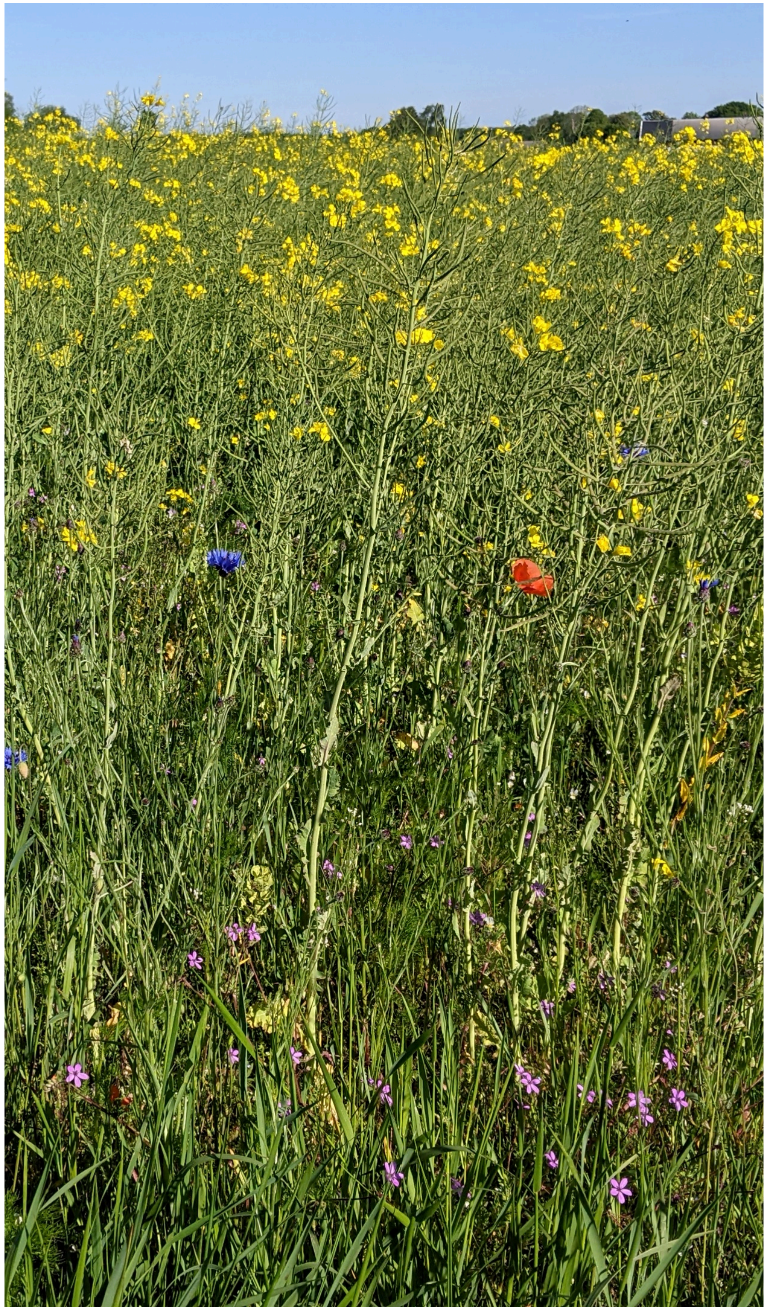
Modeling cognition: computational rationality and reinforcement learning

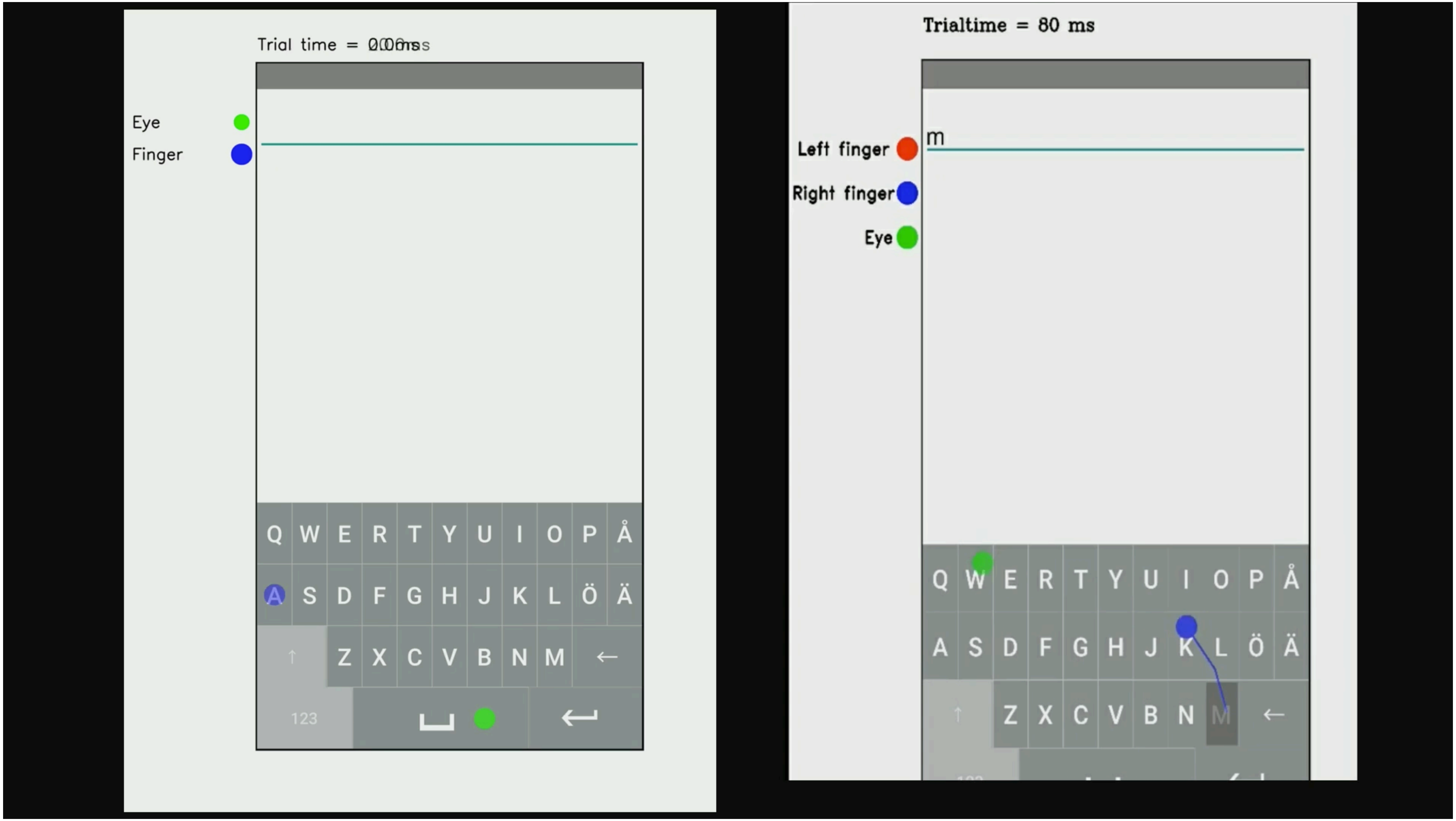
Day 3: CI Summer School 2022, Saarland

Andrew Howes

Aalto University
&
University of Birmingham

howesamail@bham.ac.uk





https://dl.acm.org/doi/abs/10.1145/3411764.3445483

Designers

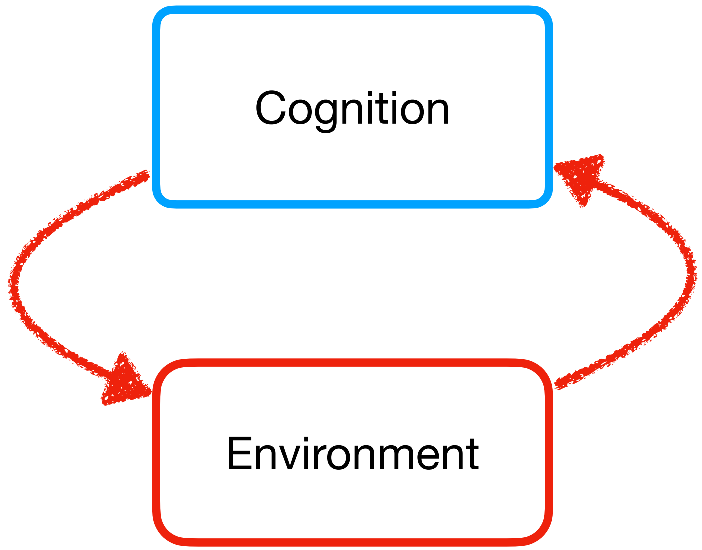
- Jussi Jokinen — University of Jyväskylä, Finland.
- Antti Oulasvirta — Aalto University, Finland.
- Andrew Howes — University of Birmingham, UK.

Learning objectives

- Understand what **cognitive modeling** is and why it is relevant to HCI.
- Understand what is meant by computational rationality and why it is important to modeling **cognition**.
- Understand the strengths and weaknesses of **cognitive models** specified as POMDPs.
- Be able to use and test **reinforcement learning** models to solve POMDPs and predict human behaviour.
- Understand the HCI cognitive modelling problems for which RL is useful.

