How we learn: changing our brain

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When you overcome a challenge through learning,
you have done more than gain knowledge.

Your brain at the beginning is different from your brain at the end.

You have physically reshaped it
into a brain that is better able handle that challenge in the future

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Intended Learning Outcomes

- By the end of this video you will be able to:
  - Describe how the brain encodes, stores and retrieves information at different timescales.
  - Understand the brain processes that facilitate new learning
  - Describe mathematically a classic computational model of memory storage and retrieval
  - Explain the purpose and basic neuroanatomy of memory consolidation

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## What is learning? (neuroscience)

- Learning is the change to neural circuits in response to experiences, which may enable a change in future behaviour.
- This often involves changes to the strength of synapses (the connections between neurons).

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What is an experience, to the brain?

- Experiences are coded as patterns of neural activity
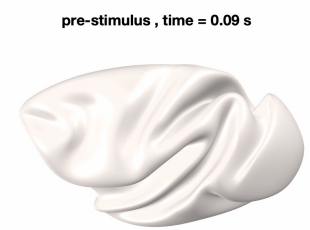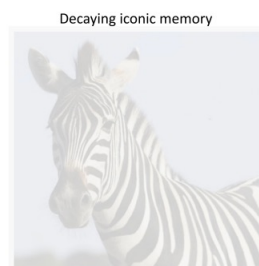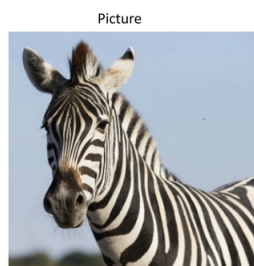- The pattern of neural activity is just the set of neurons that are active at (nearly) the same time
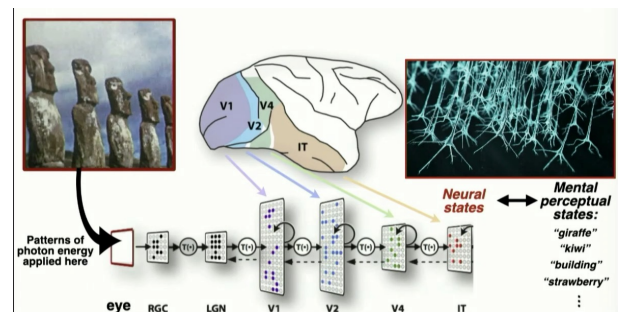
video: James DiCarlo (MIT)
Yamins et al., *PNAS*, 2014

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Sensory (iconic) memory – shallow in the brain

- Neural activity corresponding to sensory memory
  - is brief
  - is restricted to sensory parts of the cortex
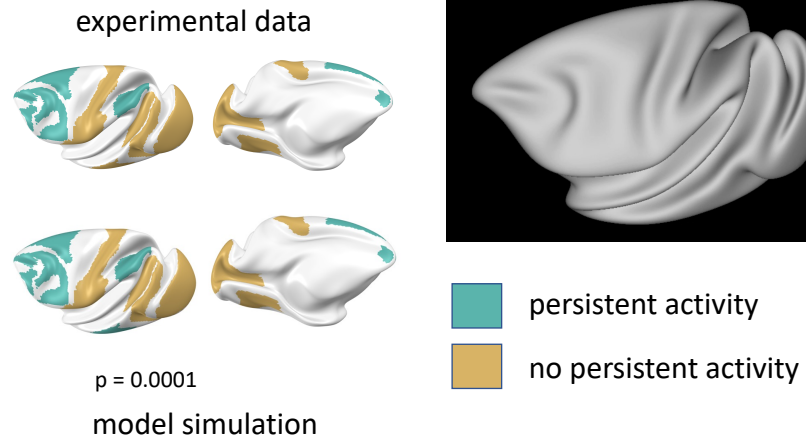 - does not propagate deeply into the brain

Teeuwen et al., *Current Biology*, 2021   Klatzmann*, Froudist-Walsh* et al., *bioRxiv,* 2022[6]

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Working memory activity – propagates deep into the brain's hierarchy

- Neural activity corresponding to working memory
  - propagates deeply into the brain
  - the pattern of neural activity largely persists after the sensory memory has died
  - activity in early sensory areas usually dies off – corresponding to a loss of fine sensory detail
    - See video on deep architectures
- Why can some areas maintain their patterns of neural activity better than others?
  - See video on recurrent architectures

experimental data

cortical hierarchy

p = 0.0001

model simulation

■ persistent activity

■ no persistent activity

Leavitt et al., *TiCS*, 2017; Froudist-Walsh et al., *Neuron*, 2021

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# What are the consequences of deeper processing for memory?

