Cognitive Neuroscience

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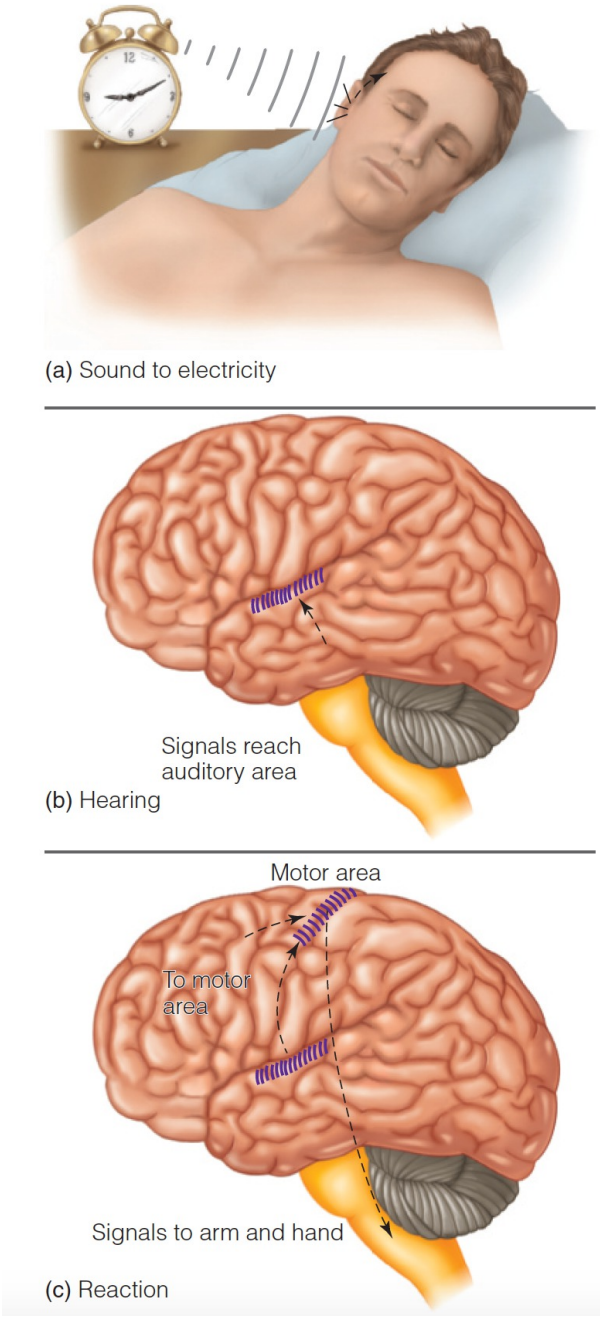
Cognitive Neuroscience

- Looking "under the hood"
- What is the hardware that the mind runs on?
- Much progress in recent years
  - understanding electro-chemical processes in neurons
  - probing neurons with electrodes
  - MRI scans of brain activity

- But: still far away from a bio-chemical model of "thinking"

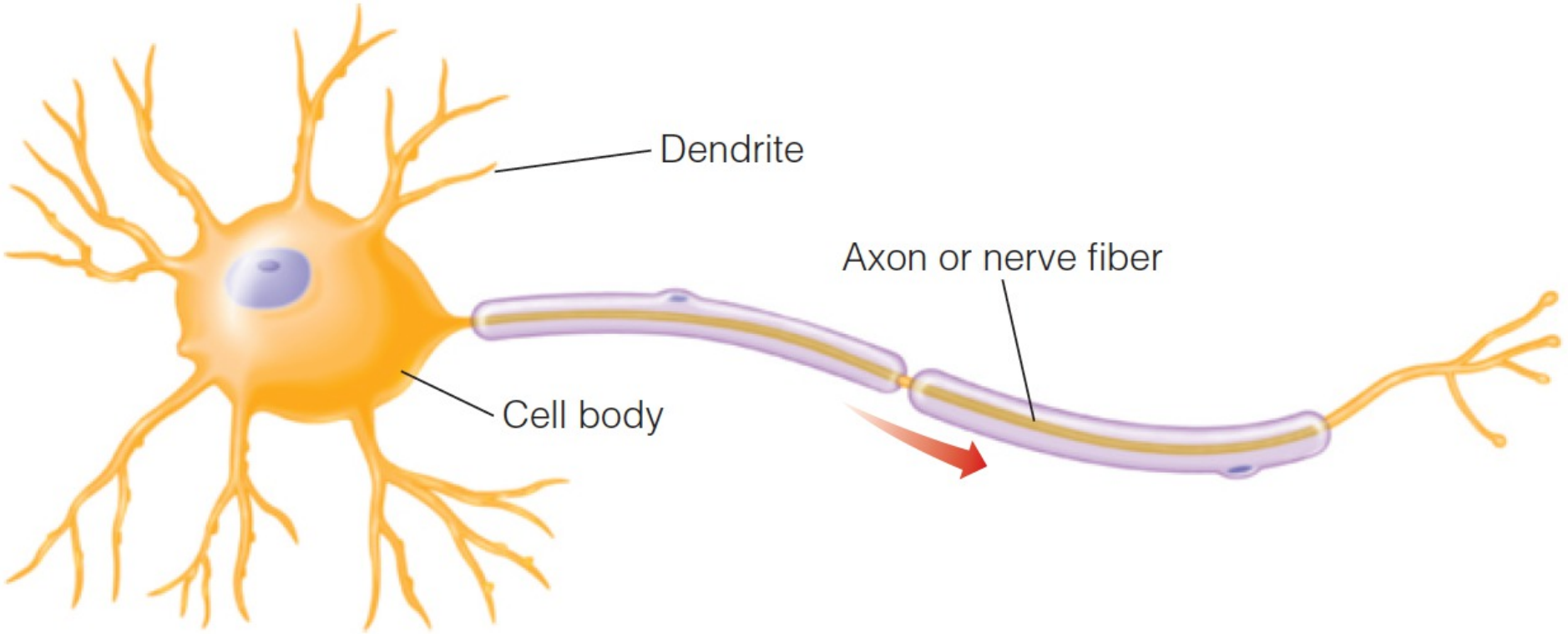
Information Processing in the Brain

- Consider the chain of events
  - you are asleep
  - the alarm clock rings
  - you press the snooze button
- What happens inside the brain?
  - sound wave hit your ear
  - your ear converts it to sensory input
  - signals reach the auditory area
  - signals are sent to the motor area
  - your arm acts