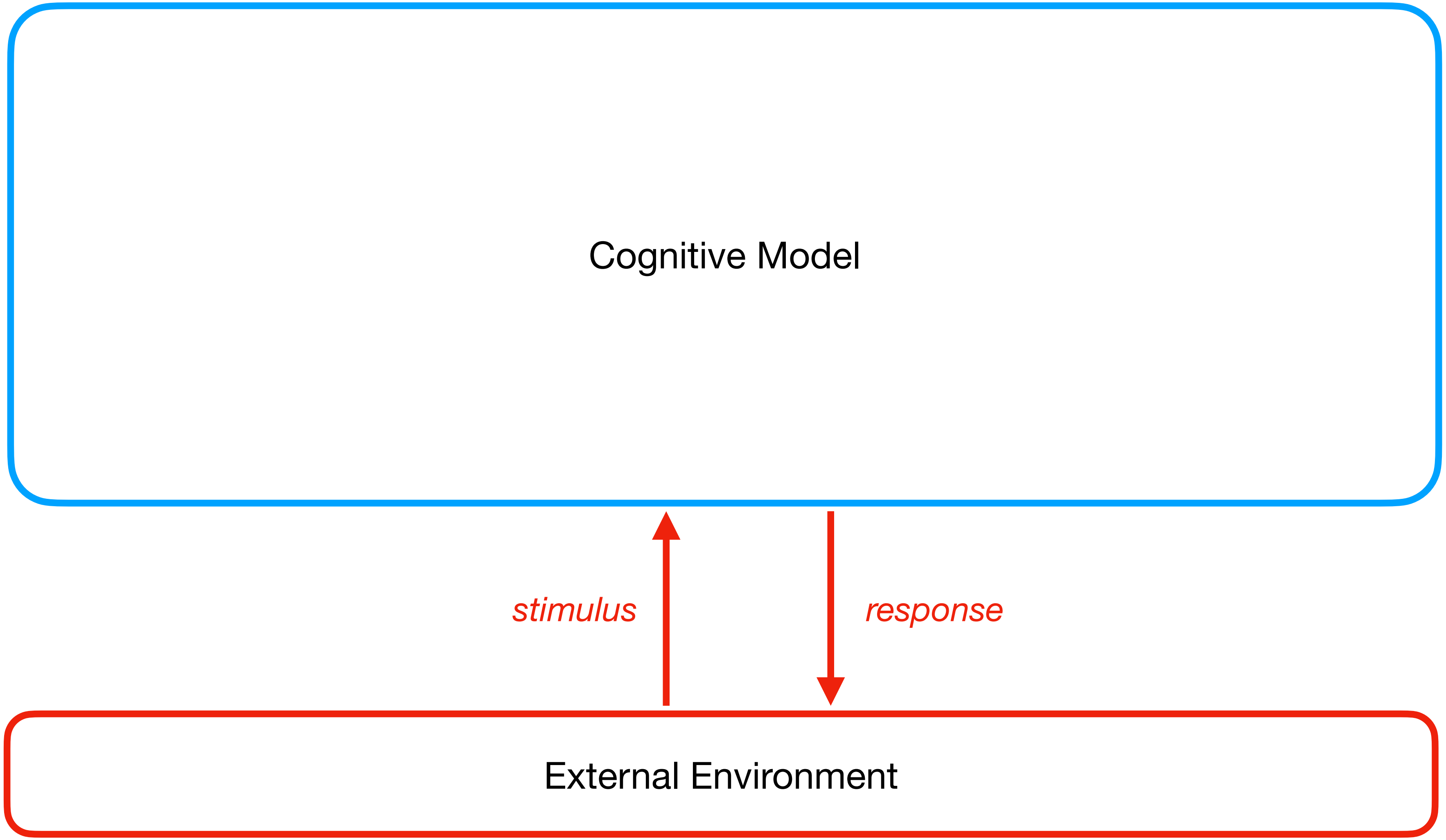
What is cognition?

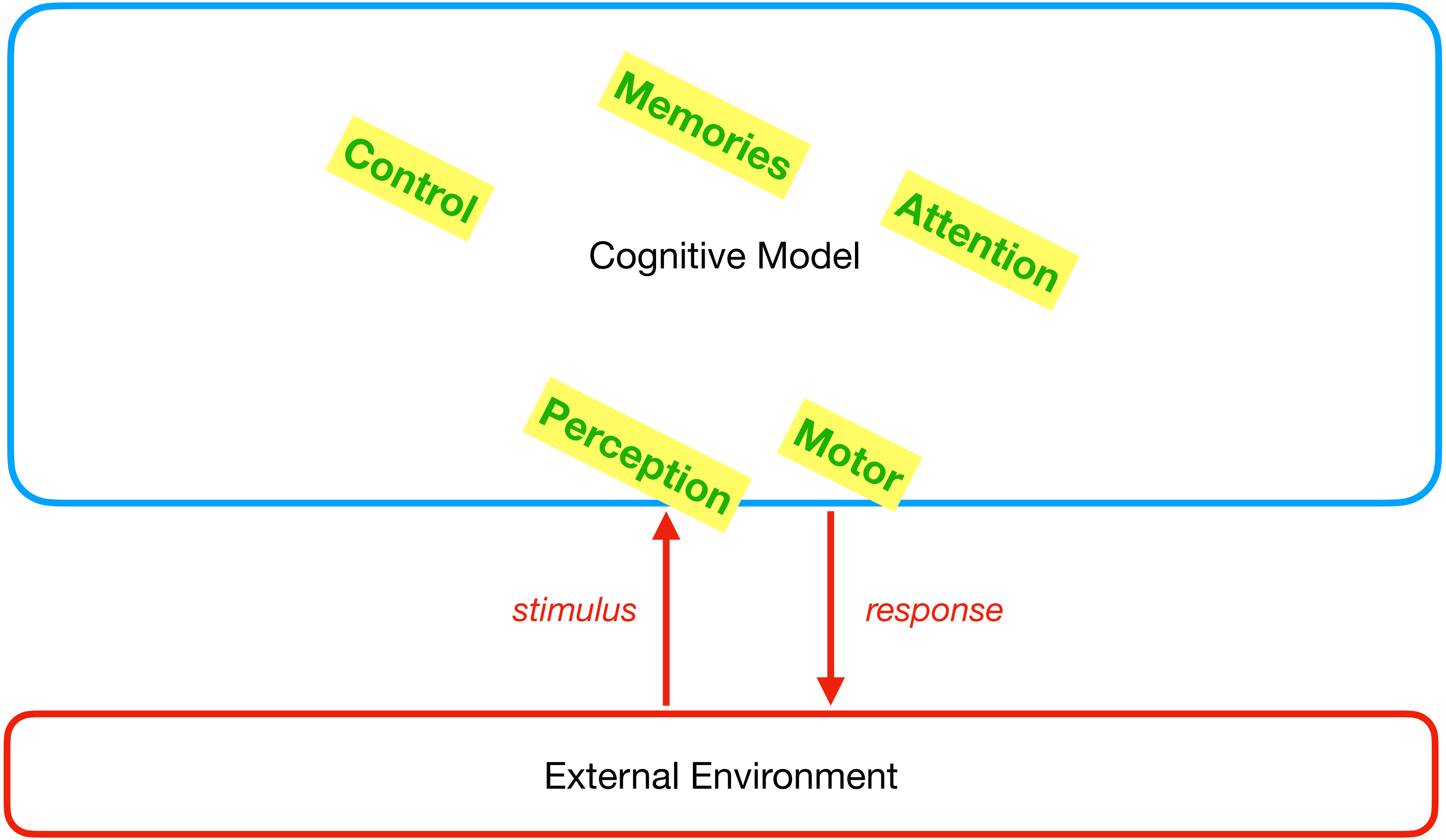
- Cognition is one part of an interactive control loop
- It senses its environment and it chooses actions
- It is goal-oriented
- It is bounded
- It adapts and it is strategic
- It learns representation in service of action
- It requires energy and effort
- It can be augmented with external aids
- It is computational — it's not a metaphor!