- Greater depth of processing – information travels further up the brain's hierarchy.

- Information is sustained for longer, neurons remain active at the same time for longer

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Hebbian Plasticity: The Foundation of Learning in the Brain

- "Neurons that fire together, wire together."
  - When one neuron frequently activates another, their synaptic connection strengthens.
  - Conversely, if two neurons rarely activate together, their connection weakens.
- Forms the basis for associating things in a single memory.
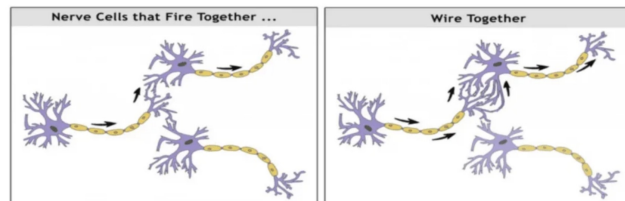
$$\dot{w} = H(pre, post)$$

The rate of change in synaptic weight from the presynaptic neuron to the postsynaptic neuron is a function of the presynaptic firing and the postsynaptic activity

Note: named after Donald Hebb, who proposed the idea in 1949.

image: The Reward Foundation

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## Selective Encoding: From Working to Long-Term Memory

- Not all working memories get transferred to long-term storage

- Do you still remember the one-time code from the video: Human memory: cognitive science foundations?

- What enables some working memories to be marked for encoding into long-term memory?
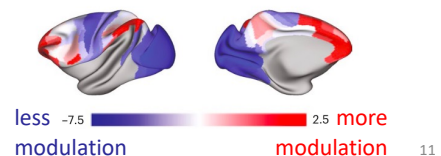
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The third player in plasticity: neuromodulators

- **Definition**: A neuromodulator is a chemical messenger released in the brain that changes (modulates) how two other neurons communicate at the synapse.
- neuromodulators like dopamine and acetylcholine signal reward, importance
- 3-factor learning rule
  - Adding dopamine or serotonin to Hebbian plasticity is like putting your name on the list of the long-term memory club
- Like all brain chemicals, neuromodulators act by binding to receptors (like a key opening a lock)
- The receptors for neuromodulators are much more prevalent deep in the cortical hierarchy than in early sensory areas.
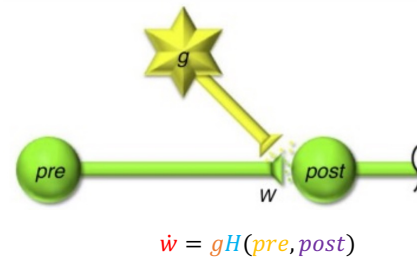
Froudist-Walsh et al., *Nature Neuroscience*, 2023

$$\dot{w} = gH(pre, post)$$

The rate of change in synaptic weight from the presynaptic neuron to the postsynaptic neuron depends on a neuromodulator and a function of the presynaptic firing and the postsynaptic activity

less −7.5 modulation   2.5 more modulation   11

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Quiz – blackboard

- Why is certain information encoded and other information forgotten? Write down initial thoughts integrating a neuroscience and a cognitive science point of view.

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Long-term memory, from retrieval to encoding

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Your experience

- Take one minute to recall, in as much detail as you can, a recent experience.
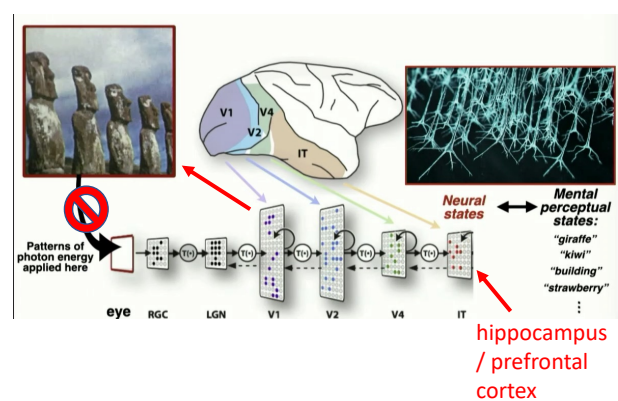- Write it down (privately)