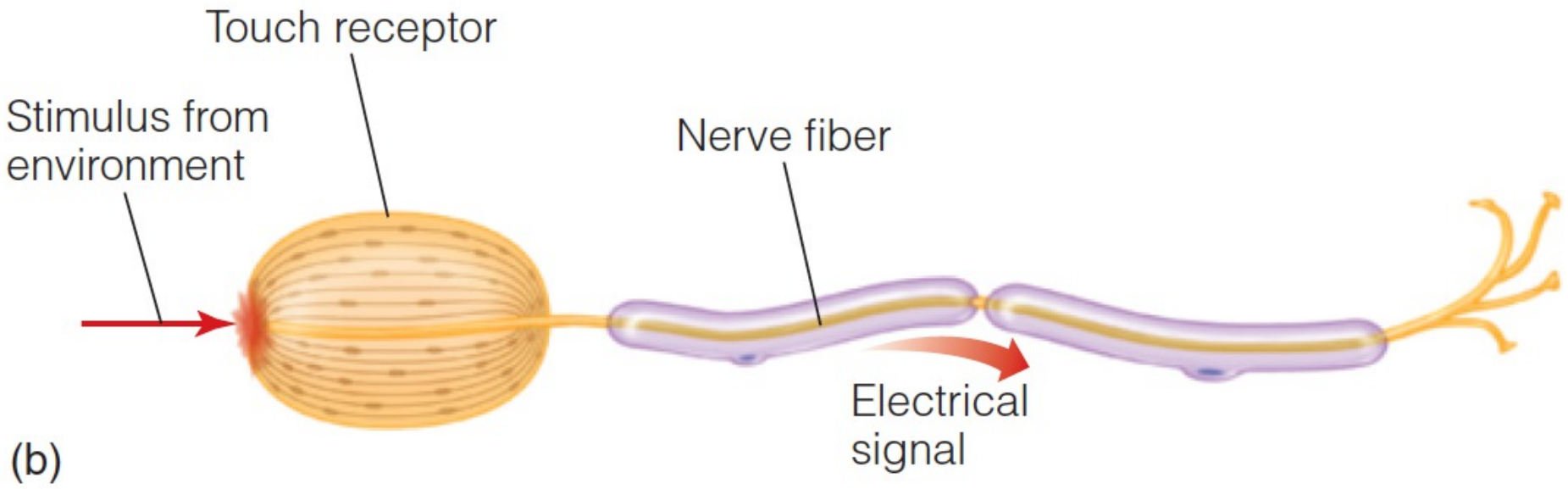


neurons

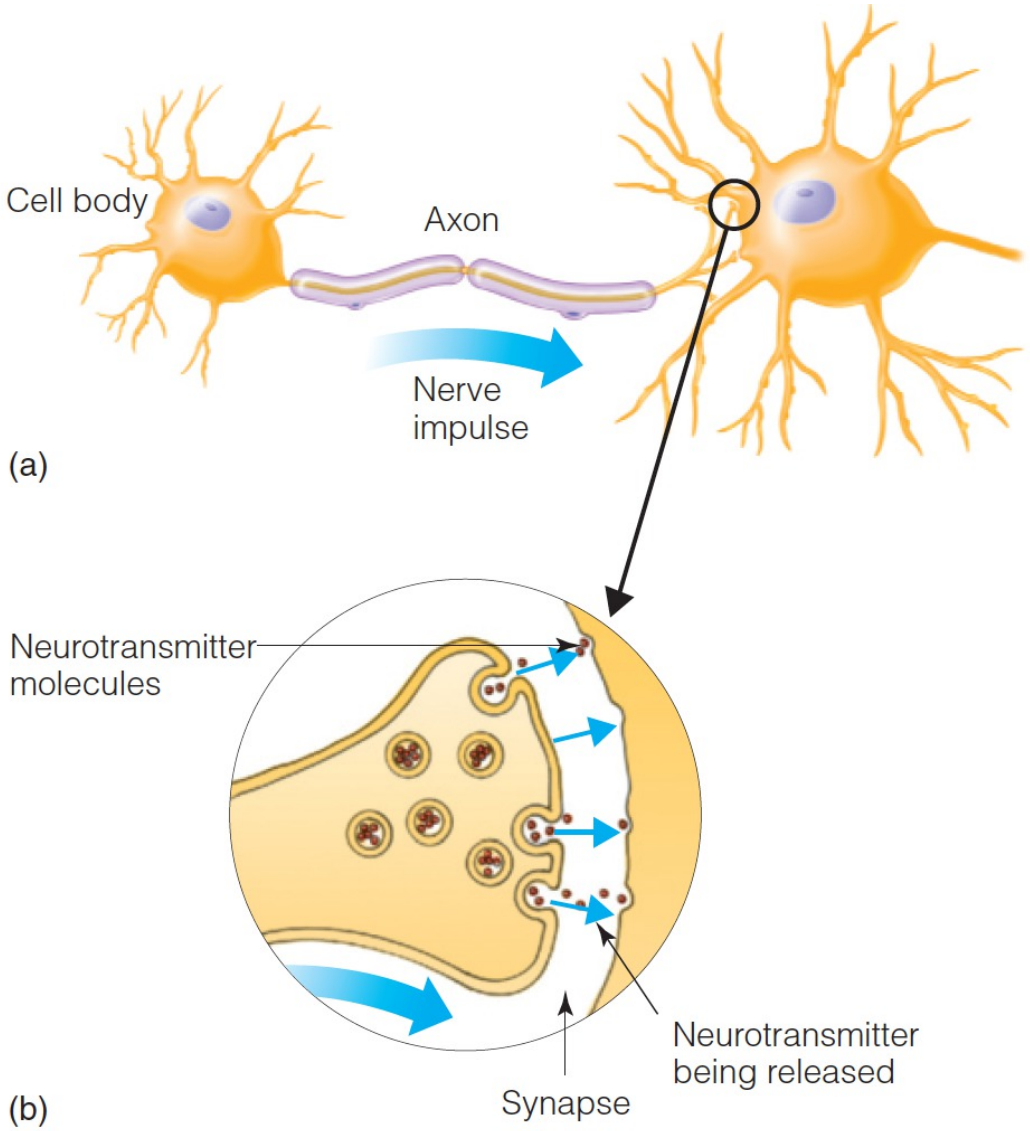
Neuron



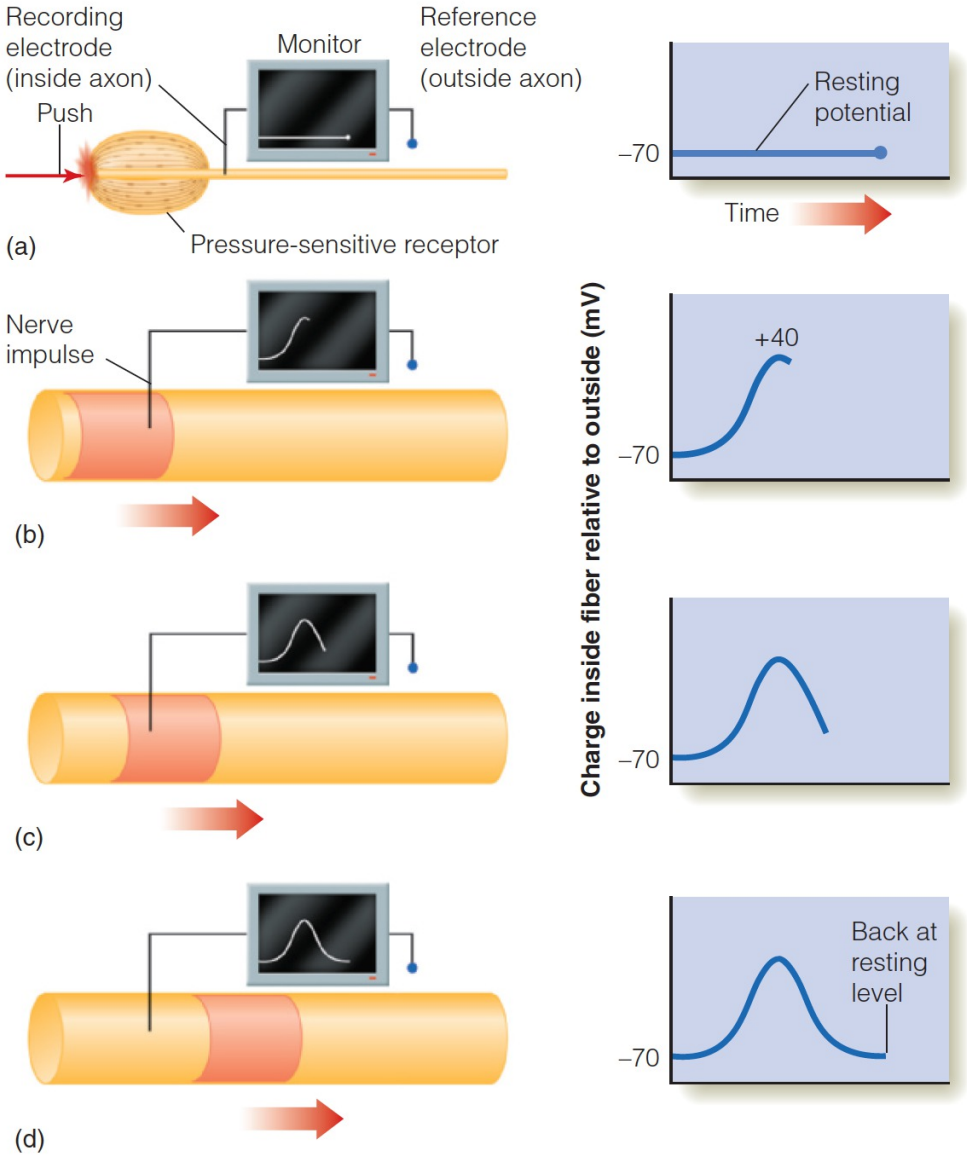
Receptor Neuron



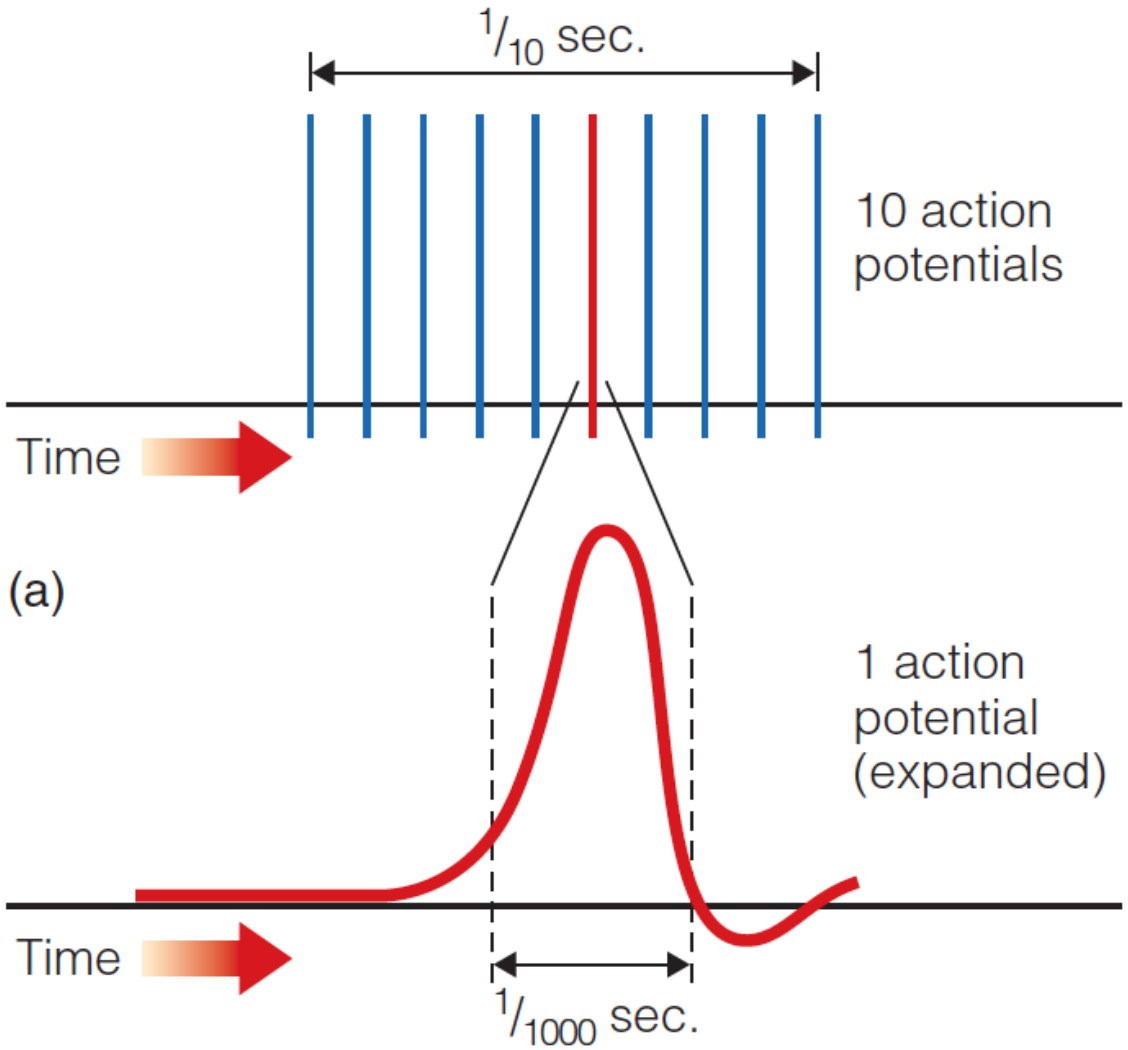
Transmission of Signals



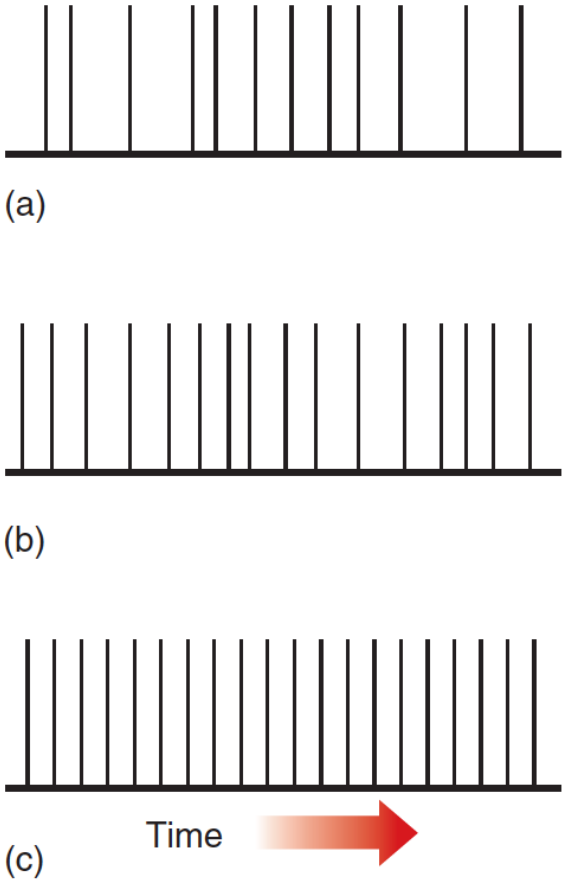
Recording Neural Activity



Sequence of Action Potentials



Strength of Signal



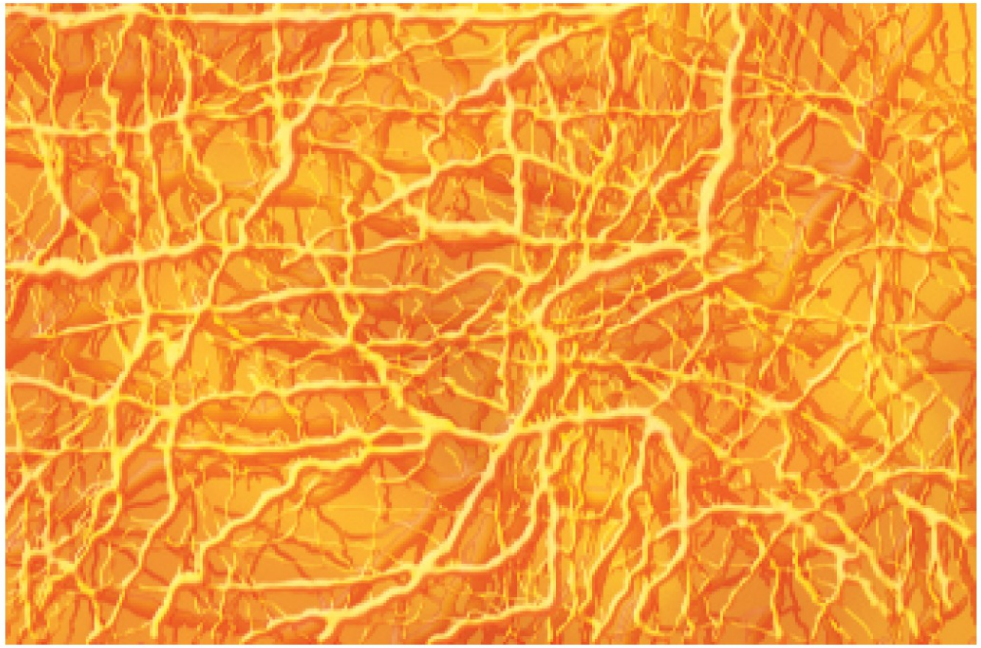
- Strength of the signal is encoded in frequency of action potentials
- Each action potential has some magnitude

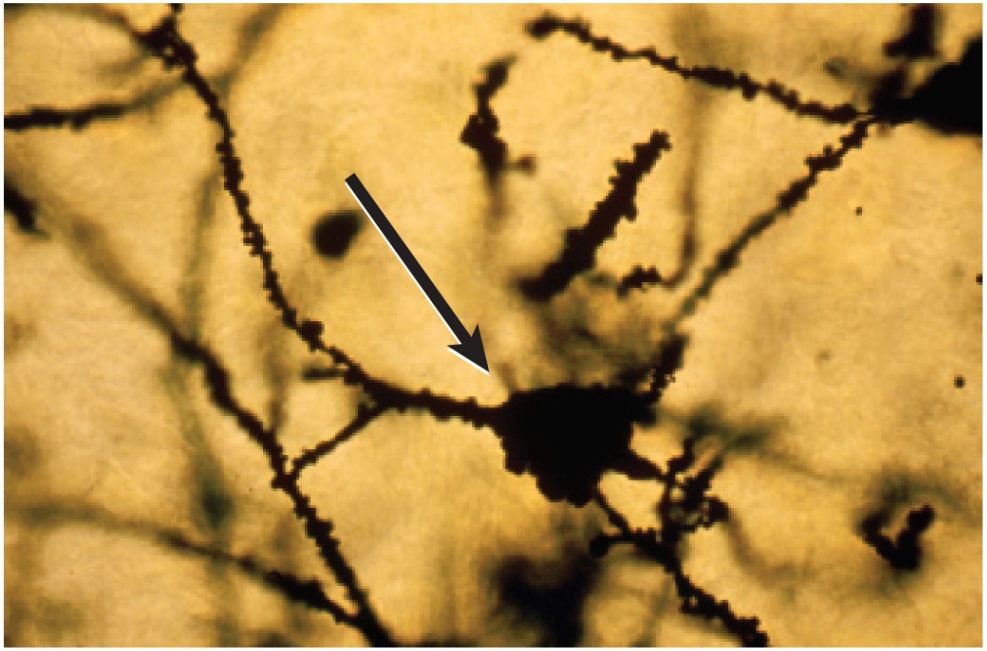
neural representation

Neural Representation

- Receptors identify very basic information
  - color at specific point in retina
  - pressure at specific point in skin
  - pain in part of an organ
- This information has to processed to higher level information

Brain Tissue

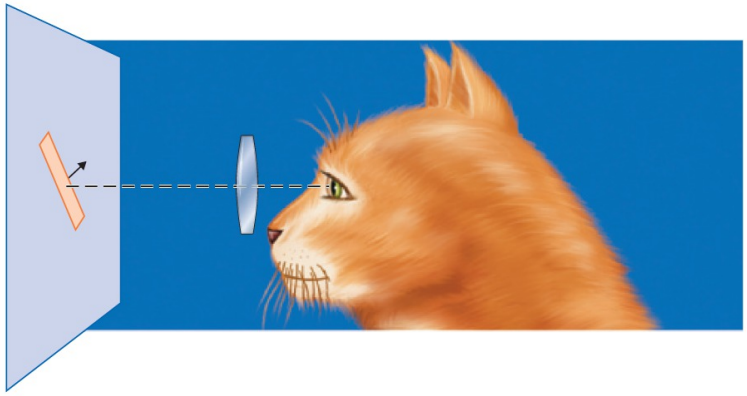




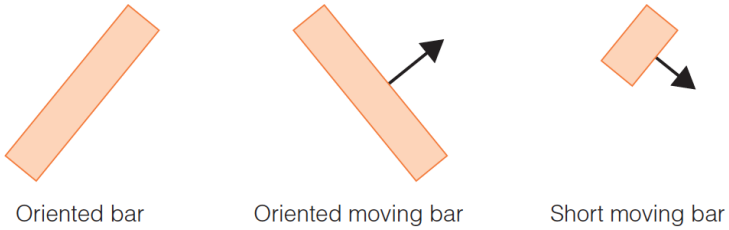
- Neurons in the brain are connected in complex ways
- Signals are processed from receptor neurons to other neurons over several stages
- But: it is wrong to view this as a strictly layered process

Probing One Neuron

- We can use electrons to probe any neuron in the brain
- We present a cat with different stimula