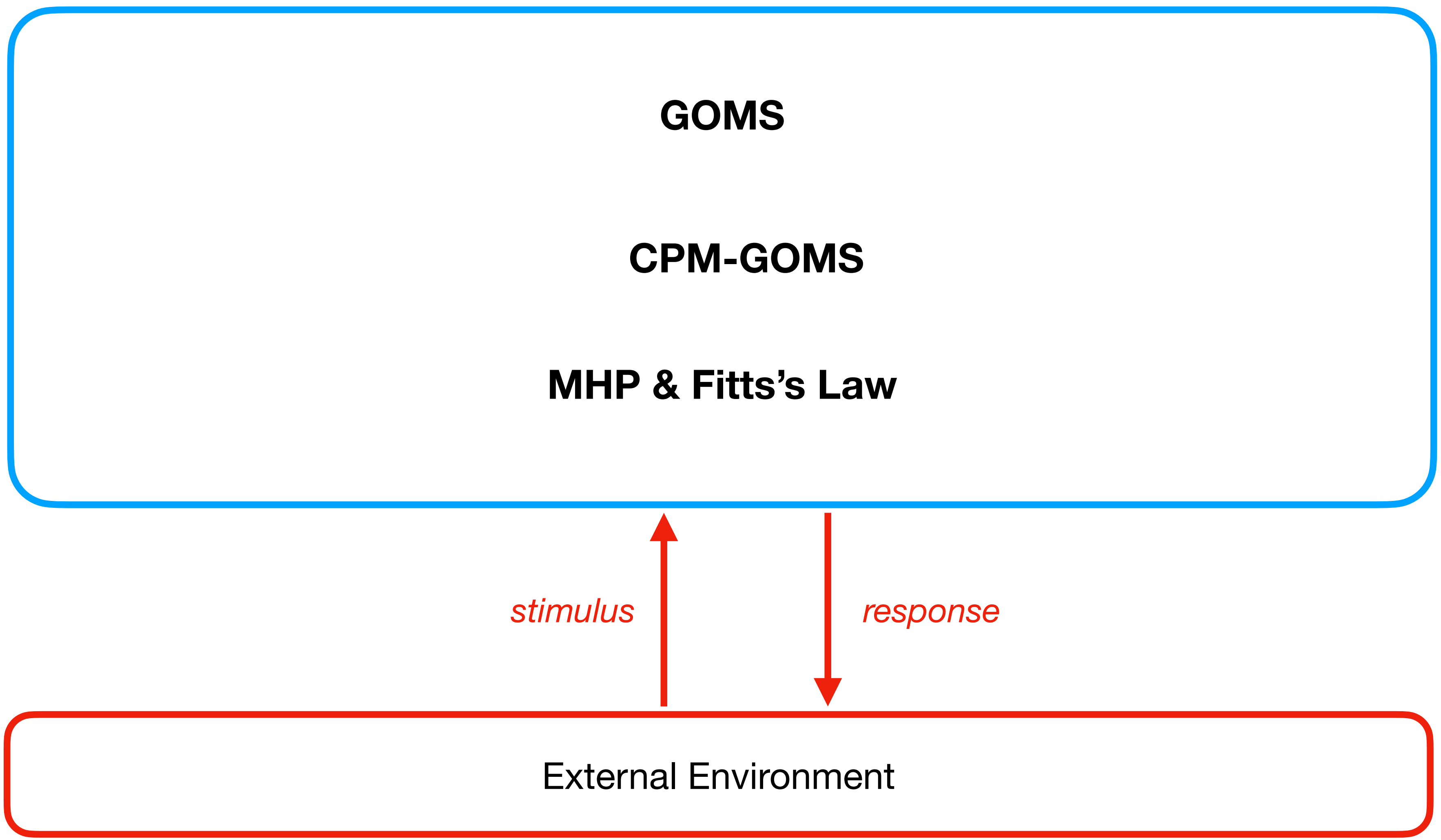


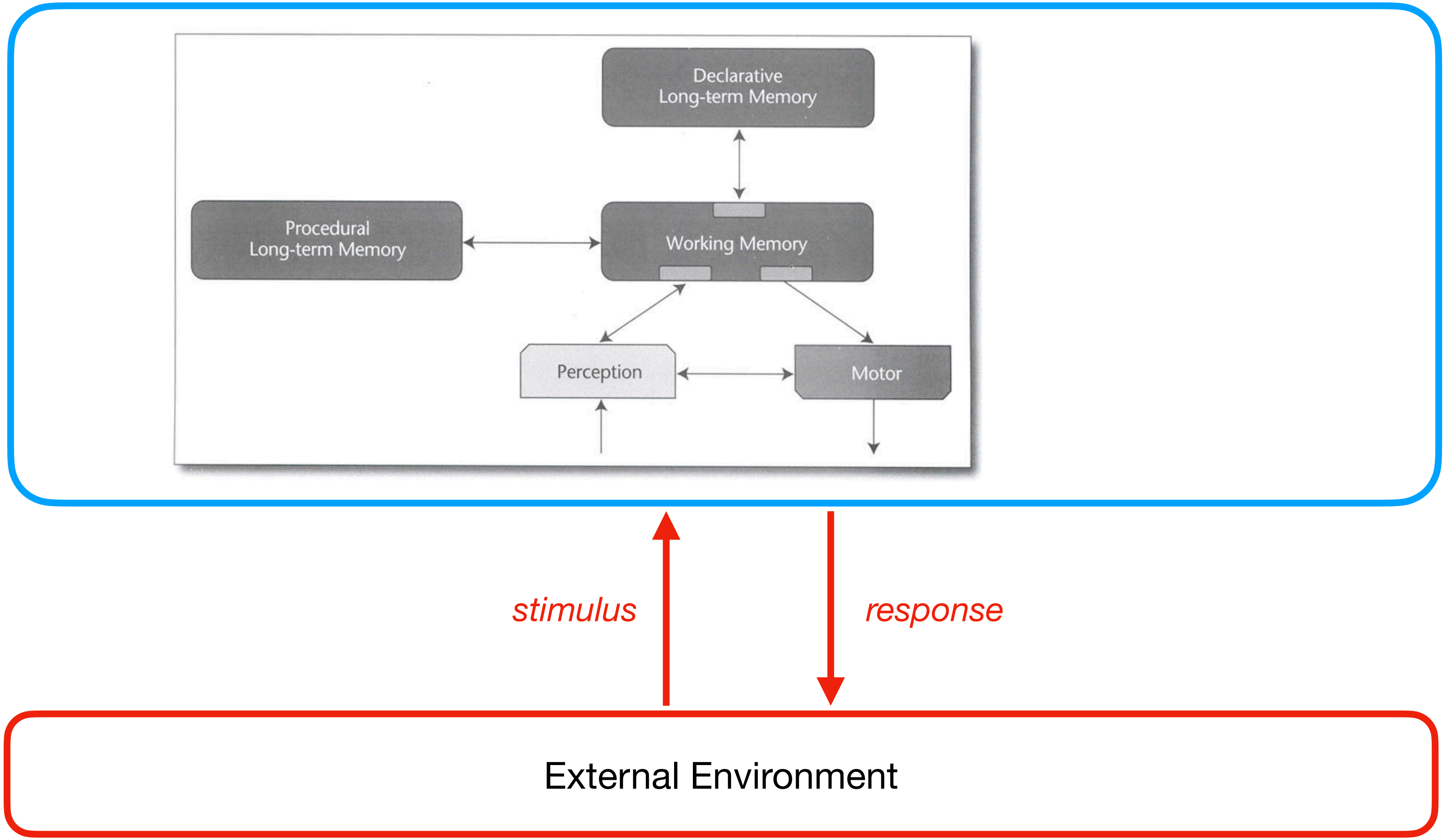
What is a cognitive model?

- **For the purposes of this tutorial**,
    - A cognitive model is a computer simulation of cognition.
    - It is based on a hypothesis about information processing.
    - It can be executed on a computer and makes predictions.
    - It commits to a level of abstraction.
    - It learns by interacting with a simulated environment.

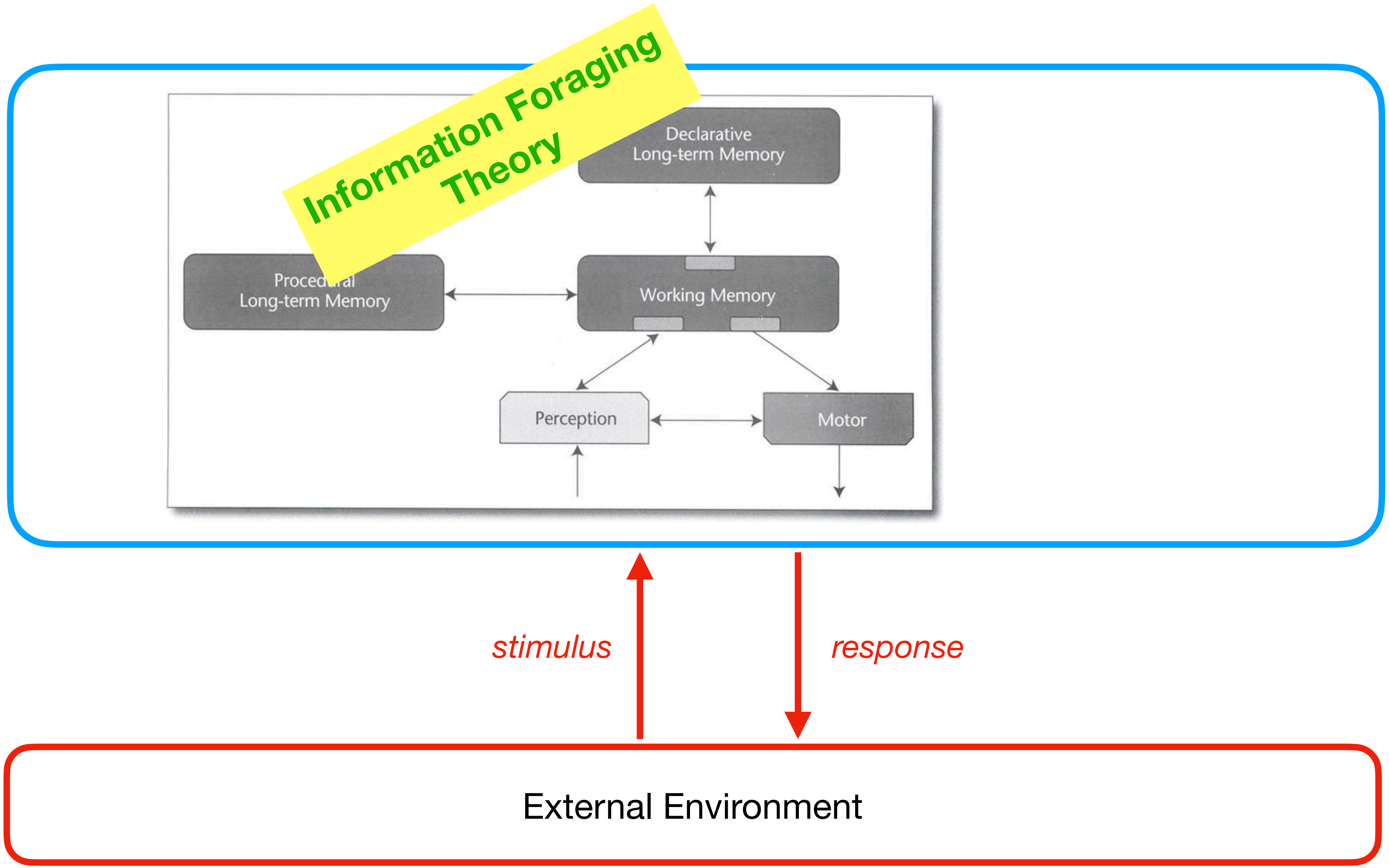

Cognitive Model
stimulus
response
External Environment


Memories
Control
Attention
Cognitive Model
Perception
Motor
stimulus
response
External Environment