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The Nature of memory retrieval:

- Retrieval is the brain's way of recreating the neural activity pattern from the original event.
- But it can't do this perfectly

hippocampus / prefrontal cortex

video: James DiCarlo (MIT)
Yamins et al., *PNAS*, 2014

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Pattern Completion in Memory Retrieval

- *Pattern completion* is the brain's ability to reconstruct a pattern of neural activity corresponding to a memory from a partially overlapping pattern of neural activity.

- The hippocampus (in particular a part called CA3) is the area most famously involved in this function

- However, some form of pattern completion must also take place across the cortex in order to recreate the original pattern of activity during retrieval

cortex

Hippocampus
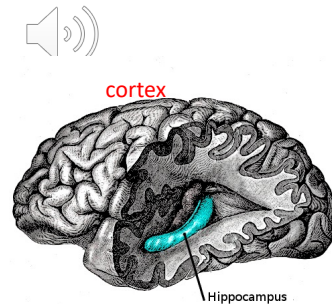
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Quiz – blackboard

- Explain the difference between sensory memory, working memory, and long-term memory in terms of neural activity patterns.

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## A classic model of pattern completion for memory retrieval (Hopfield)

- Fully connected
- symmetric weights ($w_{ij} = w_{ji}$)
- Binary outputs: (+1) or (-1).
- Energy-based system: The network seeks a state of minimum energy (attractor state)
- Can store multiple patterns, with Hebb's law
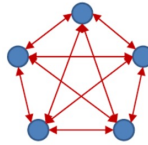
at each timestep:

$$x_i(t+1) = \begin{cases} +1 \ if \ 0 < \sum_j w_{ij}x_j - \theta \\ -1 \ otherwise \end{cases}$$

At the next timepoint neuron i is active (+1) if the weighted sum of all the other neurons activities, is greater than a threshold. Otherwise it is inactive (-1).
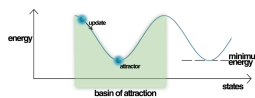
$$E = -\frac{1}{2}\sum_{ij} w_{ij}x_i x_j + \sum_i \theta_i x_i$$

Activity will continue to evolve until it reaches a local minimum of this energy function E, which is an attractor state.

$$w_{ij} = \frac{1}{P}\sum_{a=1}^{P} x_i^a x_j^a$$

If for a pattern a, both neurons i and j are active (or both inactive), then the synaptic weight should be increase, and decrease otherwise. If the network has seen the entire collection of patterns P, the synaptic weight between i and j should reflect the fraction of patterns for which the two neurons are co-active.
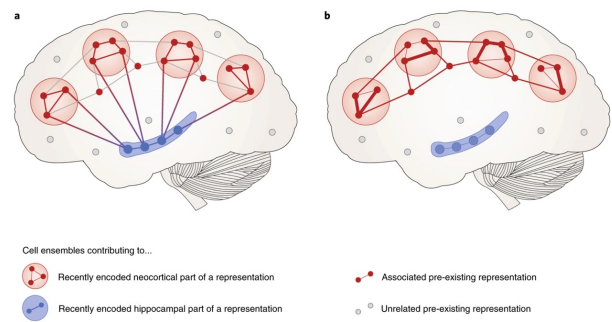
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Quiz – Blackboard

- Briefly explain the main principle behind the Hopfield model of memory storage and retrieval.

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Consolidating episodic memories during sleep: strengthening and generalising

- During sleep, neurons in the hippocampus replay the activity that played out during the day, at ~10x speed
- Hippocampal activity spreads to the cortex
- The representation of the memory may gradually move from the hippocampus to the cortex
- This could coincide with older memories seeming less 'episodic' and more 'semantic' (the gist).


Cell ensembles contributing to...