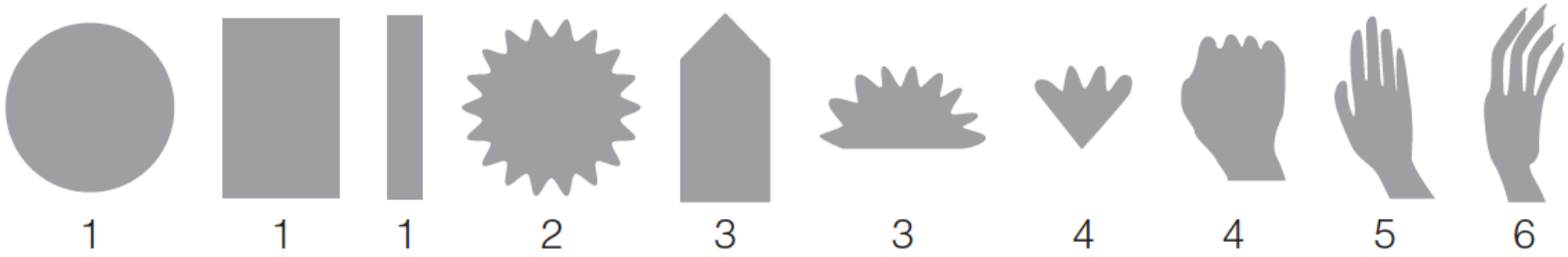


- Example shapes



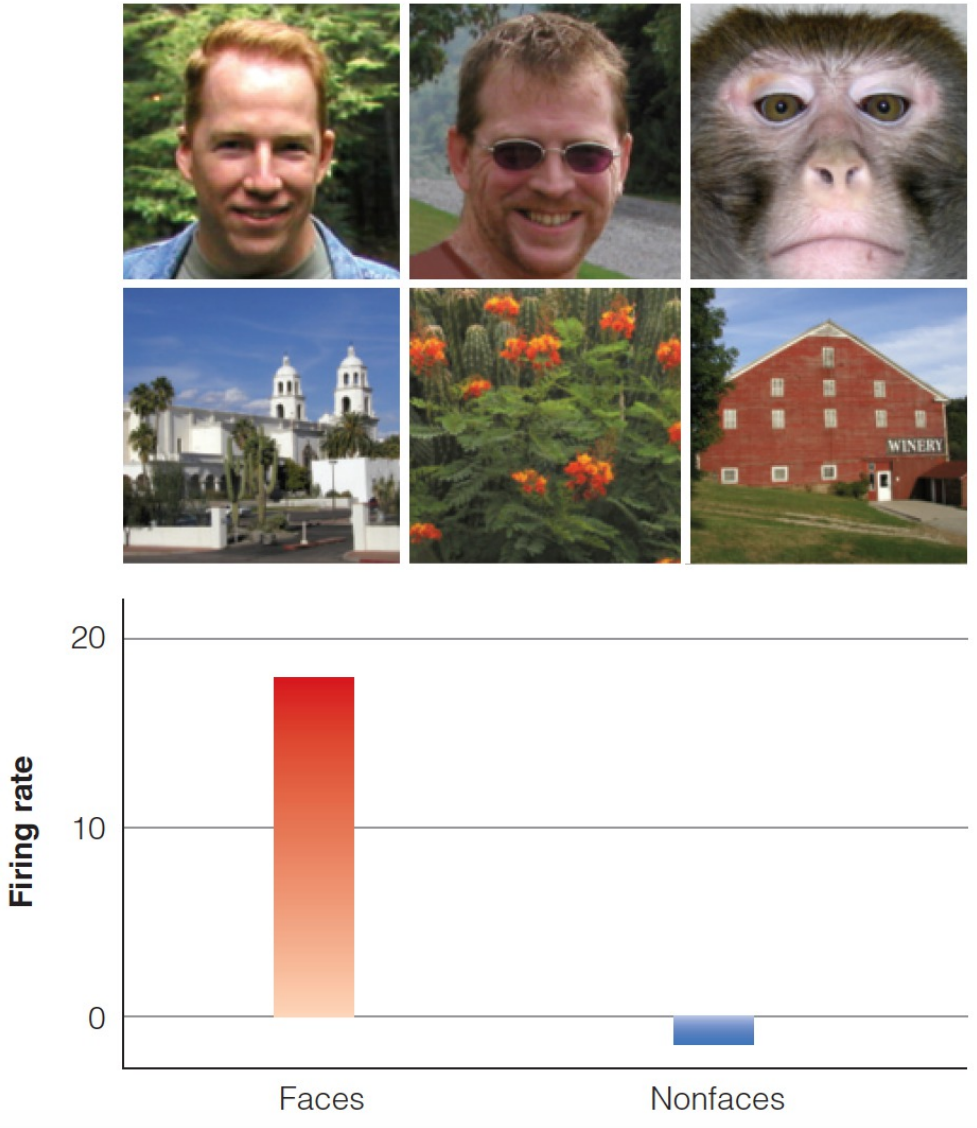
- Neuron is active when shape presented → part of processing pipeline for shape

Hand Recognition Neuron



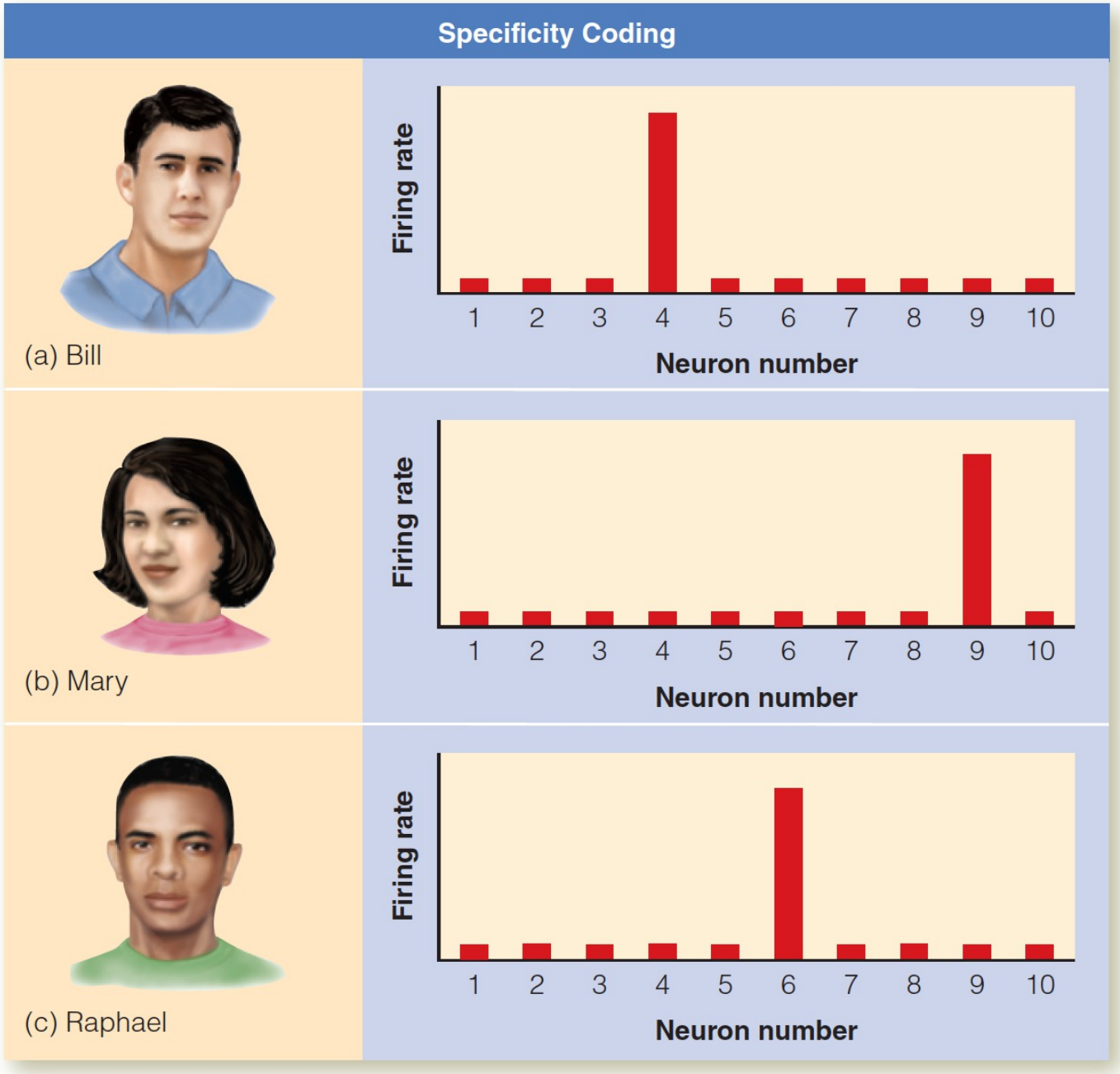
- Example: neuron in a monkey brain
- Shapes and strengths of neural activity shown
- Neuron most active when hand symbols are shown

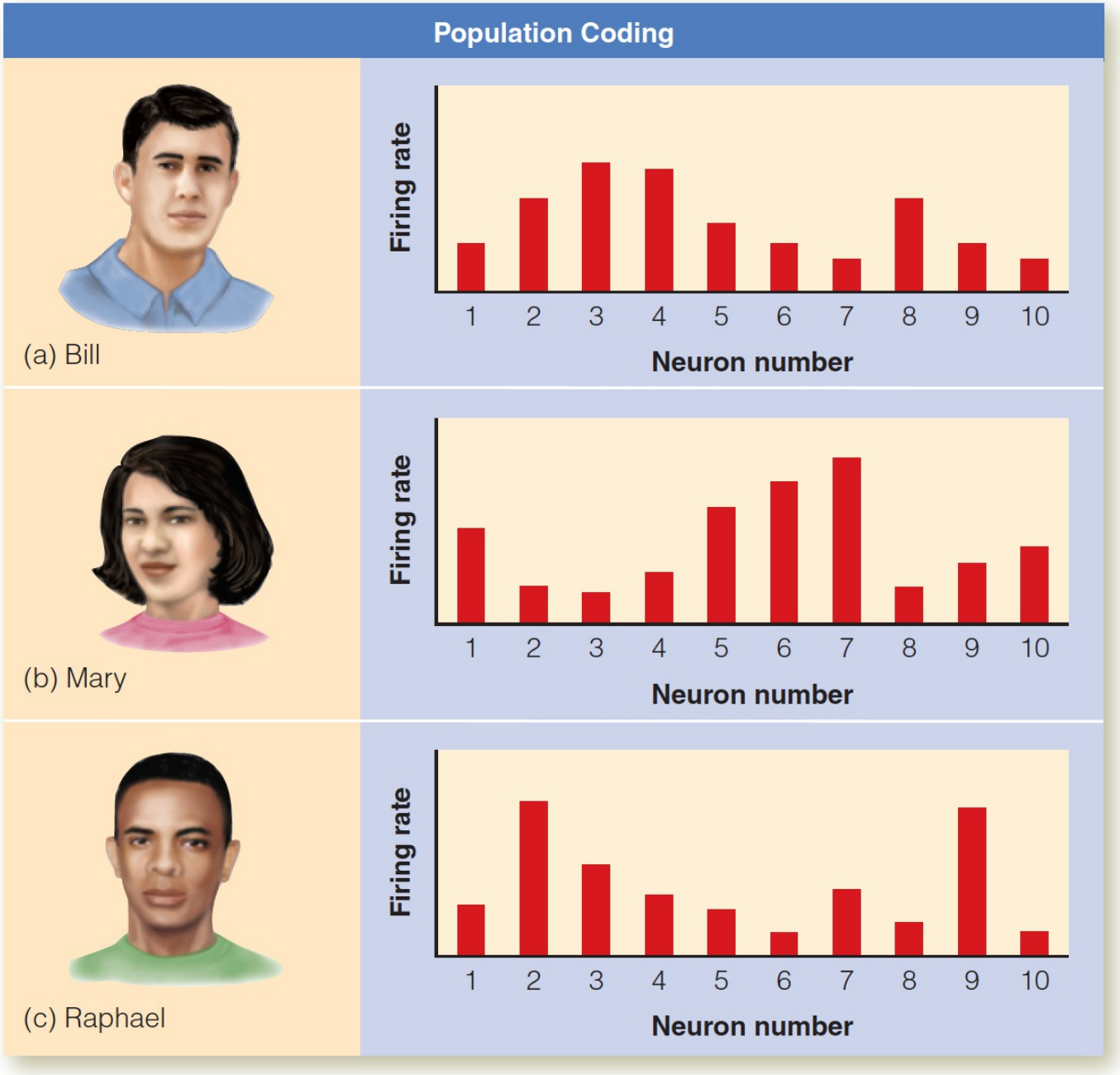
Face Recognition Neuron

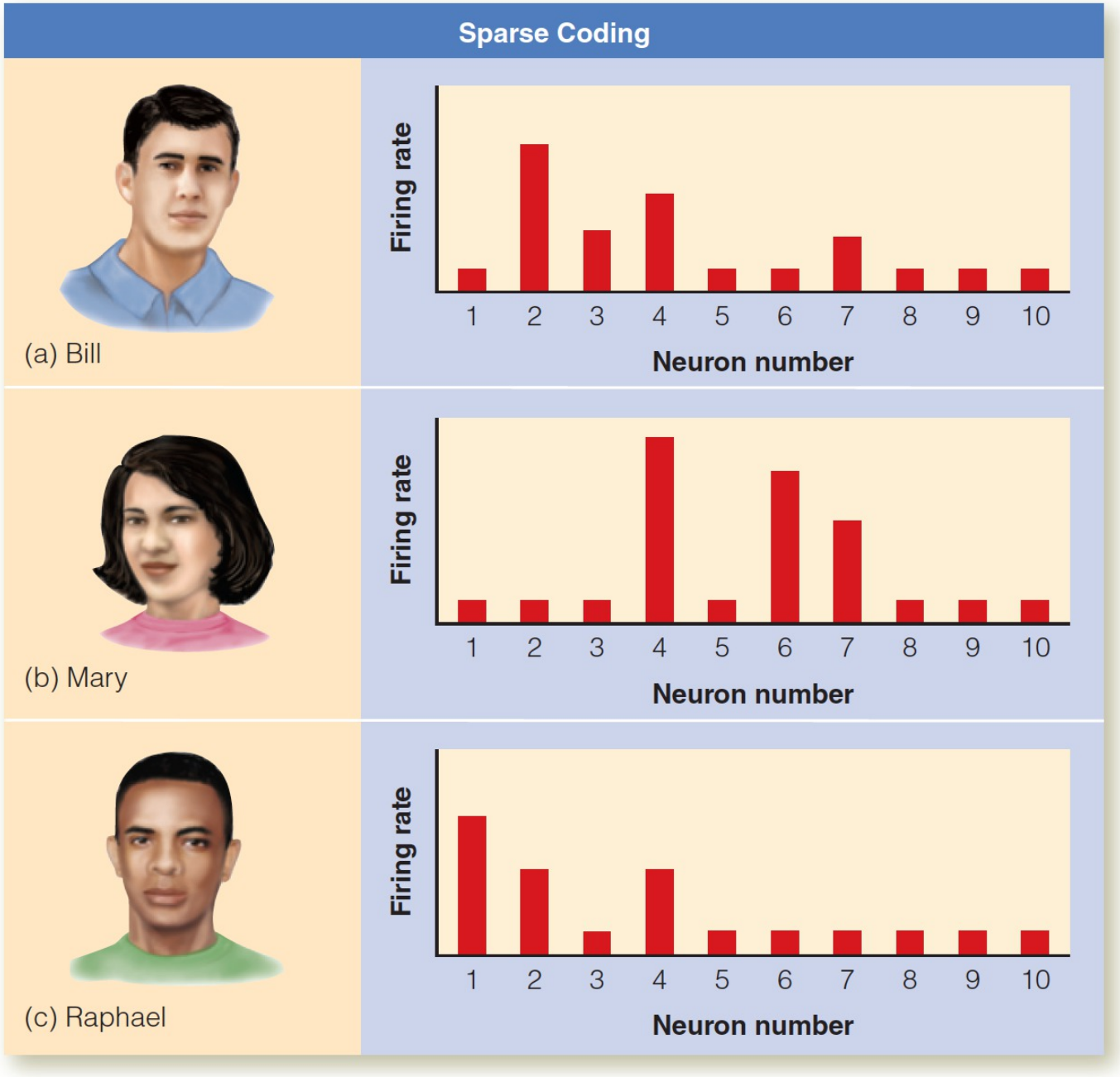


Sensory Coding

- Specific neurons may be involved in
  - detecting basic features
  - recognizing complex shapes
  - identifying class of objects
  - identifying known object / person
- Sensory coding: encode various characteristics of the environment
- Our examples so far suggest specificity coding