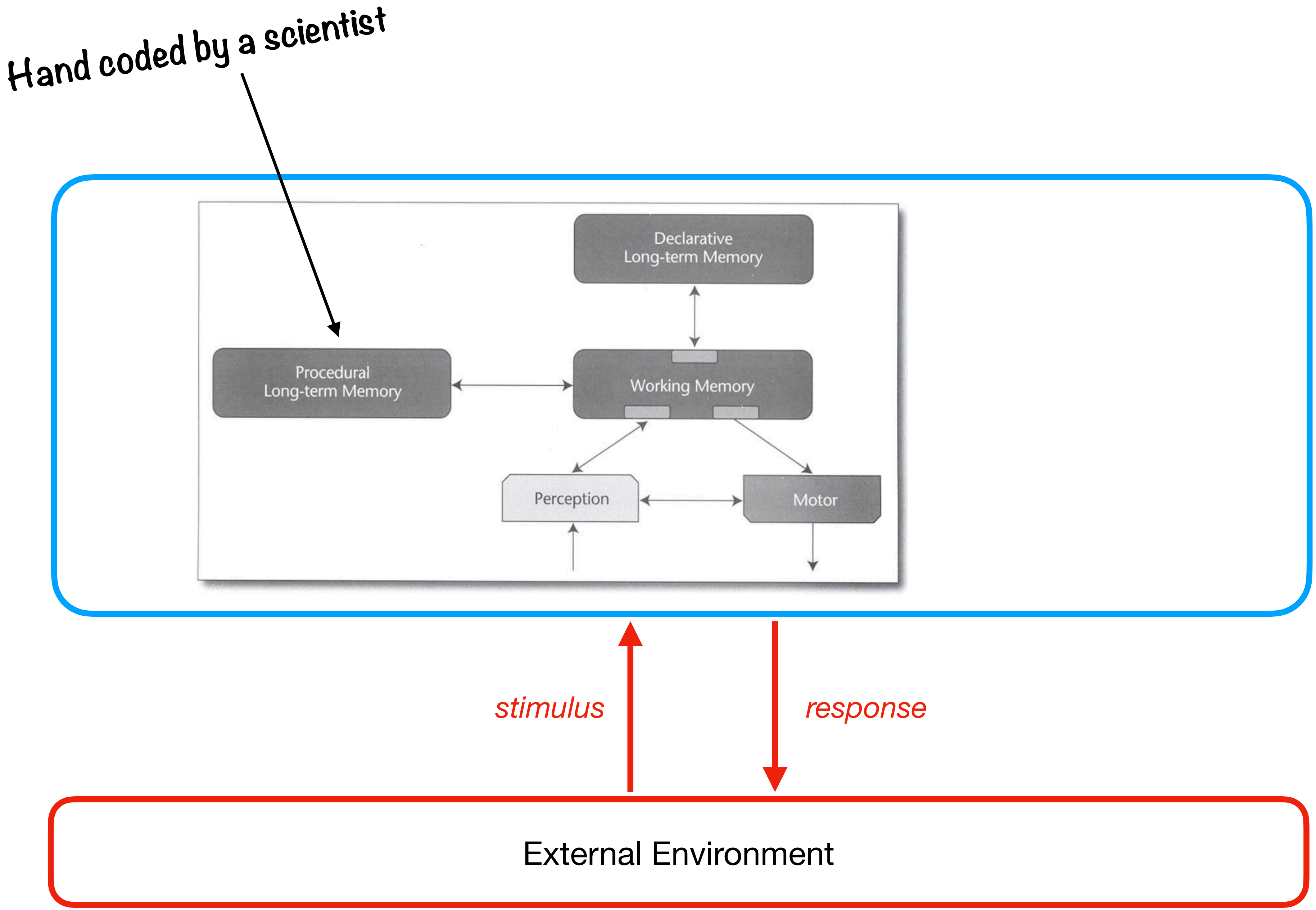

GOMS
CPM-GOMS
MHP & Fitts's Law
stimulus
response
External Environment



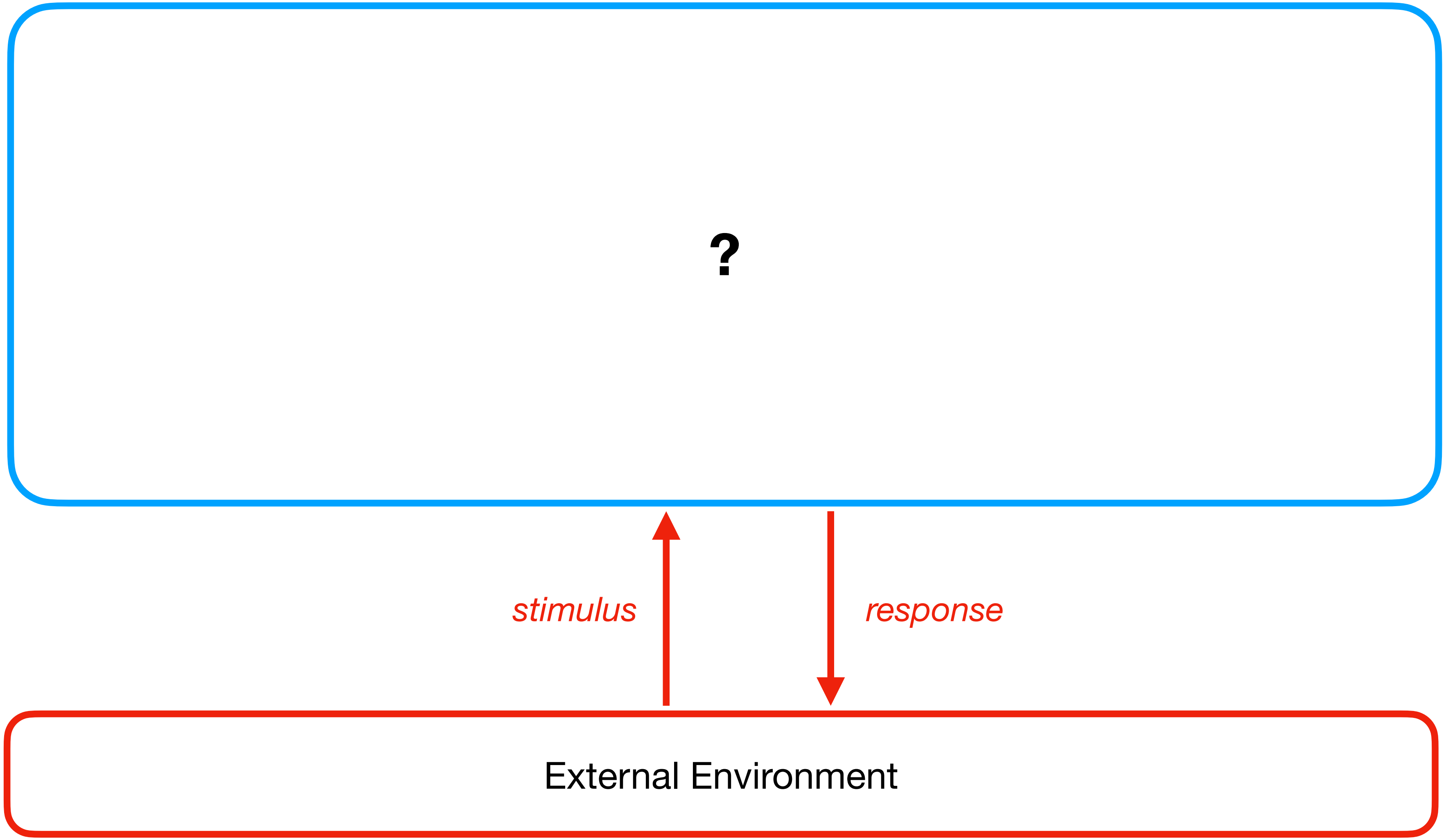
ACT-R, Soar, EPIC "standard architecture"
Laird, Lebiere, Rosenbloom, 2017

