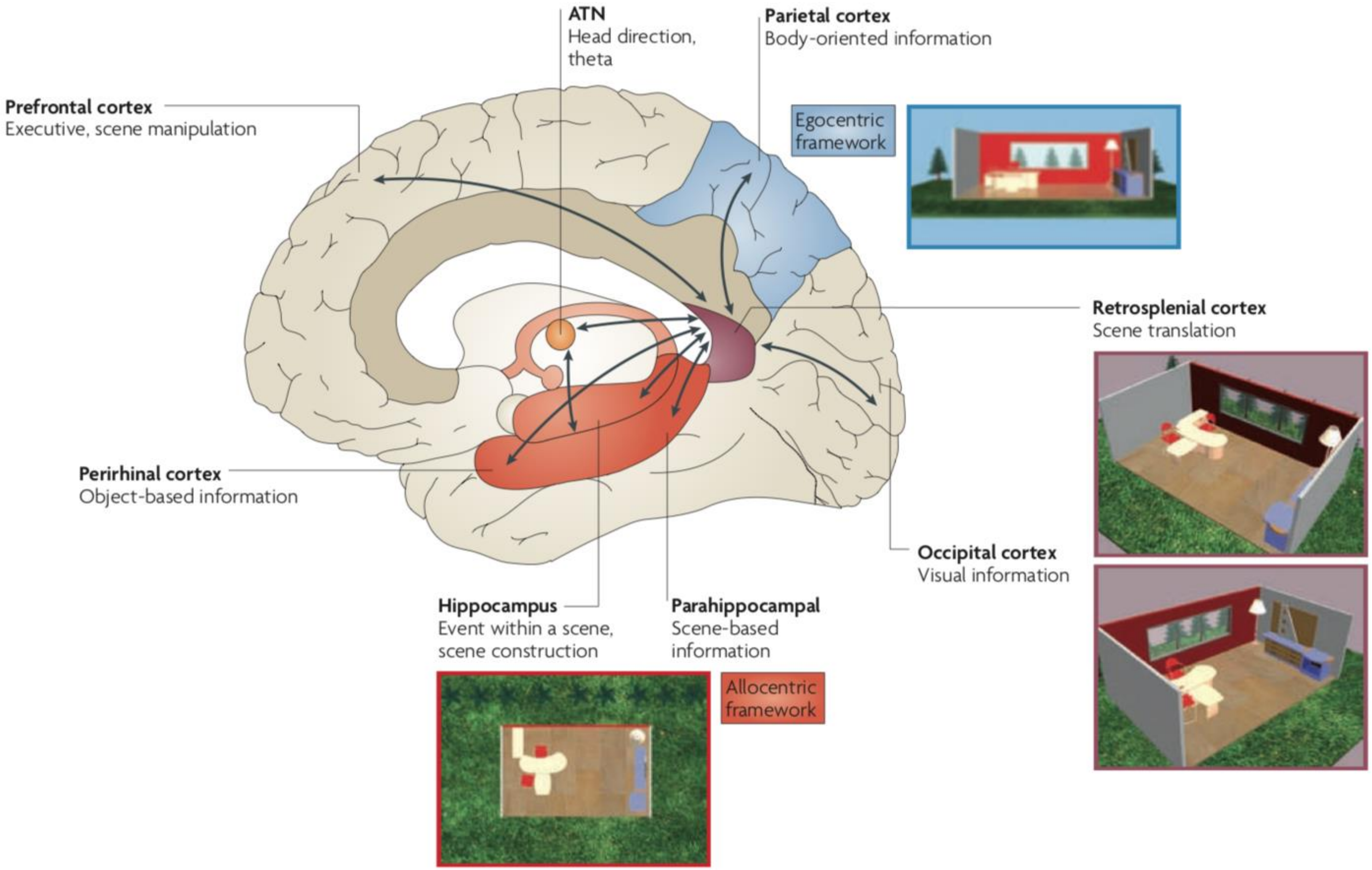


Figure 3 | **The key anatomical and functional relationships of the retrosplenial cortex.** Effective episodic memory, navigation and future thinking all require the ability to integrate and manipulate different frameworks of information, for example egocentric (self-centred) and allocentric (world-centred) frameworks. By virtue of its principal connections, the retrosplenial cortex is uniquely placed to enable translation within these domains. ATN, anterior thalamic nuclei.

Vann, S. D., Aggleton, J. P., & Maguire, E. A. (2009). What does the retrosplenial cortex do? *Nature Reviews Neuroscience*, *10*(11), 792–802. http://doi.org/10.1038/nrn2733

Summary

- **Adaptive Significance**: Spatial skills are thought instrumental to foraging and exploration in the physical world; in modern societies spatial skills are also associated with performance in STEM.
- **Comparative approaches:** Animal models have been instrumental in identifying dissociable processes and neural structures responsible for navigation (hippocampus) as well as object location/manipulation (parietal cortex) vs. identification/recognition (temporal cortex).
- **Developmental approaches:** Egocentric perspective enables first-person view, while allocentric perspective requires a more global representation - both types of representations are available to the cognitive system and can become cultural defaults across development in humans. A default allocentric spatial strategy seems to be shared across primates but can be overridden in humans by cultural norms that emphasise an egocentric perspective. Sex differences in spatial abilities are well established; different theories emphasise different reasons, including biological preparedness, however, empirical findings suggest these sex differences are not biological “fate” but are strengthened (if not engendered) by experience and cultural factors.
- **Neural and computational model:** Current models distinguish between structures responsible for object location/manipulation (parietal cortex) vs. identification/recognition (temporal cortex); complex skills such as navigation require the cognitive system to integrate egocentric and allocentric information, with parietal brain areas particularly involved in egocentric representation, while temporal brain areas, in particular the hippocampus, are heavily involved in coding a allocentric map of the external world; the retrosplenial cortex helps mediate between these representations.