Specificity Coding
(a) Bill
Firing rate
1 2 3 4 5 6 7 8 9 10
Neuron number
(b) Mary
Firing rate
1 2 3 4 5 6 7 8 9 10
Neuron number
(c) Raphael
Firing rate
1 2 3 4 5 6 7 8 9 10
Neuron number


Population Coding
(a) Bill
Firing rate
1 2 3 4 5 6 7 8 9 10
Neuron number
(b) Mary
Firing rate
1 2 3 4 5 6 7 8 9 10
Neuron number
(c) Raphael
Firing rate
1 2 3 4 5 6 7 8 9 10
Neuron number

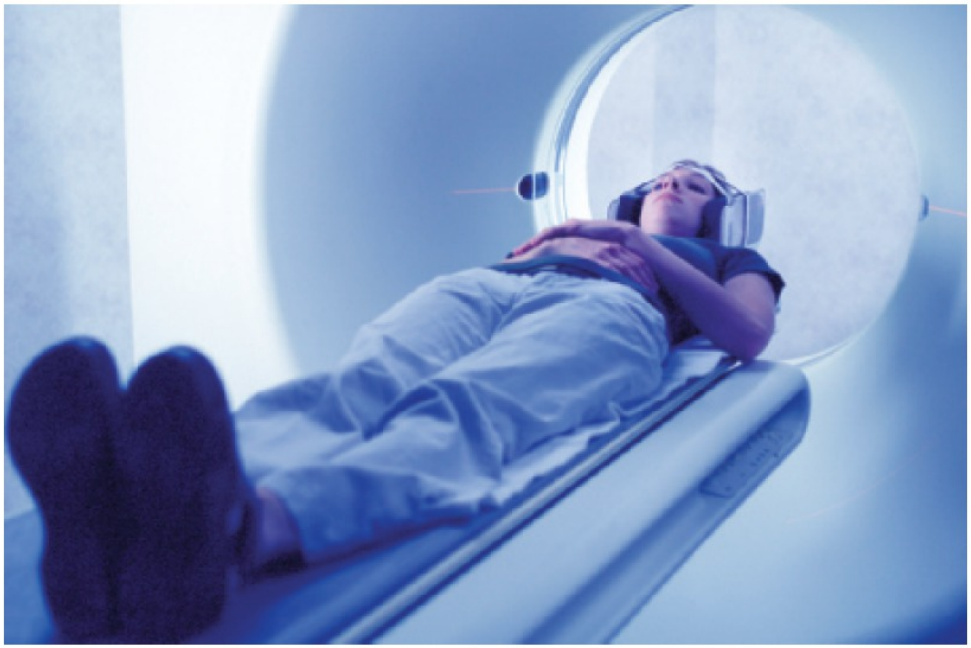

Sparse Coding
(a) Bill
Firing rate
1 2 3 4 5 6 7 8 9 10
Neuron number
(b) Mary
Firing rate
1 2 3 4 5 6 7 8 9 10
Neuron number
(c) Raphael
Firing rate
1 2 3 4 5 6 7 8 9 10
Neuron number

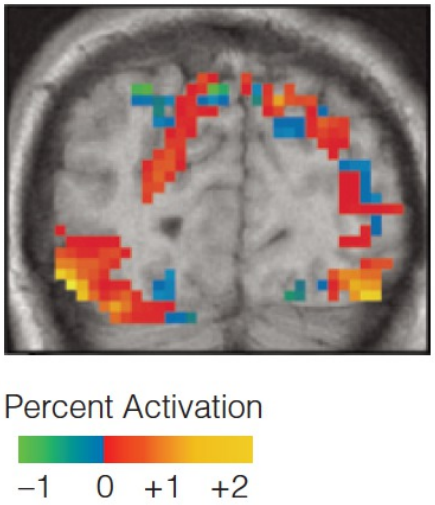
Organization of the Brain

- Different areas of the brain deal with different brain functions
- Learning from brain injuries: double dissociation
  - person A has brain injury and cannot do X, but still do Y
  - person B has brain injury and cannot do Y, but still do X
  - e.g., X = recognize faces, Y = recognize objects

  $\rightarrow$ X and Y operate independently from each other
- Learning from brain imaging

MRI Scans of Brain Activity



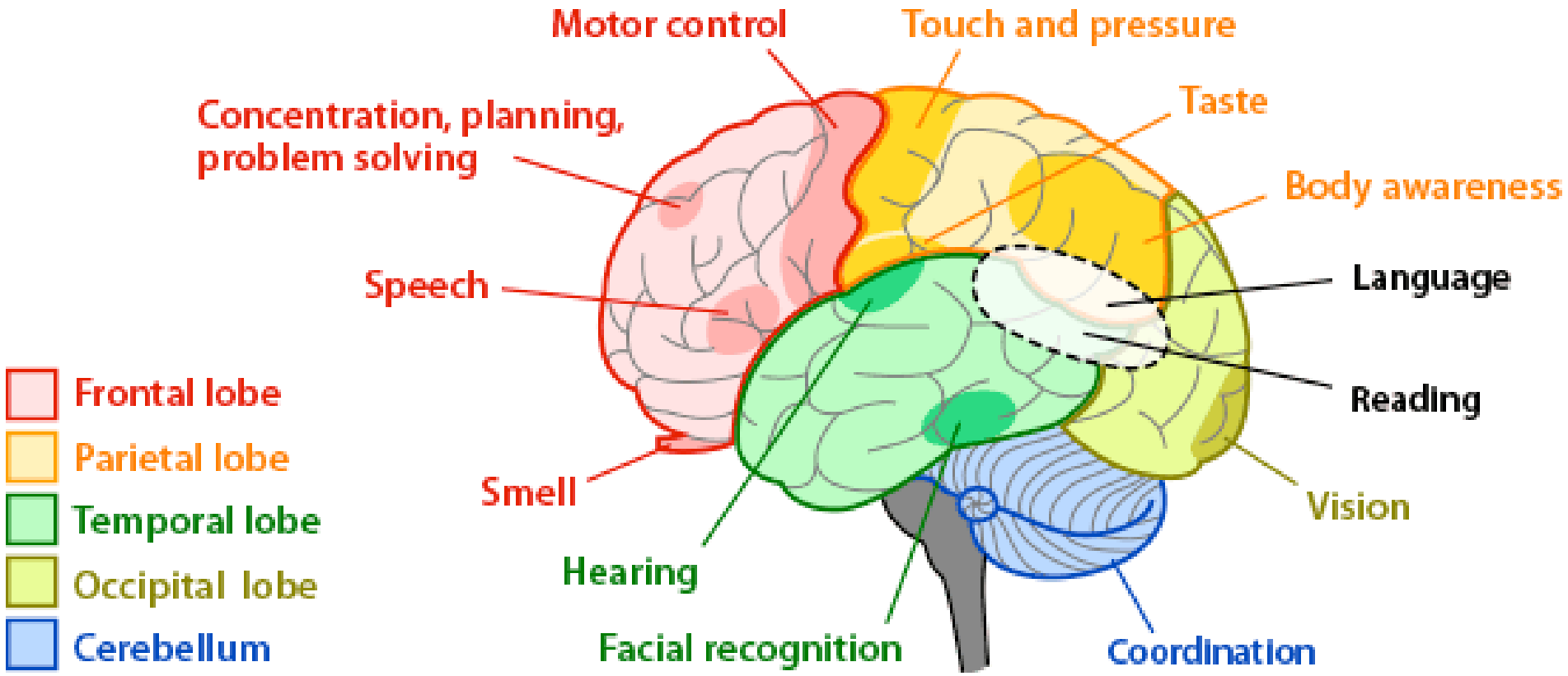


- Measure brain activity in a specific voxel during specific cognitive task
- Contrast with baseline activity
- Quality (some numbers from the web)
  - as of 2011, best spatial resolution $0.3mm^3$, about 270-2700 neurons per voxel
  - functional MRI: 0.5*0.5*1.0mm, about 2500-25000 neurons per voxel

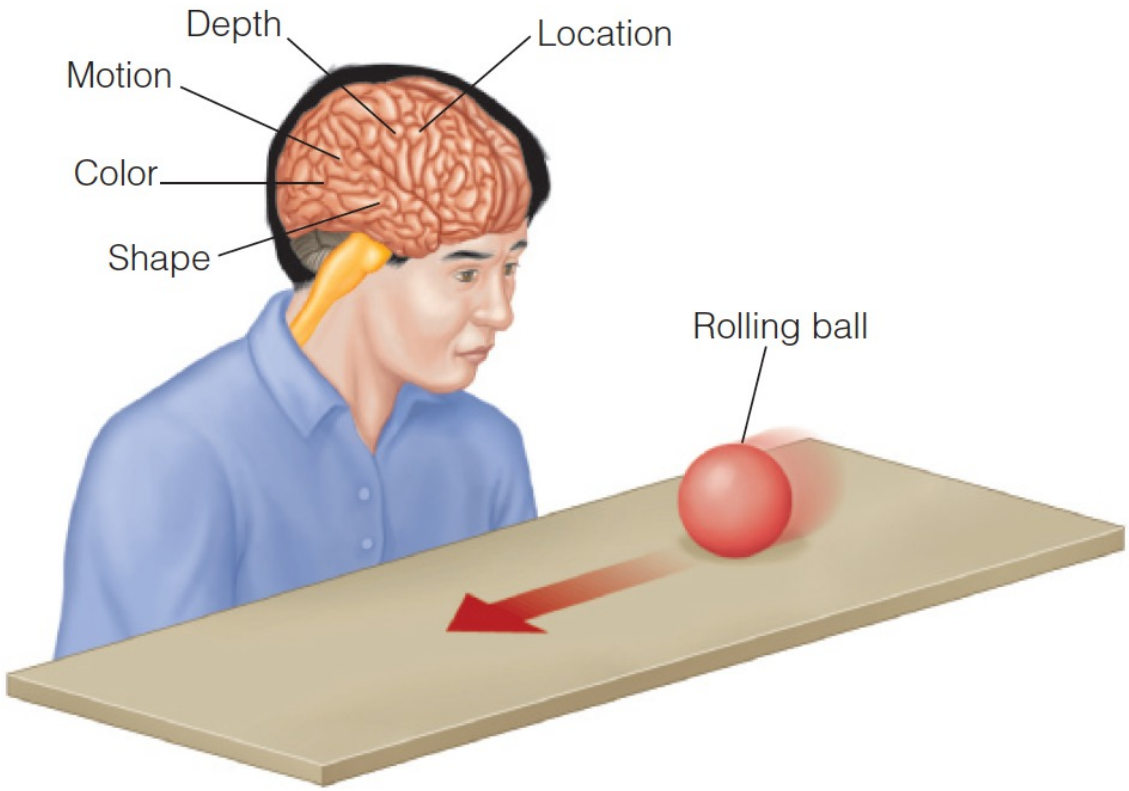
Functional magnetic resonance imaging (fMRI)

- Brain activity (neurons firing) $\rightarrow$ increased blood flow
- Hemoglobin in blood contains ferrous (iron) molecule with magnetic properties
- Brain activity $\rightarrow$ hemoglobin loses some oxygen, becomes more magnetic
- fMRI detects changes in magnetic fields
- Similar to MRI but uses the change in magnetization as basic measure

Regions in the Brain



But it's Complicated



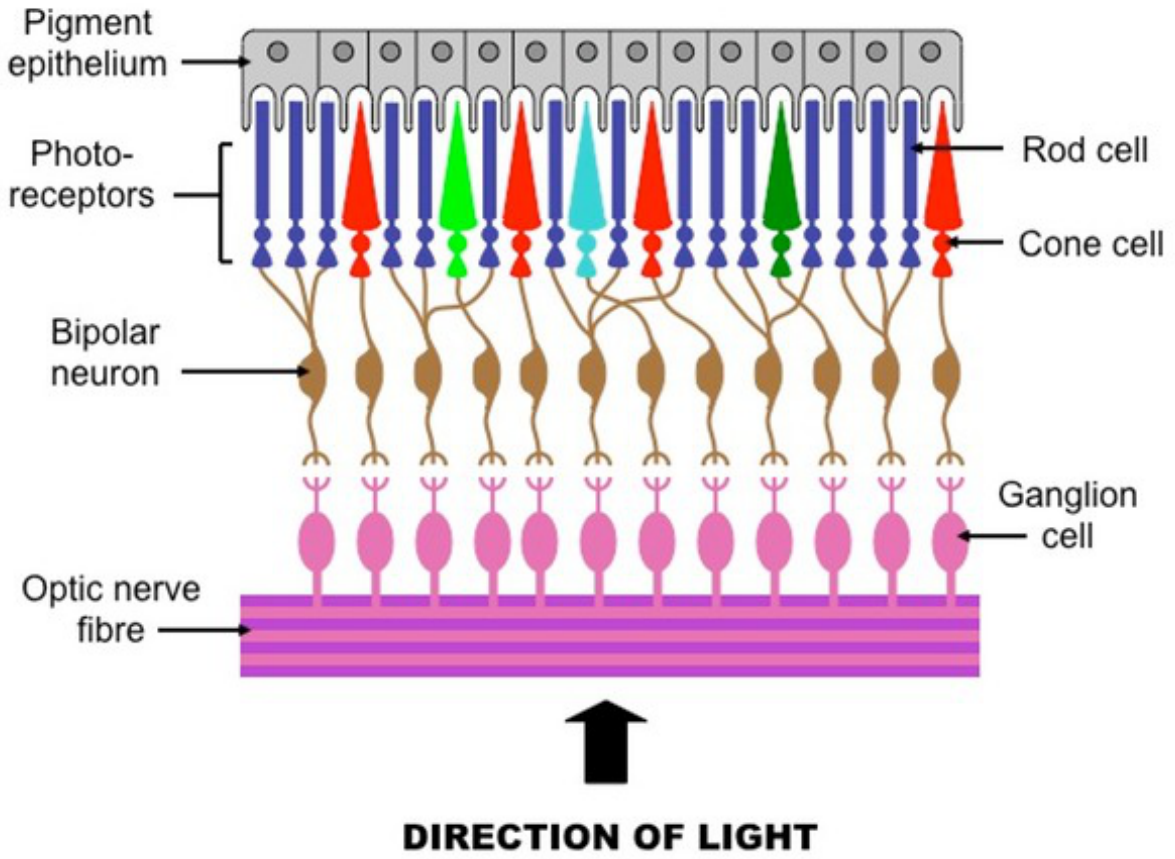
- Observing a rolling ball
- Many different cognitive processes → many brain regions involved
- All this seems very effortless to us