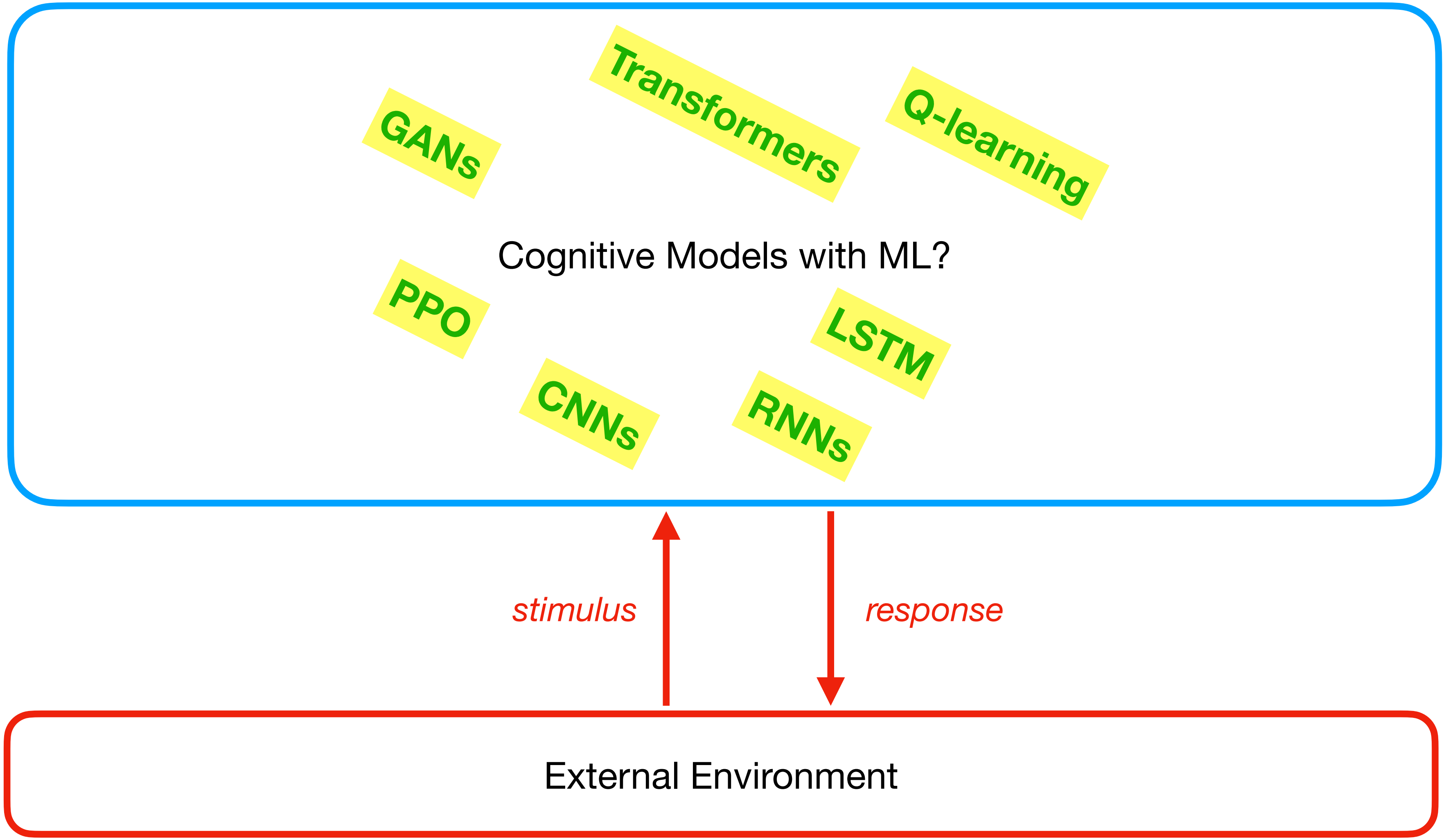


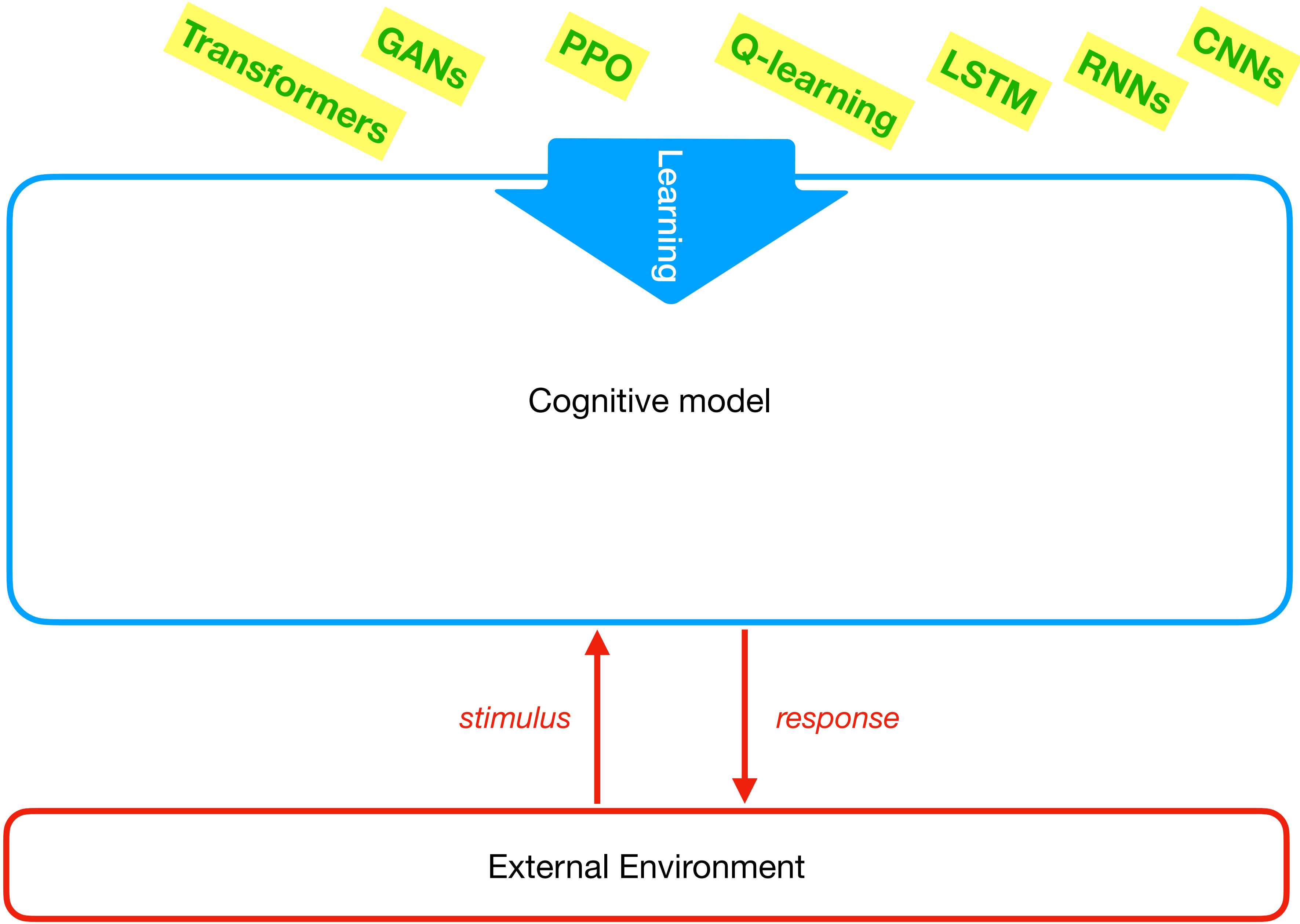
ACT-R, Soar, EPIC "standard architecture"
Laird, Lebiere, Rosenbloom, 2017

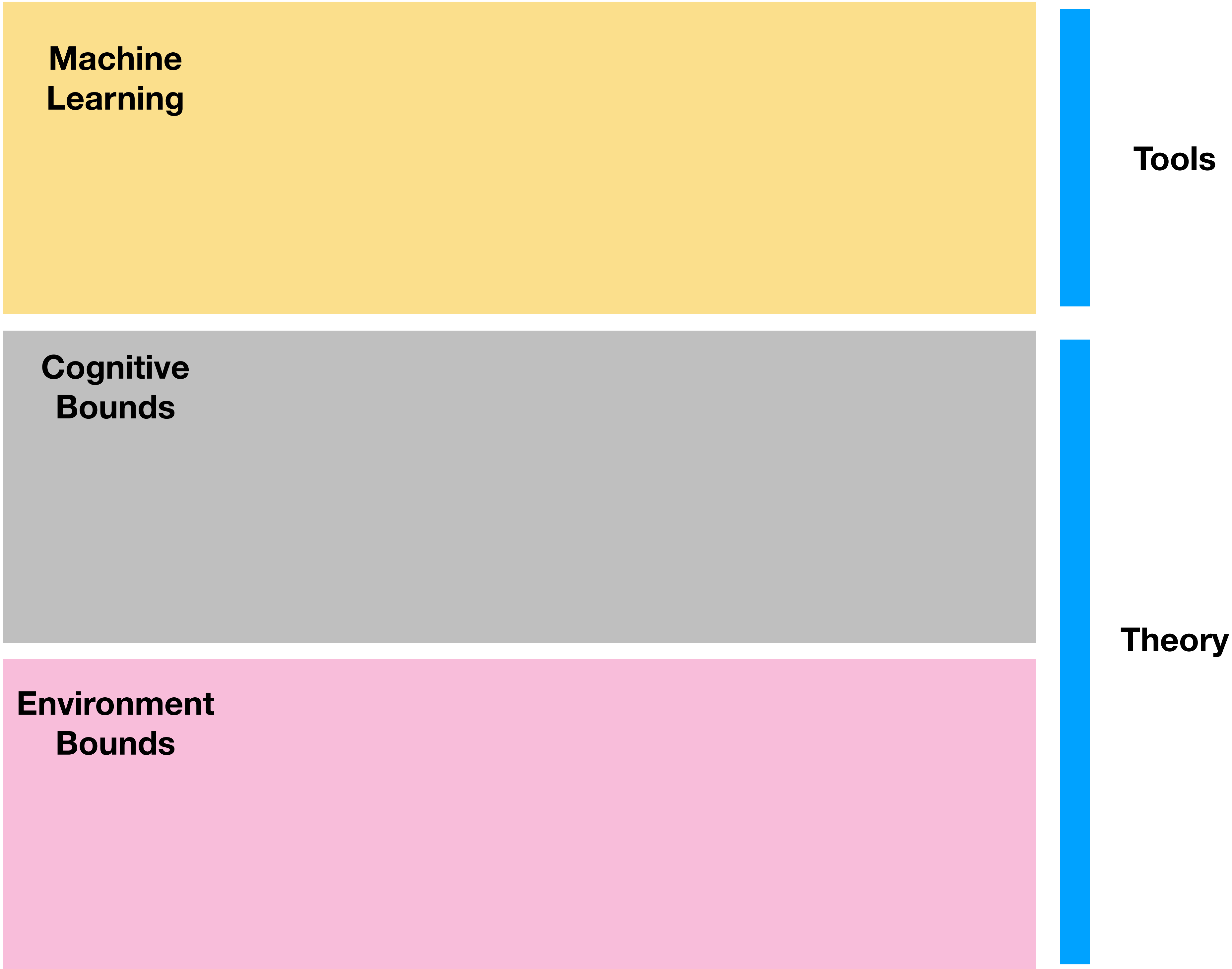


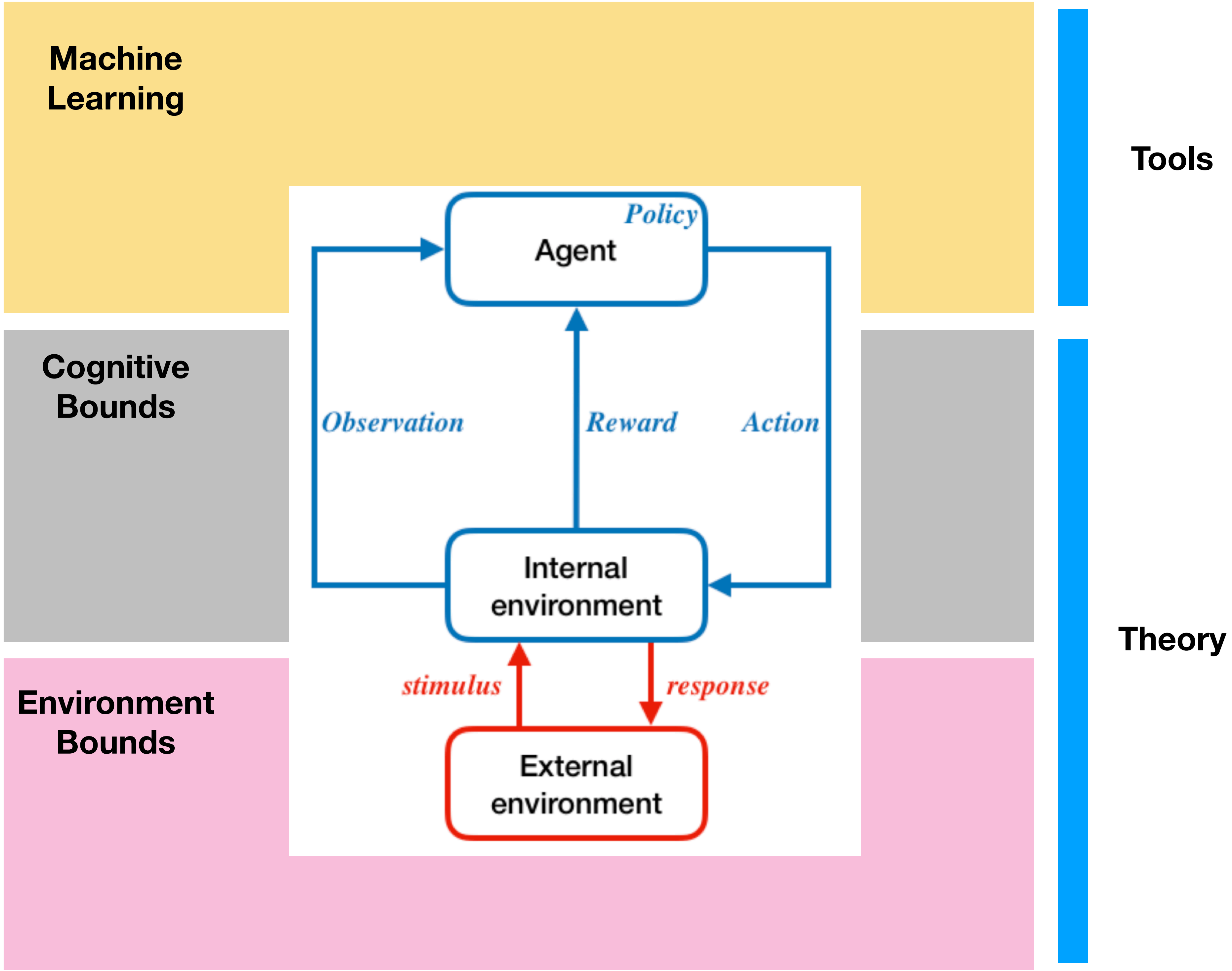
ACT-R, Soar, EPIC "standard architecture"
Laird, Lebiere, Rosenbloom, 2017


?
stimulus
response
External Environment


Transformers
GANs
Q-learning
Cognitive Models with ML?
PPO
LSTM
CNNs
RNNs
stimulus
response
External Environment


Transformers
GANs
PPO
Q-learning
LSTM
RNNs
CNNs
Learning
Cognitive model
stimulus
response
External Environment


Machine Learning
Cognitive Bounds
Environment Bounds
Tools
Theory



Machine Learning
Cognitive Bounds
Environment Bounds
Policy
Agent
Observation
Reward
Action
Internal environment
stimulus
response
External environment
Tools
Theory

Computational rationality

Human behaviour can be predicted by calculating the optimal policy given a theory of the bounds on cognition.