Recently encoded neocortical part of a representation

Recently encoded hippocampal part of a representation

Associated pre-existing representation

Unrelated pre-existing representation

Wilson & McNaughton, Science, 1994; Winocur and Moscovitch, *JINS,* 2011; Klinzing et al., *Nature Neuroscience*, 2019

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Consolidating skills during sleep: automatising and freeing up cortex

- With expertise skills (a.k.a. procedural memories such as reading) activate less of the cortex, and can be performed automatically
- Automatic expertise relies more on areas deep in the brain that are involved in habits (basal ganglia)
- This frees up major cortical networks to consciously tackle challenging problems
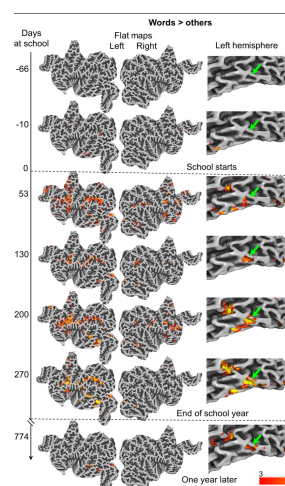
Dehaene-Lambertz et al., *PLoS biology,* 2018

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Quiz – blackboard

- Compare and contrast episodic, semantic and procedural memories in terms of their consolidation during sleep.

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Recap

- Experiences are represented as patterns of neural activity
- Sensory memory neural activity patterns are restricted to the outer sensory areas of the cortex and fade quickly (100s of ms).
- Working memory activity patterns spread deep into the cortical hierarchy and are maintained for 10s of seconds
- Working memories may fade or be encoded into long-term memory through Hebbian plasticity
- Encoding into long-term memory is more likely if a neuromodulator is present
- Memory retrieval is the brain's attempt to reconstruct a pattern of activity that arose during the original event (Hopfield model)
- Consolidation of memory during sleep can strengthen, generalise and/or automatise a memory.
- Consolidation involves a shift in the anatomical storage sites of memory

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Still curious? You can dive in deeper to any of today's topics:

- Sensory/iconic memory
  - Teeuwen, Rob RM, Catherine Wacongne, Ulf H. Schnabel, Matthew W. Self, and Pieter R. Roelfsema. "A neuronal basis of iconic memory in macaque primary visual cortex." *Current Biology* 31, no. 24 (2021): 5401-5414.
- Working memory
  - Froudist-Walsh, Sean, Daniel P. Bliss, Xingyu Ding, Lucija Rapan, Meiqi Niu, Kenneth Knoblauch, Karl Zilles, Henry Kennedy, Nicola Palomero-Gallagher, and Xiao-Jing Wang. "A dopamine gradient controls access to distributed working memory in the large-scale monkey cortex." *Neuron* 109, no. 21 (2021): 3500-3520.Attention:
- Hebbian plasticity
  - Hebb, Donald Olding. *The organization of behavior: A neuropsychological theory.* Psychology press, 2005
- Neuromodulators and plasticity
  - Frémaux, Nicolas, and Wulfram Gerstner. "Neuromodulated spike-timing-dependent plasticity, and theory of three-factor learning rules." *Frontiers in neural circuits* 9 (2016): 85.
  - Kuśmierz, Łukasz, Takuya Isomura, and Taro Toyoizumi. "Learning with three factors: modulating Hebbian plasticity with errors." *Current opinion in neurobiology* 46 (2017): 170-177.
  - Froudist-Walsh, Sean, Ting Xu, Meiqi Niu, Lucija Rapan, Ling Zhao, Daniel S. Margulies, Karl Zilles, Xiao-Jing Wang, and Nicola Palomero-Gallagher. "Gradients of neurotransmitter receptor expression in the macaque cortex." *Nature Neuroscience* (2023): 1-14.
- Hopfield network
  - Hopfield, John J. "Neural networks and physical systems with emergent collective computational abilities." *Proceedings of the national academy of sciences* 79, no. 8 (1982): 2554-2558.
- Replay of neural activity during sleep
  - Wilson, Matthew A., and Bruce L. McNaughton. "Reactivation of hippocampal ensemble memories during sleep." *Science* 265, no. 5172 (1994): 676-679.
- Consolidation of memories
  - Episodic-to-semantic transfer Winocur, Gordon, and Morris Moscovitch. "Memory transformation and systems consolidation." *Journal of the International Neuropsychological Society* 17, no. 5 (2011): 766-780.

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