Summary

- We can easily study one individual neuron
- We can easily study regions of the brain
- But: tracking down exact processing pipelines is hard
- Human brain has about 100 billion neurons
  $\rightarrow$ it would be hard even if we could record each individual neuron

visual perception

Receptors



- Photo-receptors in the eye detect intensity of light (red/green/blue)

Primal Visual Cortex

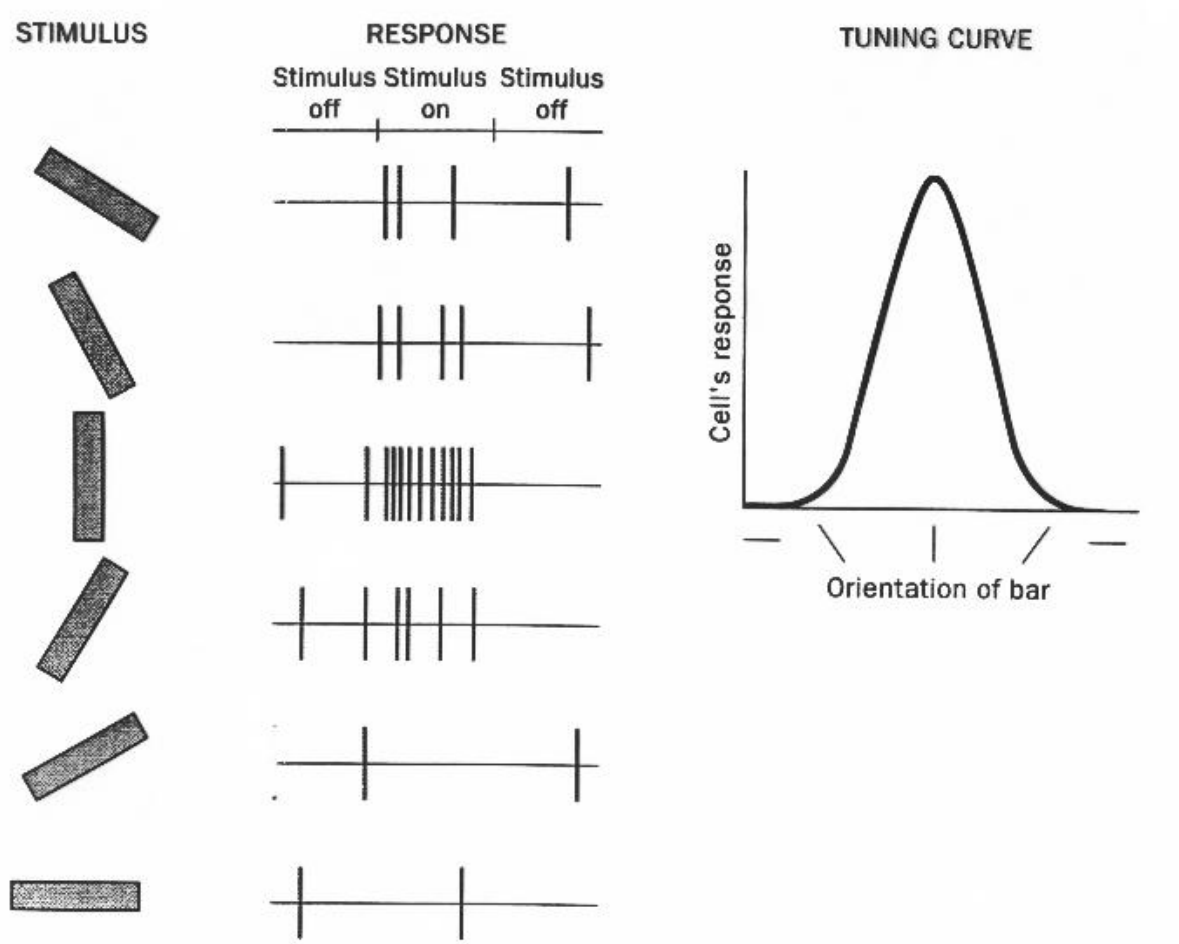
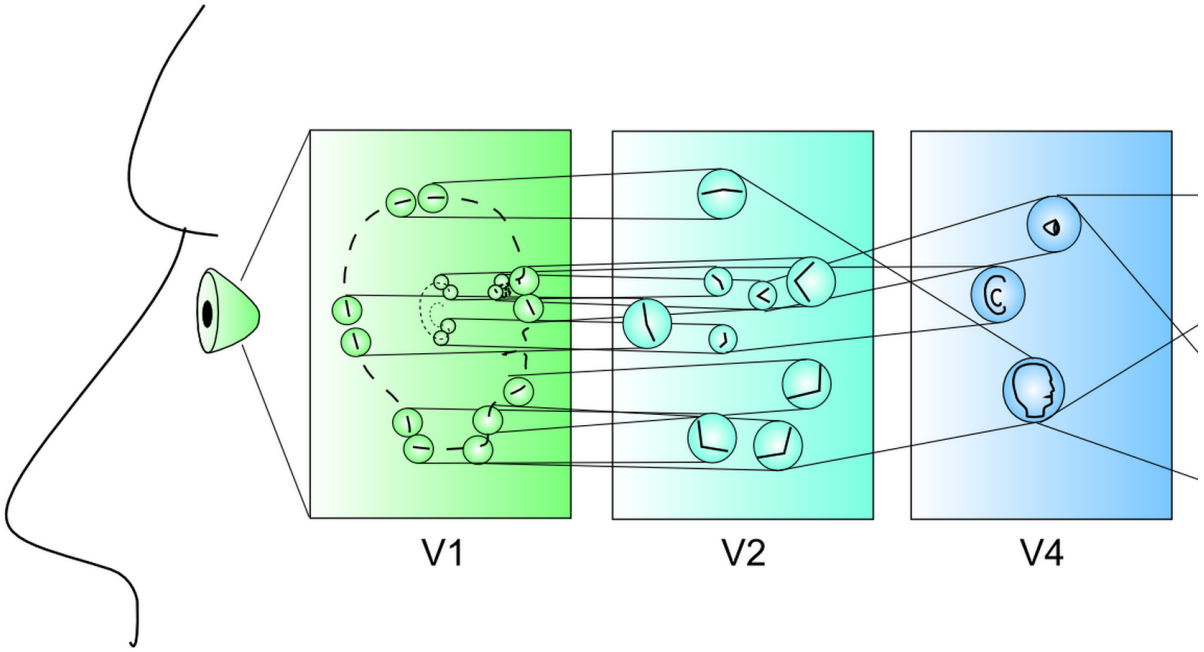


FIGURE 4.8 Response of a single cortical cell to bars presented at various orientations.

- Detecting lines, especially horizontal and vertical lines

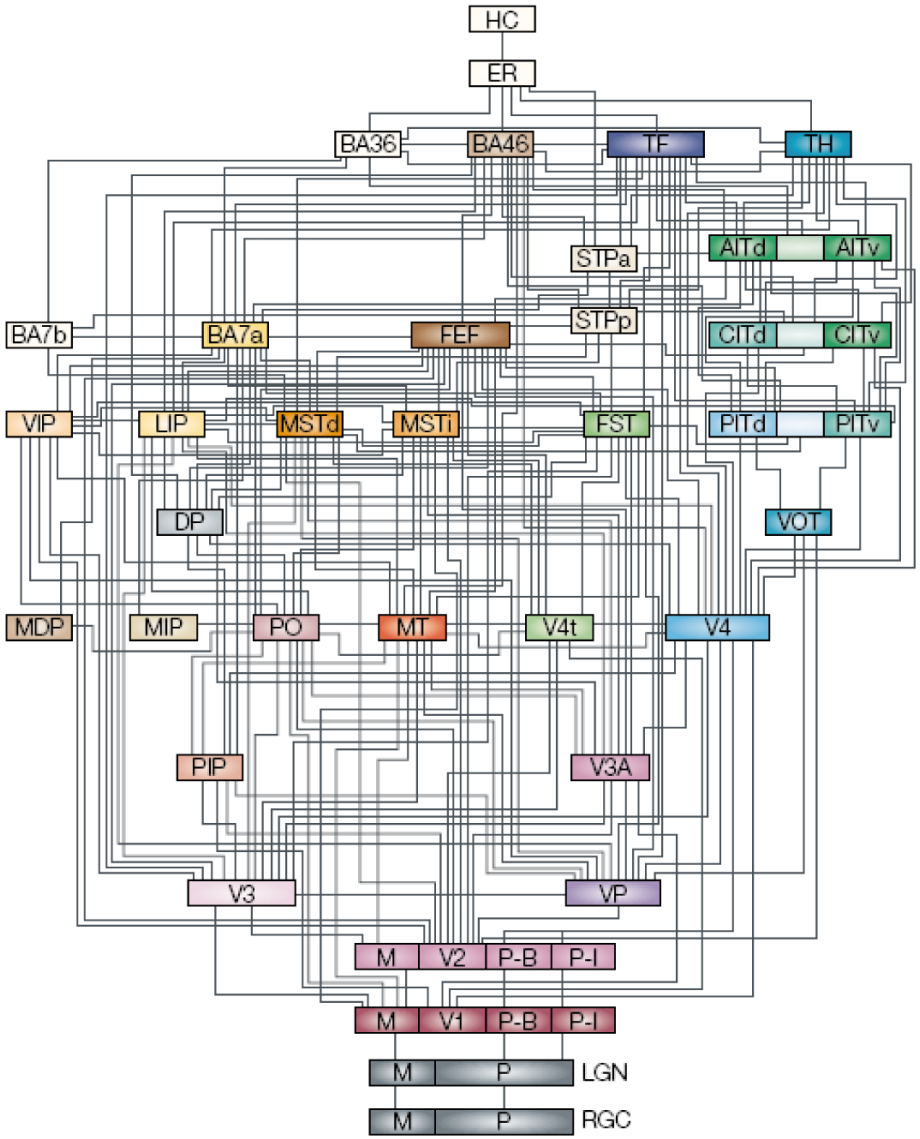
Secondary Visual Cortex

- Encodes combinations of edge detectors
  - intersections and junctions
  - 3D depth selectivity
  - basic textures
- Simple visual characteristics
  - orientation
  - spatial frequency
  - size
  - color
  - shape

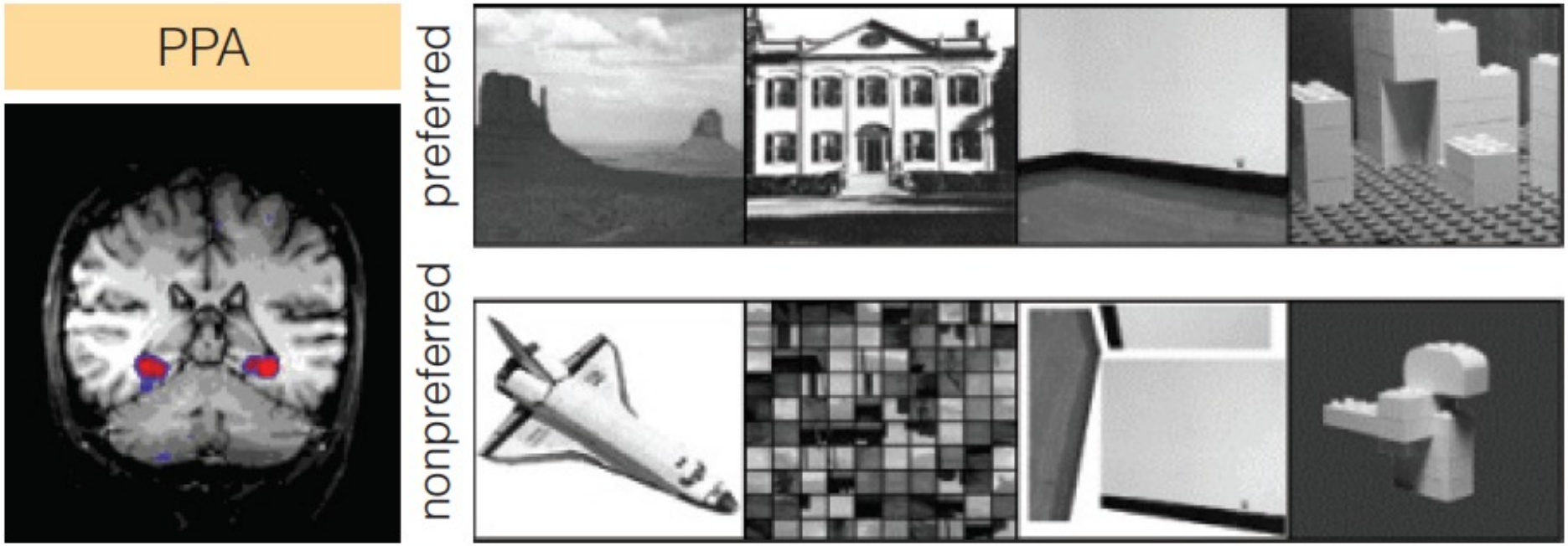


- Start of invariant object recognition: recognize an object regardless of where it appears in the visual field