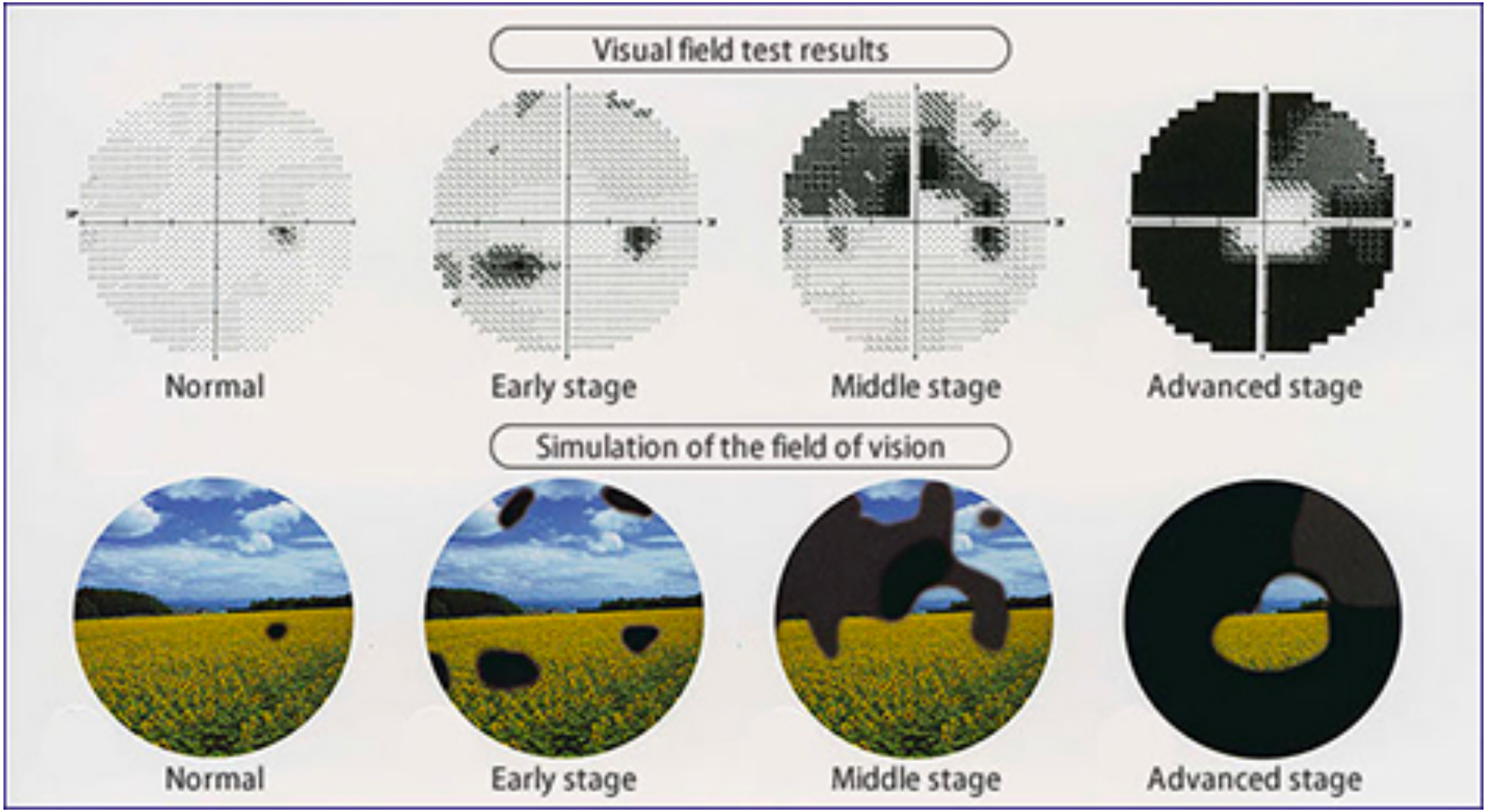
- Lewis, R. L., Howes, A., & Singh, S. (2014). Computational rationality: Linking mechanism and behavior through bounded utility maximization. Topics in cognitive science, 6(2), 279-311.

- Oulasvirta, A., Jokinen, J. P., & Howes, A. (2022, April). Computational Rationality as a Theory of Interaction. In CHI Conference on Human Factors in Computing Systems (pp. 1-14).

Why build cognitive models?

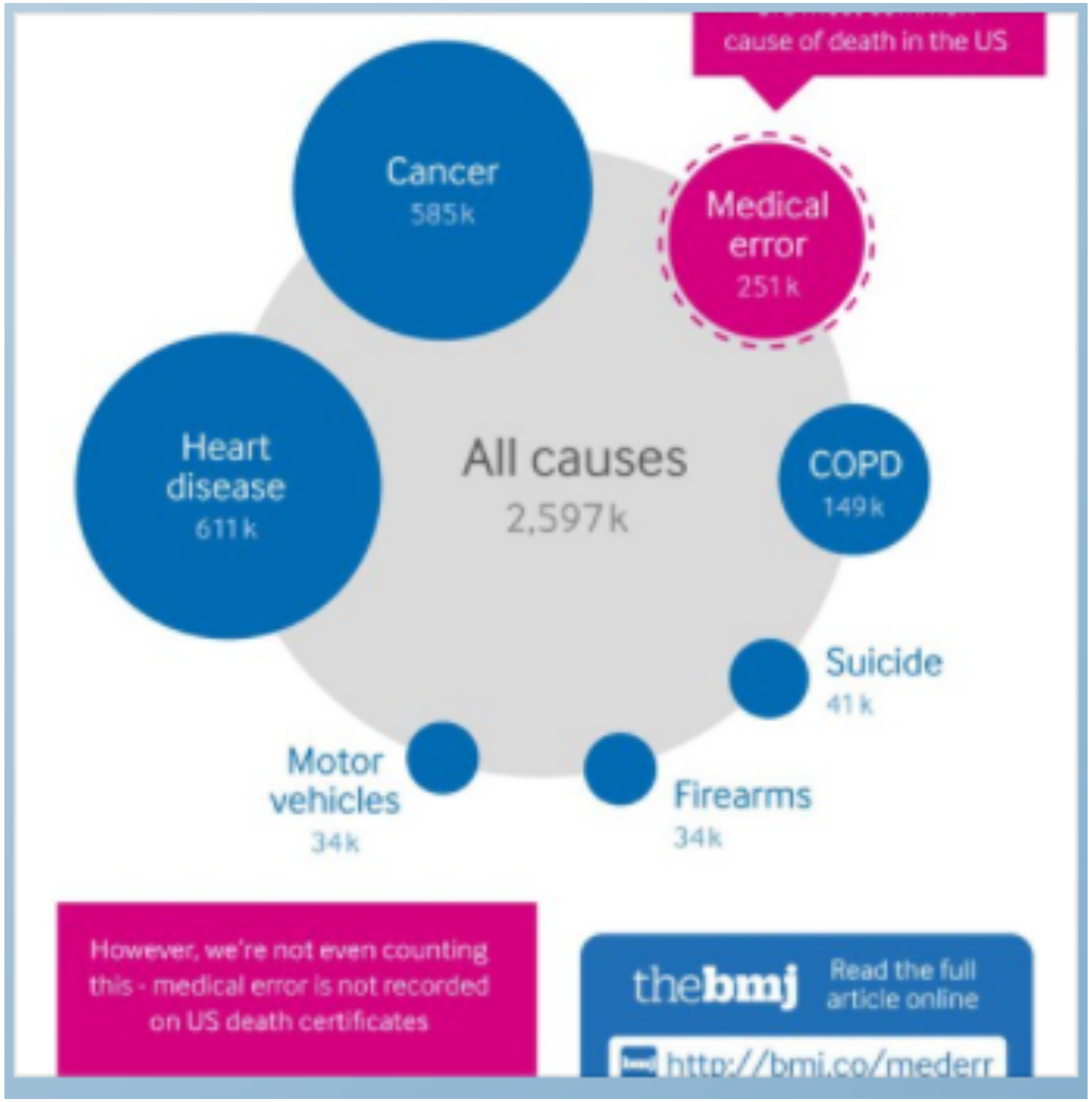
Why? Why?

- To provide a strong test of whether we understand interaction and thereby help in the creation and validation of new HCI **theory**.
- To help **design** more robust interaction, with improved system safety, and accessibility.
- To reduce financial, temporal and human cost of **usability testing**.
- To take full advantage of **recent advances** in other engineering and scientific fields including pharma, weather, climate, etc.
- To advance the next generation of **intelligent interactive systems.**



https://laser-eye.gr/en/glaucoma/glaucoma-symptoms-and-eye-examination/

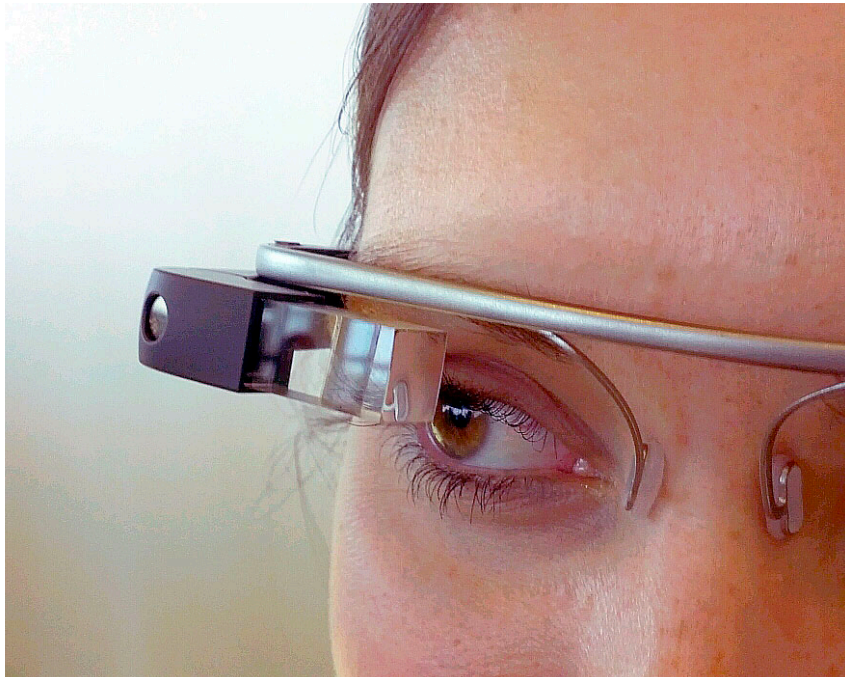
Medical error - the 3rd leading cause of death in the US