Visual Pathways

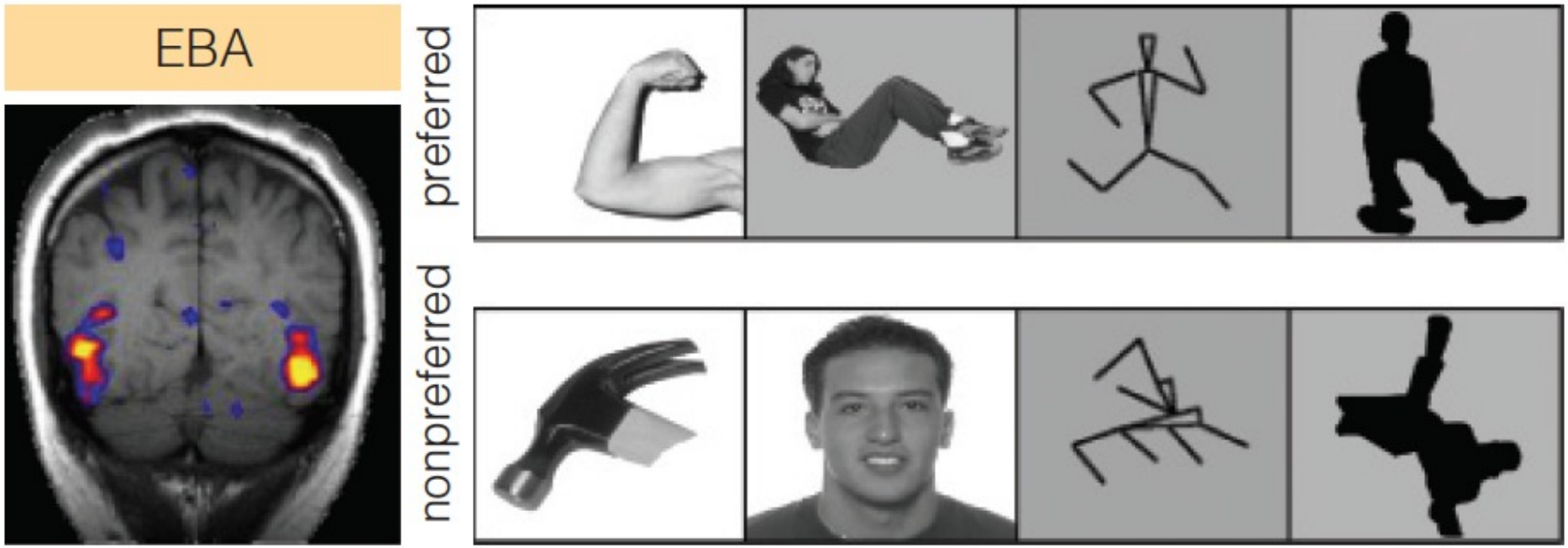


Deeper Processing: Places



- Parahippocampal place area (PPA)
  activated by places (top) but not other stimuli (bottom).

Deeper Processing: Bodies



- Extrastriate body area (EBA)
  activated by bodies (top) but not other stimuli (bottom).

Viewpoint Invariance

- We have to recognize an object when seen from different angles
- Interesting finding: time to match 3d objects related to relative angle ($\rightarrow$ we mentally turn the object)

Top-Down Processing

- What is in the red circle?

Top-Down Processing

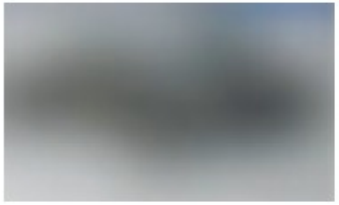
- What is in the red circle?

Top-Down Processing

- What is in the red circles?

Top-Down Processing

- Same blob in all the pictures:

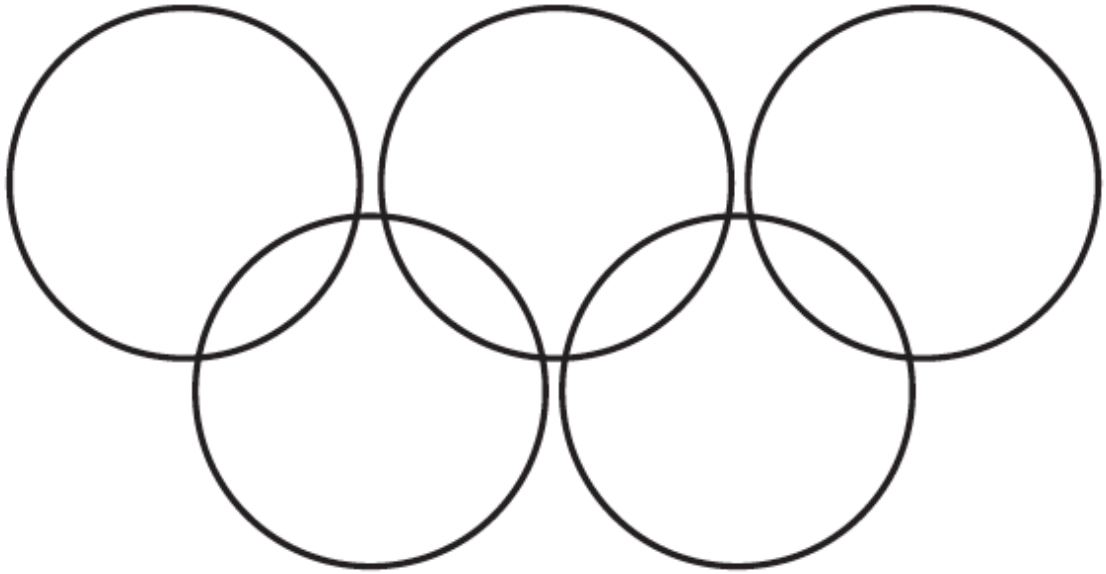


Principles of Object Perception: Good Continuation

- We assume that the rope continues when hidden

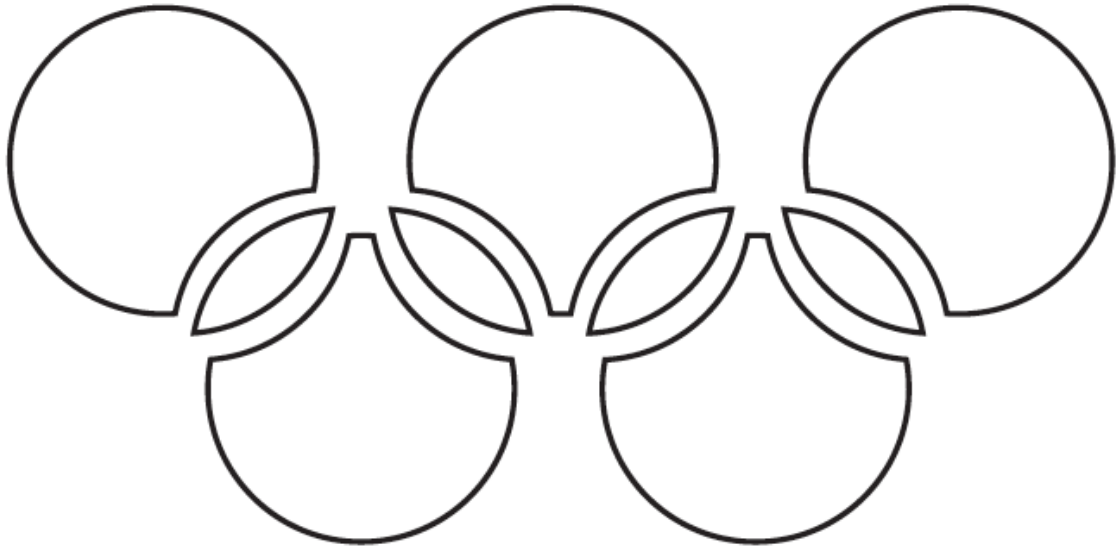
$\Rightarrow$ Perception as a single strand

Principles of Object Perception: Prägnanz



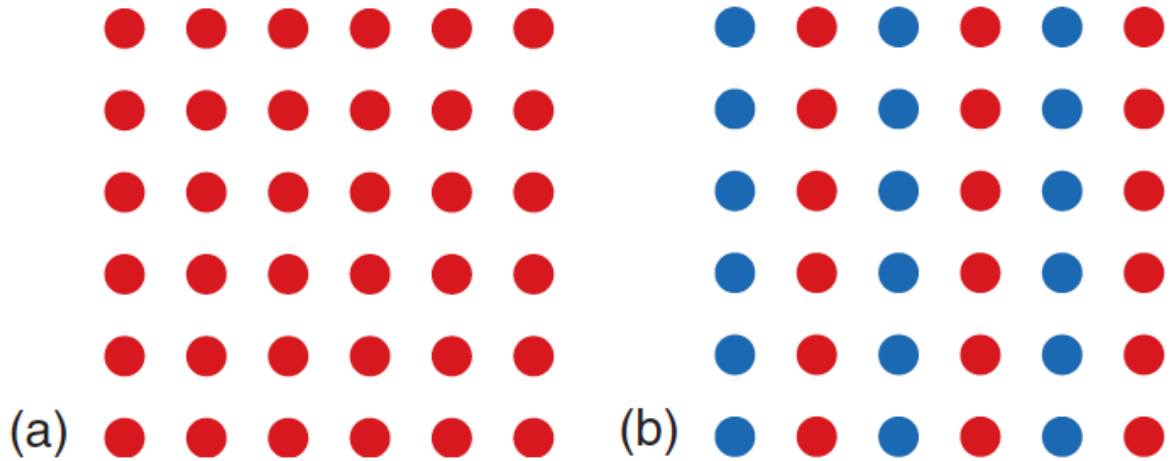
- Prägnanz = Conciseness, perception of image using simple shapes
- Figure seen as 5 circles

Principles of Object Perception: Prägnanz



- Alternative interpretation: possible, but too complex

Principles of Object Perception: Similarity



- Similarity = grouping similar items together
- (a) is perceived as rows or columns
- (b) is viewed as columns

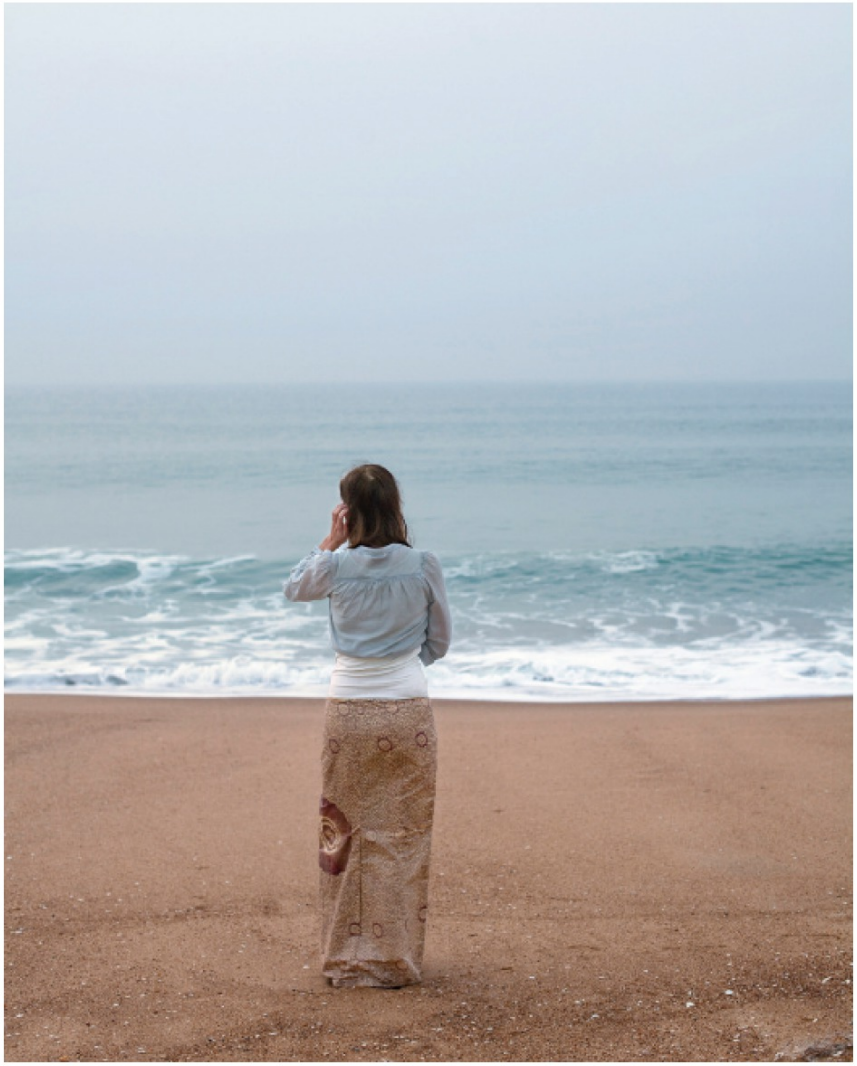
Principles of Object Perception: Similarity

- Similarity of colors

  → initially grouped together

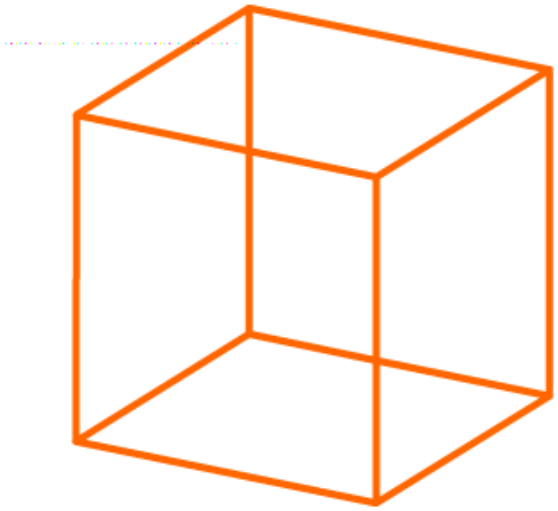
- More cogntive processing

  → woman in front of beach
  more plausible interpretation



Bayesian Inference

- In early processing stages, various possible interpretations considered
- Parallel processing of features, interpretations of elements of a scene
- Only distinct interpretations reach the consciousness (more on that later)

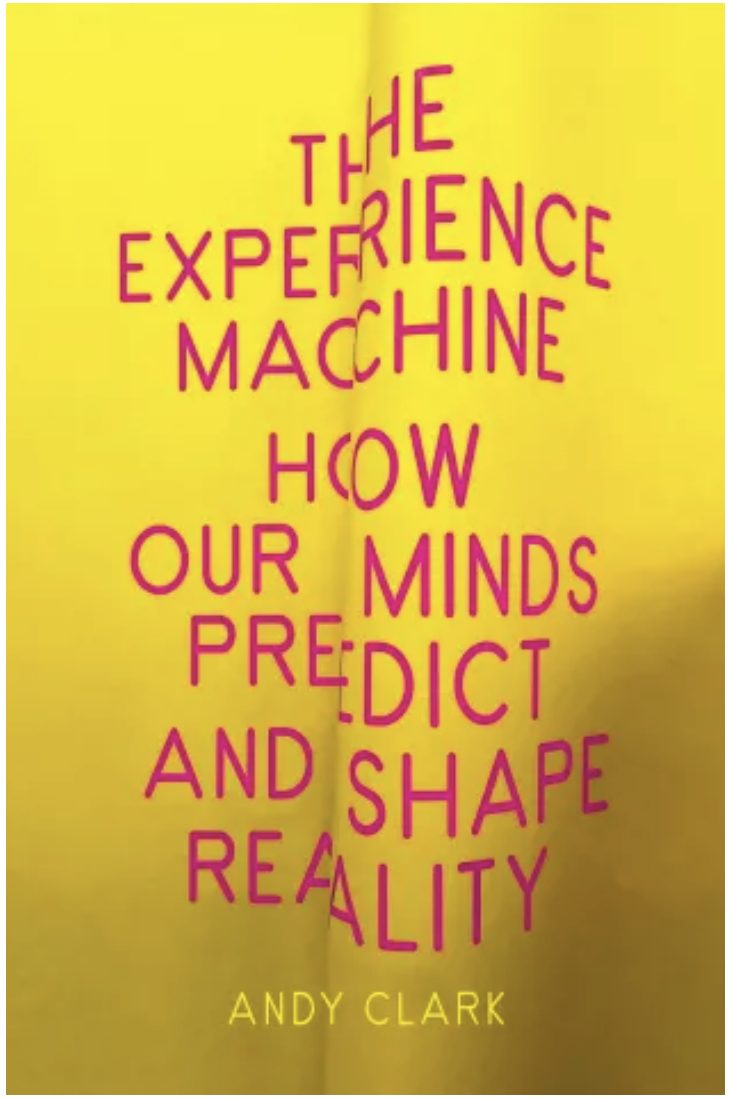


- Classic example: switch between two interpretations (intentionally or not)

brain as prediction machine

Prediction, not Perception

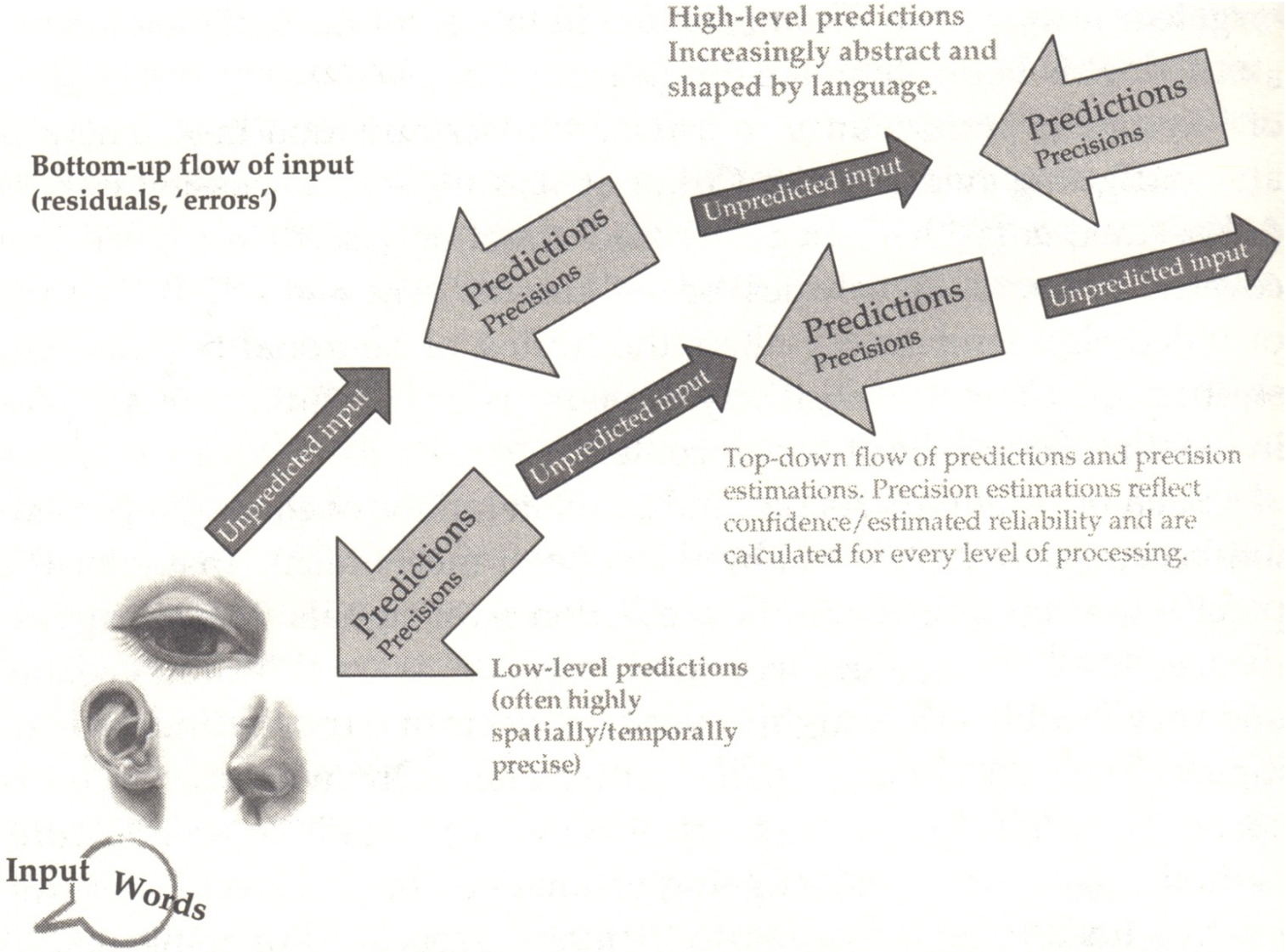
- Brain spends more energy on prediction
- If perception matches
  $\Rightarrow$ keep going
- If perception does not match
  $\Rightarrow$ correction needed (surprise)



Example

- Reading left to right: A B C
- Reading top-down: 12 13 14
- No confusion: perception matches prediction

Prediction, Residual Error Feedback



Implications

- Matches unsupervised training setups in machine learning

  for instance, large language models:
  just predicting next words leads to a powerful model

- Dreams: At night no feedback, prediction keeps going

learning

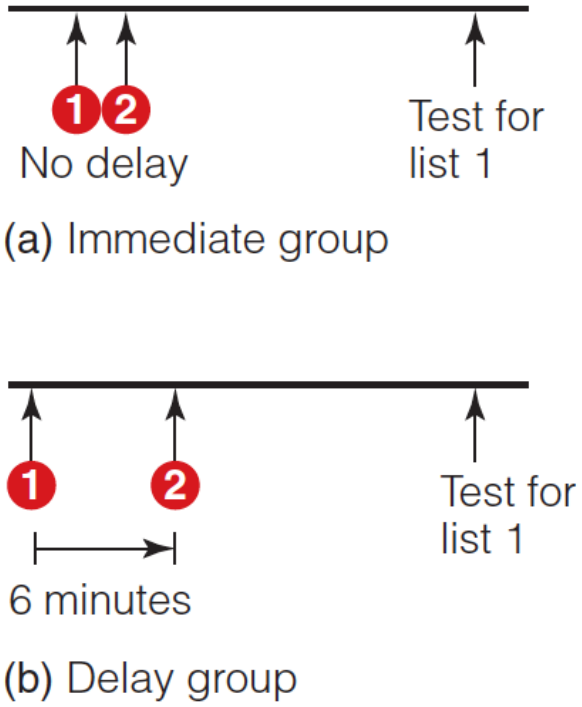
Consolidation

- Remembering takes time

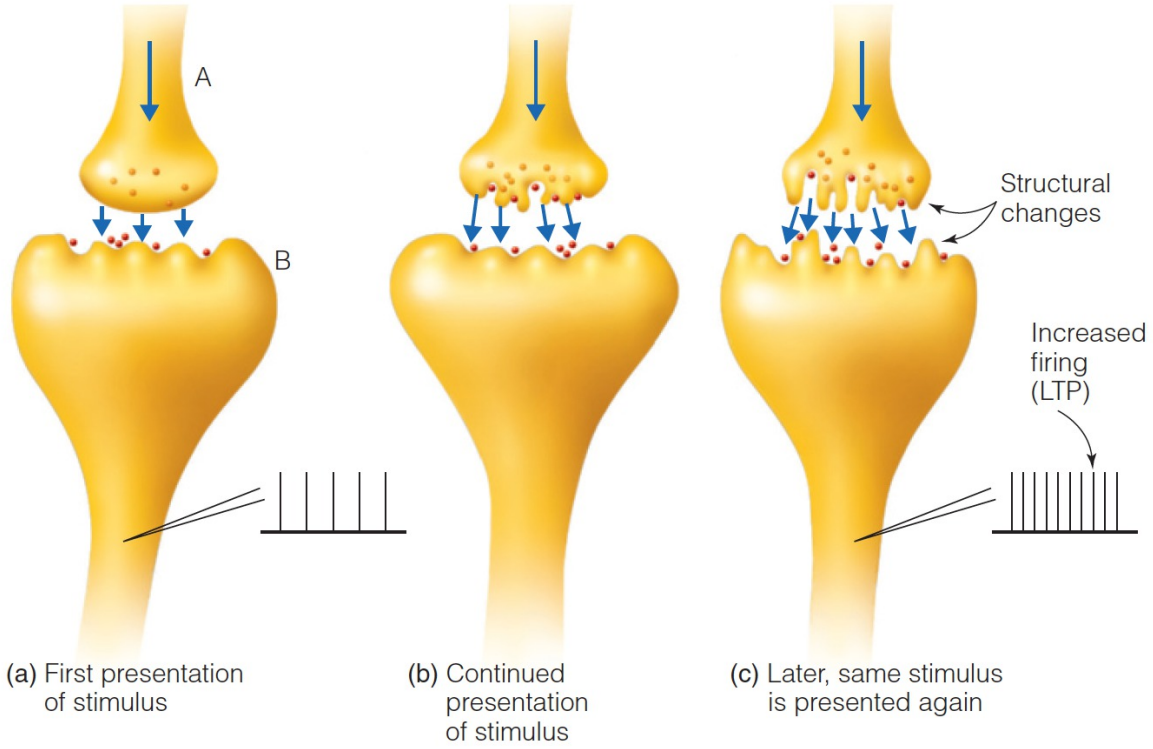
- Experiment (Müller and Pilzecker, 1900)
  - step 1: a list of items to memorize
  - condition A: no pause
  - condition B: 6 minute pause
  - step 2: second list

⇒ Condition B: Much better recollection (46% vs. 28%)

- Consolidation: process to transform new memories from a fragile state into permanent state



Synaptic Consolidation

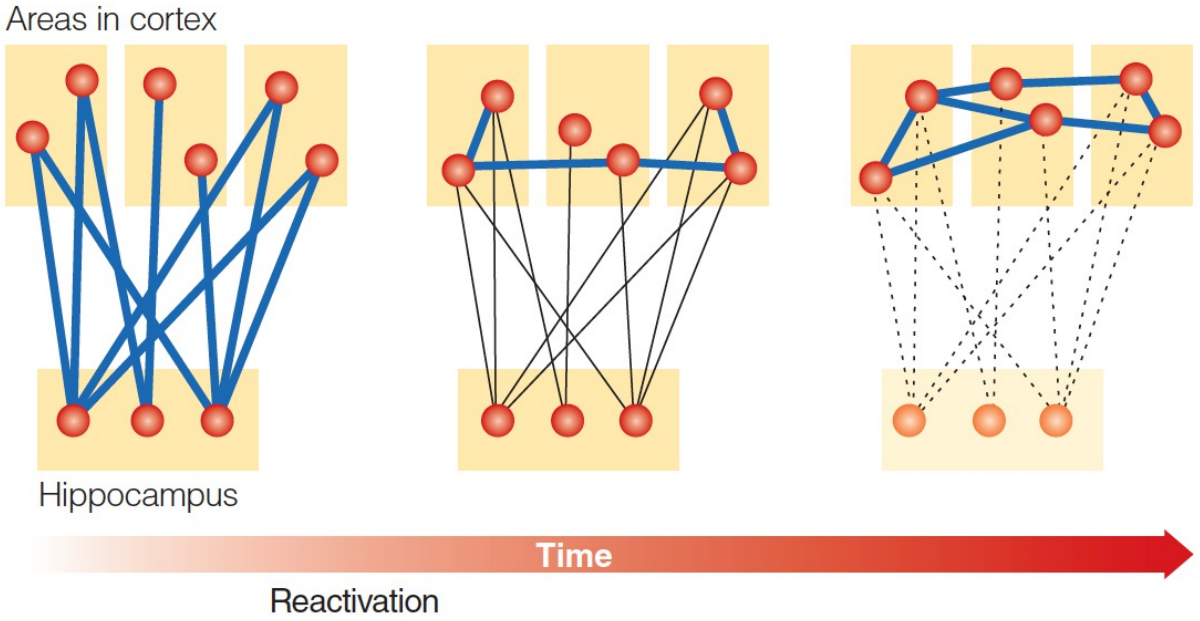


- Recall
  - signals are transmitted at synapse
  - strength of synapse = importance of input

- Repetition of stimulus

  $\Rightarrow$ strengthening of connection (”long term potentiation”)

Systems Consolidation



- Initial experience activates neurons in the hippocampus (sensory memory)
- Reactivation
  - hippocampus replays neural activity
  - connections in cortex are formed
  - connections to original memory in hippocampus are lost