https://www.bmj.com/content/353/bmj.i2139

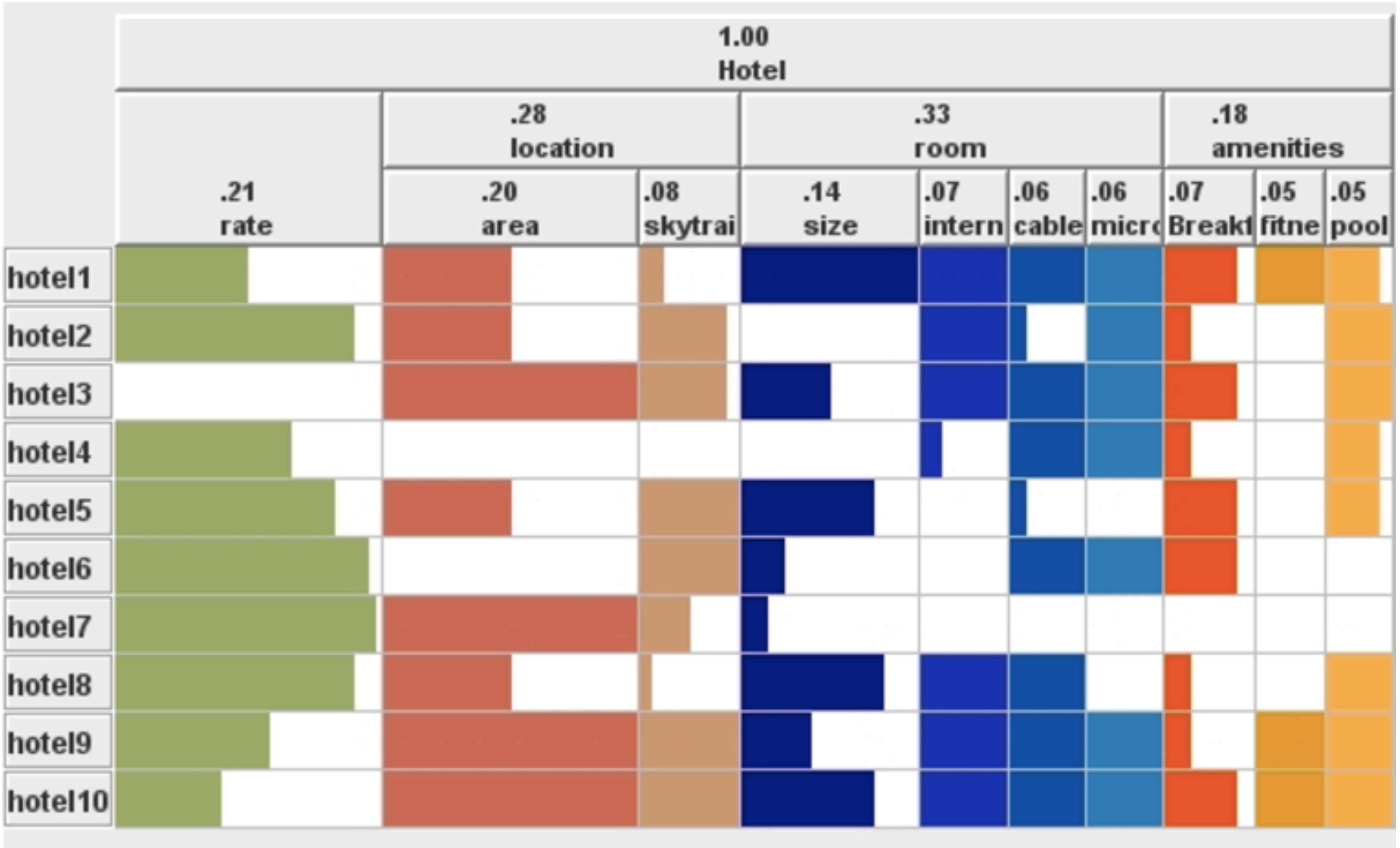
Design problems

- You want to design a new icon that can be easily found.
- What is more important? Colour, shape or size?
- Or, you want to design a peripheral head-mounted display, e.g. for Google Glass or to be integrated into Meta/ Facebook/Ray-Ban Smart glasses.



https://www.wired.com/2013/12/glasshole/

Decision making and visualisation



Conati et al., 2014

Scope: what tasks do we model?

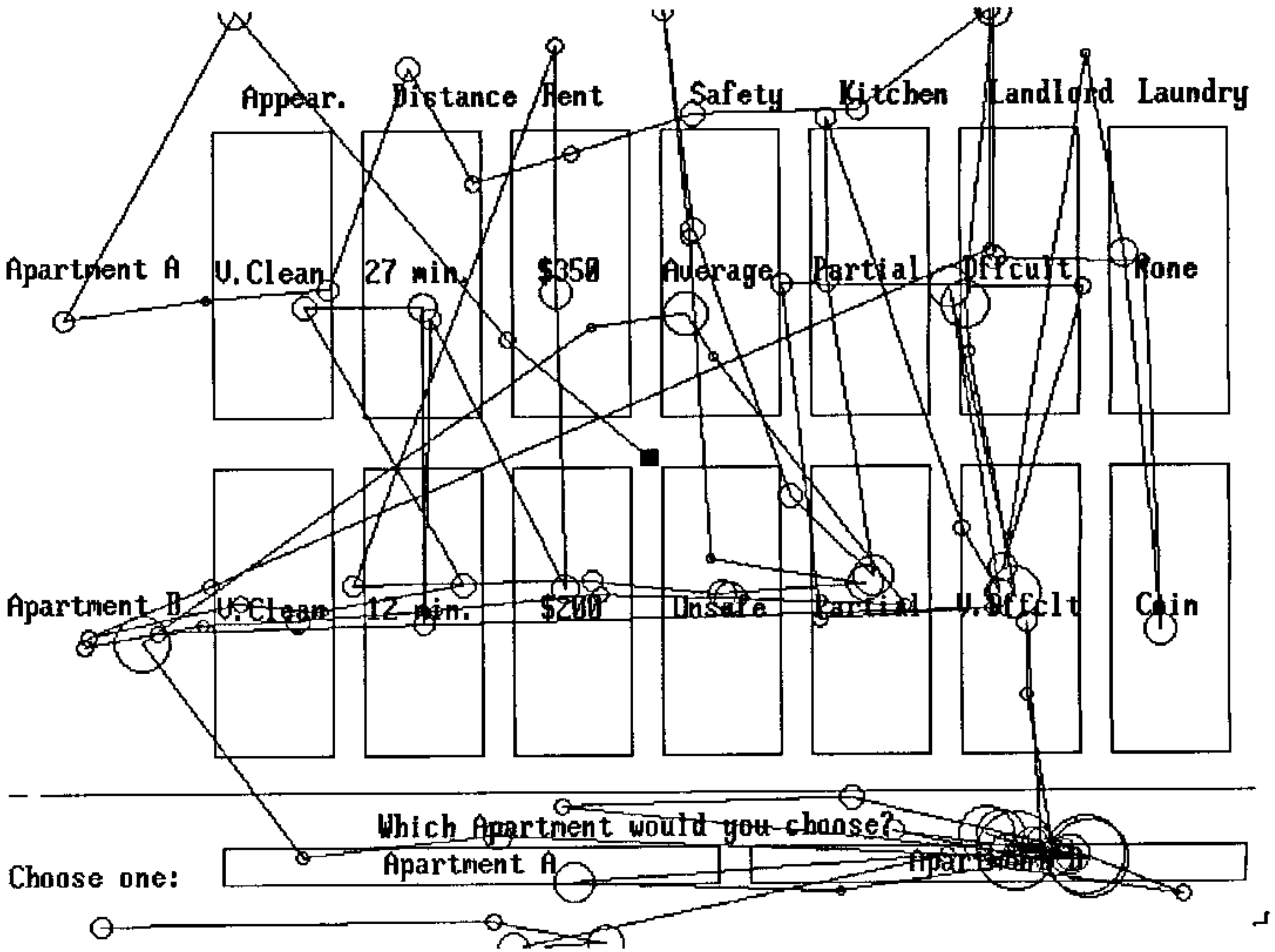
- **Perceptual-motor tasks** - eye movements, foveated vision, perceptual integration, etc.
- **Cognitive tasks** - typing, menu search, information foraging, decision making.
- **Collaborative tasks** - reciprocity and trust.

Adaptation

Adaptation

Adaptation

Adaptation



Lohse and Johnson, 1996

Lohse, G. L., & Johnson, E. J. (1996). A comparison of two process tracing methods for choice tasks. *Organizational Behavior and Human Decision Processes*, *68*(1), 28-43.

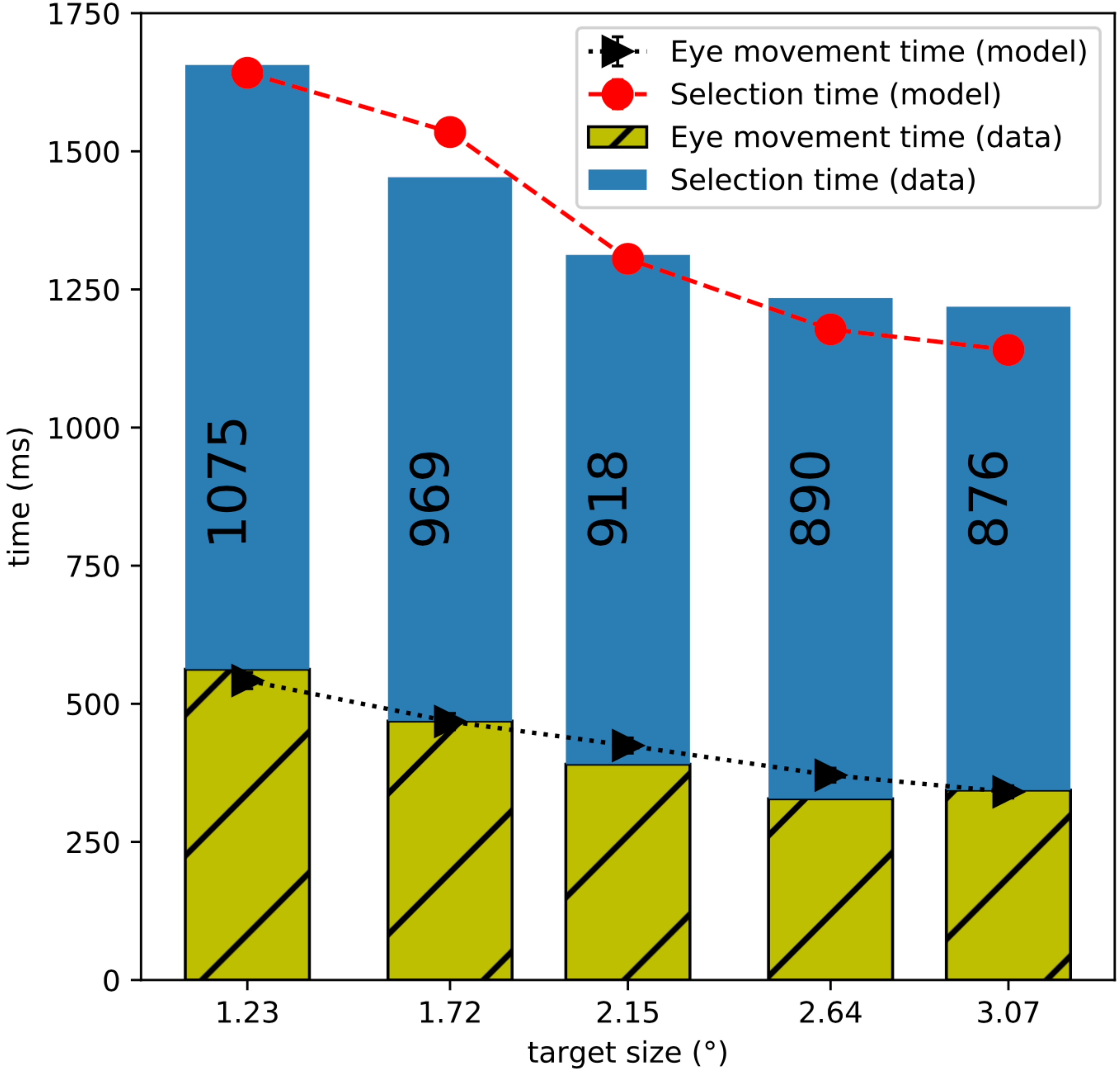
	Appear.	Distance	Rent	Safety	Kitchen	Landlord	Laundry
Apartment A	V.Clean	27 min.	$350	Average	Partial	Dffcult	None
Apartment B	V.Clean	12 min.	$200	Unsafe	Partial	V.Dffclt	Coin