Reconsolidation

- When a memory is recalled, it becomes *fragile*

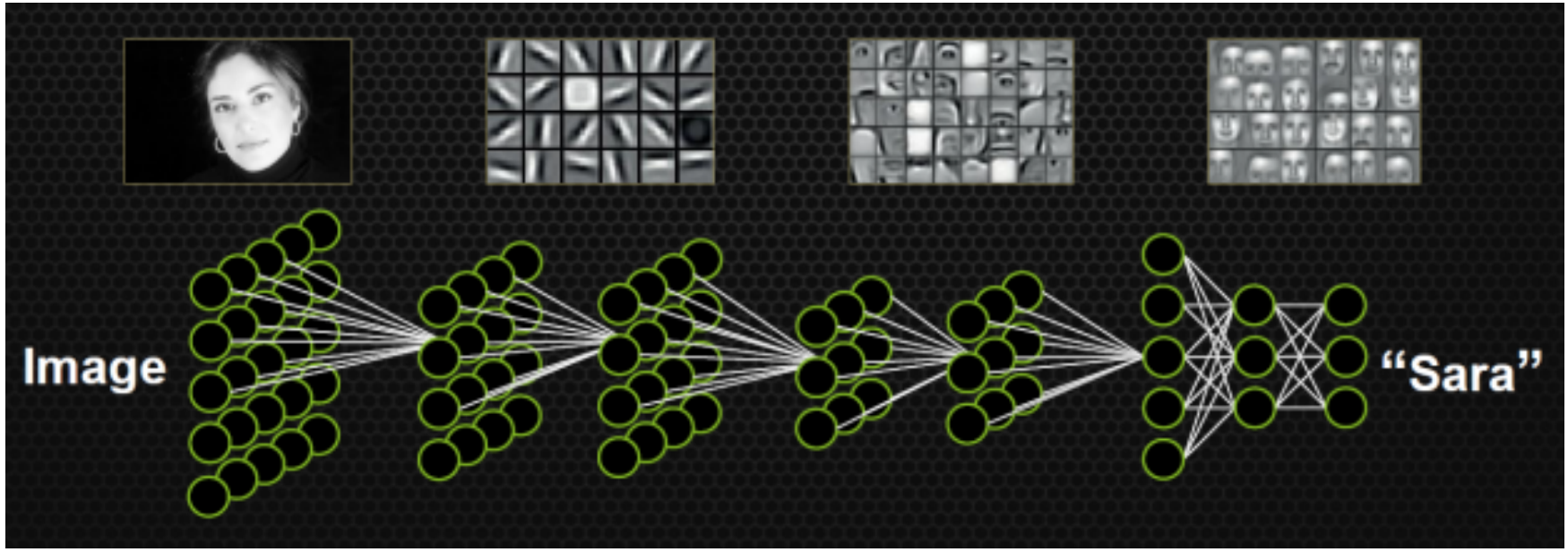
$\Rightarrow$ more likely to be changed

- Experiment (Hupach et al., 2007)
  - day 1: learn a list of words
  - day 2, condition A: asked to remember training sesssion, learn new list
  - day 2, condition B: just asked to learn new list of words
  - day 3: asked to recall the list from day 1

$\Rightarrow$ Condition A: Worse recollection, mistakenly recalled words from data 2

Artificial Neural Networks

- Neuroscience inspired research in artificial neural networks
- Latest trend: deep neural networks (many layers)
- Example: image classification



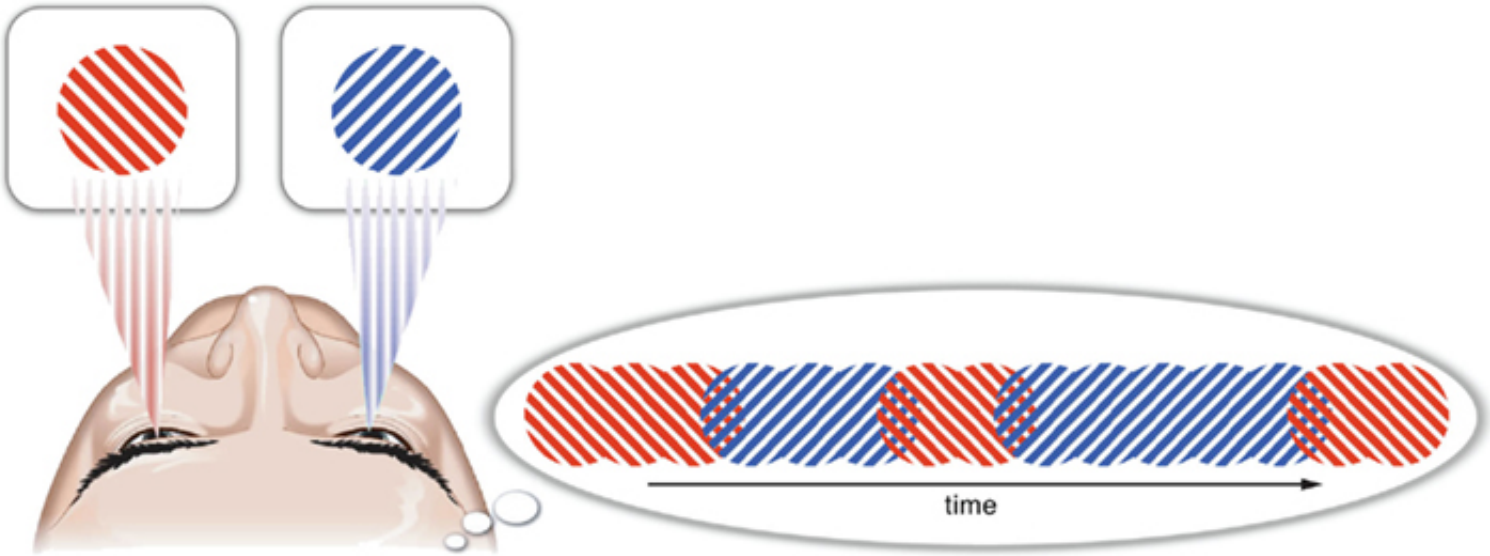
- More on that in future lectures...

research of consciousness

Consciousness

- Multiple meanings of "consciousness"
  - vigilance = state of wakefulness
  - attention = focusing mental resources to task
  - conscious access = information enters awareness and becomes reportable
- Currently increased research into "conscious access"
- Conscious access can be detected in patterns of brain activity

Single Interpretations



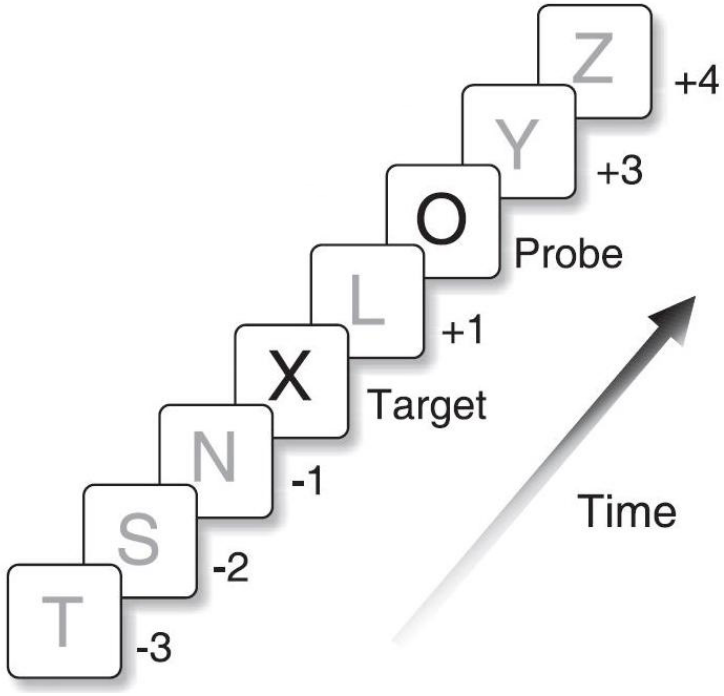
- Each eye is shown different image
- Conscious perception is either the left-eye image, or right-eye image
- Not a merged image!

Attentional Blink

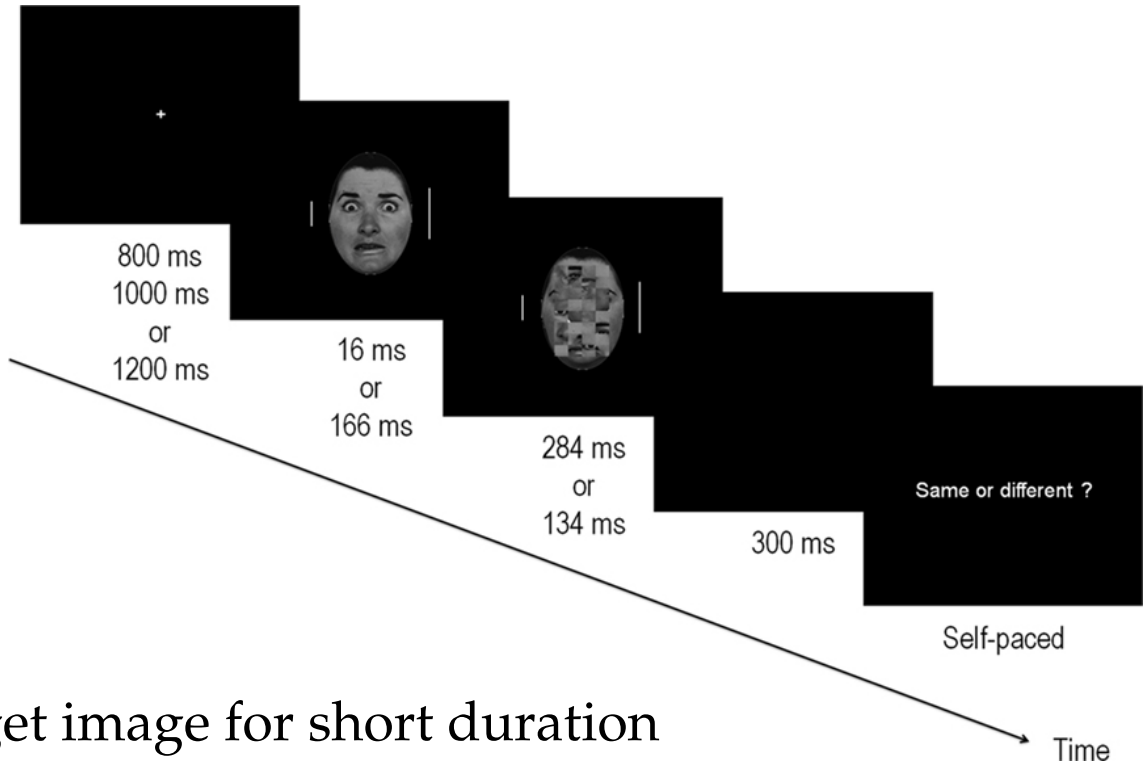
- Perception experiment
  - showing sequence letters (100ms each)
  - ask subject to remember letters **x** and o
  - if two target letters follow too closely, only first one is remembered

⇒ Conscious processing is busy with first letter

- Brain imagining shows that second letter is processed deep into visual system



Masking Image



- Showing a target image for short duration
- Immediately followed by a masking image
- If target image is shown < 50ms, it is not consciously perceived
- Note: In isolation much shorter exposure is sufficient

$\Rightarrow$ It takes time for the consciousness to process information processing can be overwritten by new information

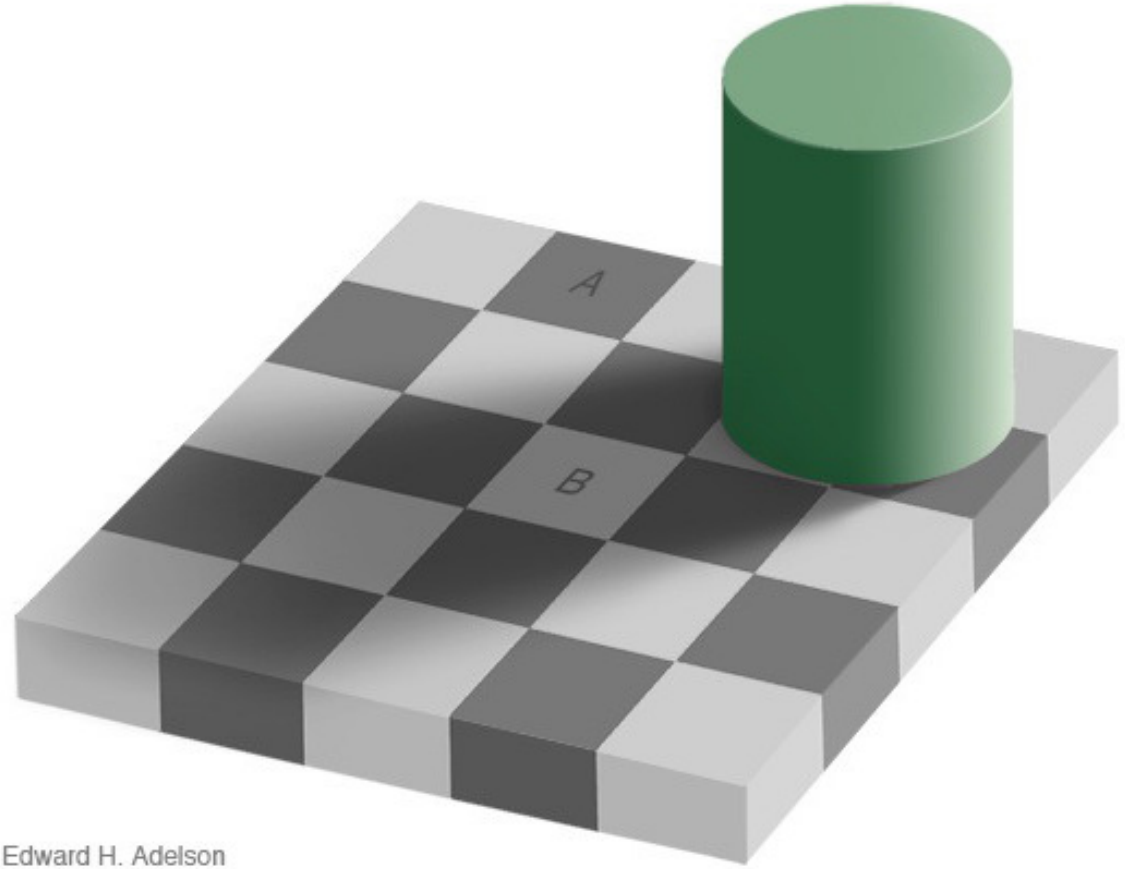
Subliminal Messages

- Image masking can be used to show information
  that does not reach consciousness

- But:
  Many experiments have shown that these images can effect decision making

[video]

Unconscious Processing



- Tremendous amount of unconscious processing
- In the image above image ″A″ and ″B″ have the same greyscale

What is the Consciousness For?

- A Bayesian view
  - unconsciousness computes probability distribution
  - consciousness samples from it — picks one item
- Example
  - what percentage of world's airports are in the US?
  - give second guess
  - compute average
  - correct answer is 34%
- Lasting thoughts, working memory
- Conscious cognitive processes: 12x13?
- Conscious thoughts can be communicated to others