Which Apartment would you choose?

Choose one: Apartment A | Apartment B

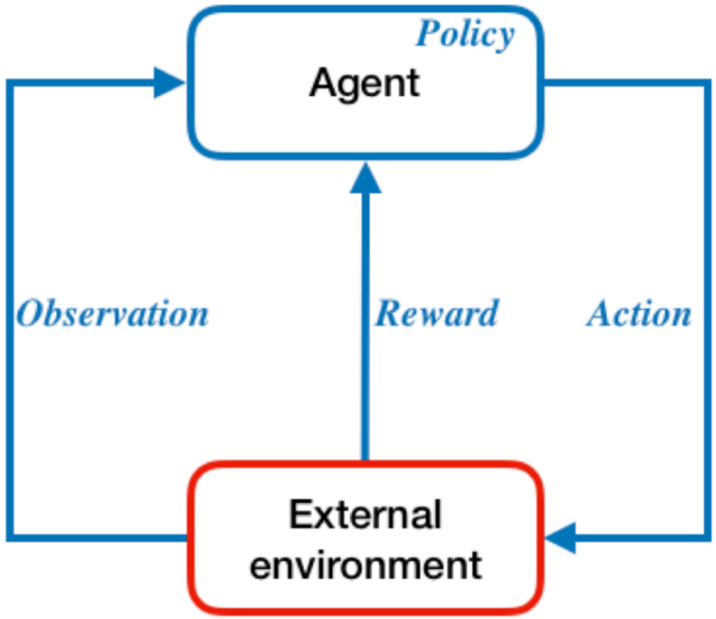
Gaze-based selection

Gaze-based selection

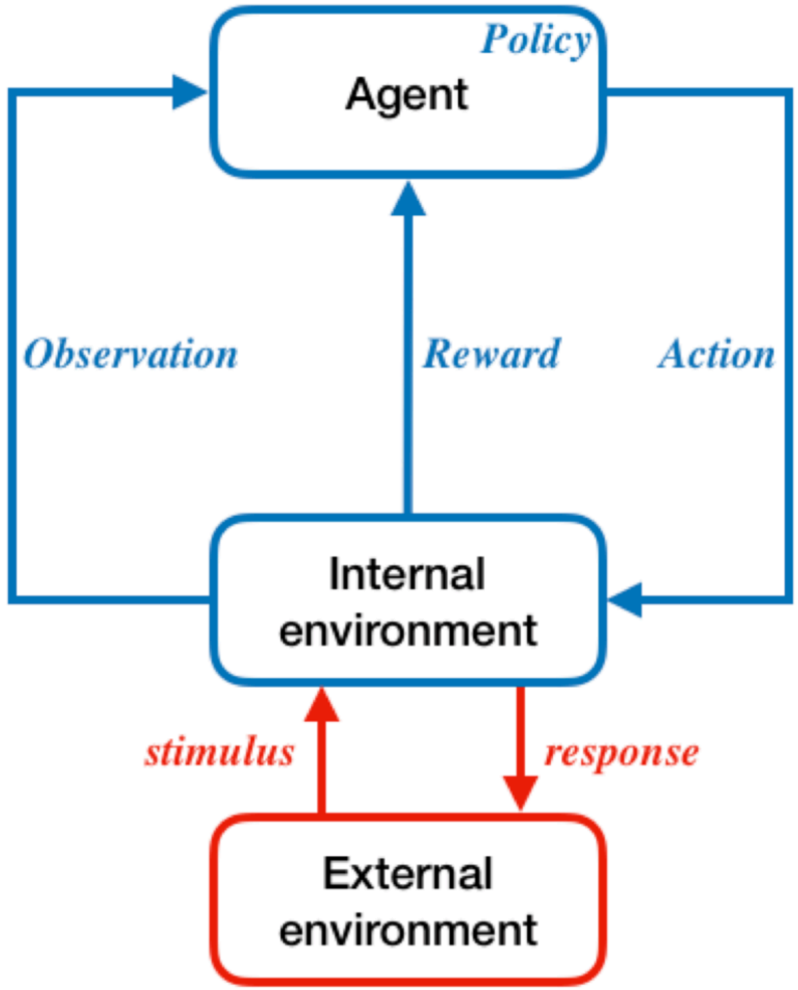


Eye movement time (model)
Selection time (model)
Eye movement time (data)
Selection time (data)
1075
969
918
890
876
time (ms)
target size (°)
1.23
1.72
2.15
2.64
3.07
0
250
500
750
1000
1250
1500
1750

Markovian decision processes



POMDP



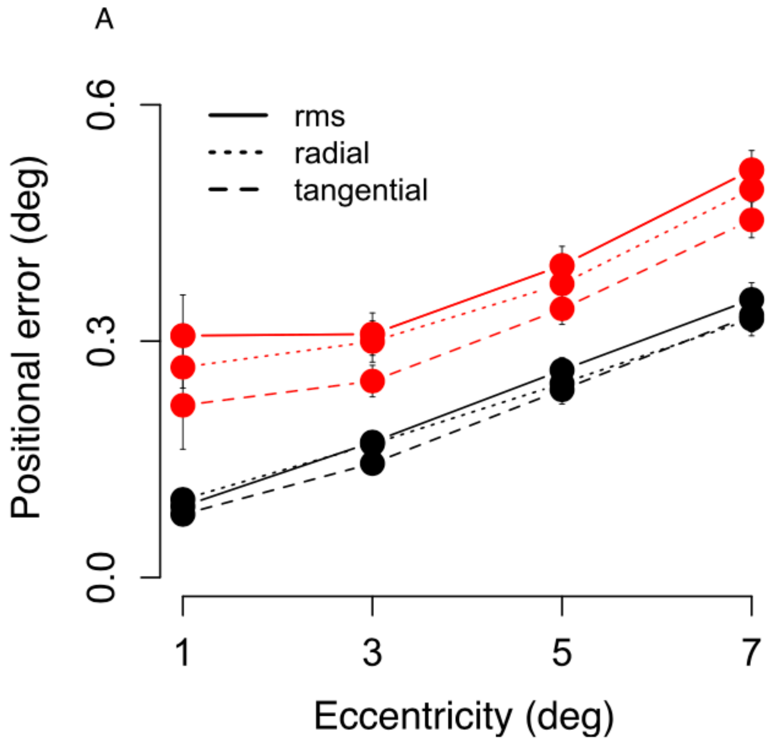
Cognitive POMDP

Foveated vision

- Human vision gets noisier the greater the eccentricity from the fovea.

Noise

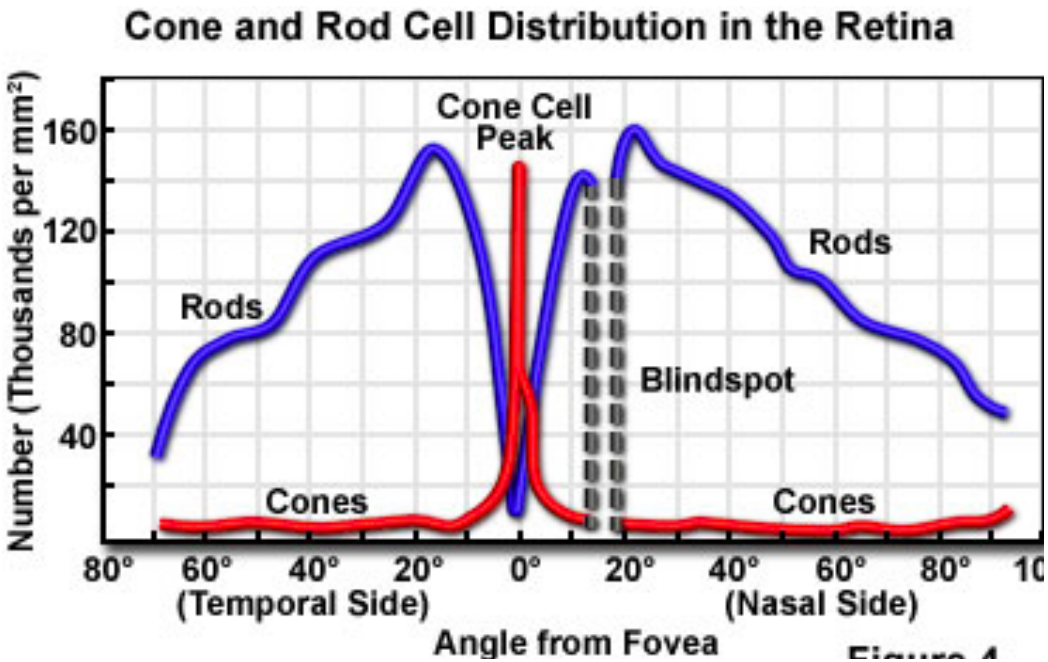
- It is known that observations get less accurate with eccentricity from the fixation.



Hussain et al. (2015). Estimation of cortical magnification from positional error in normally sighted and amblyopic subjects. Journal of Vision.

Foveated vision

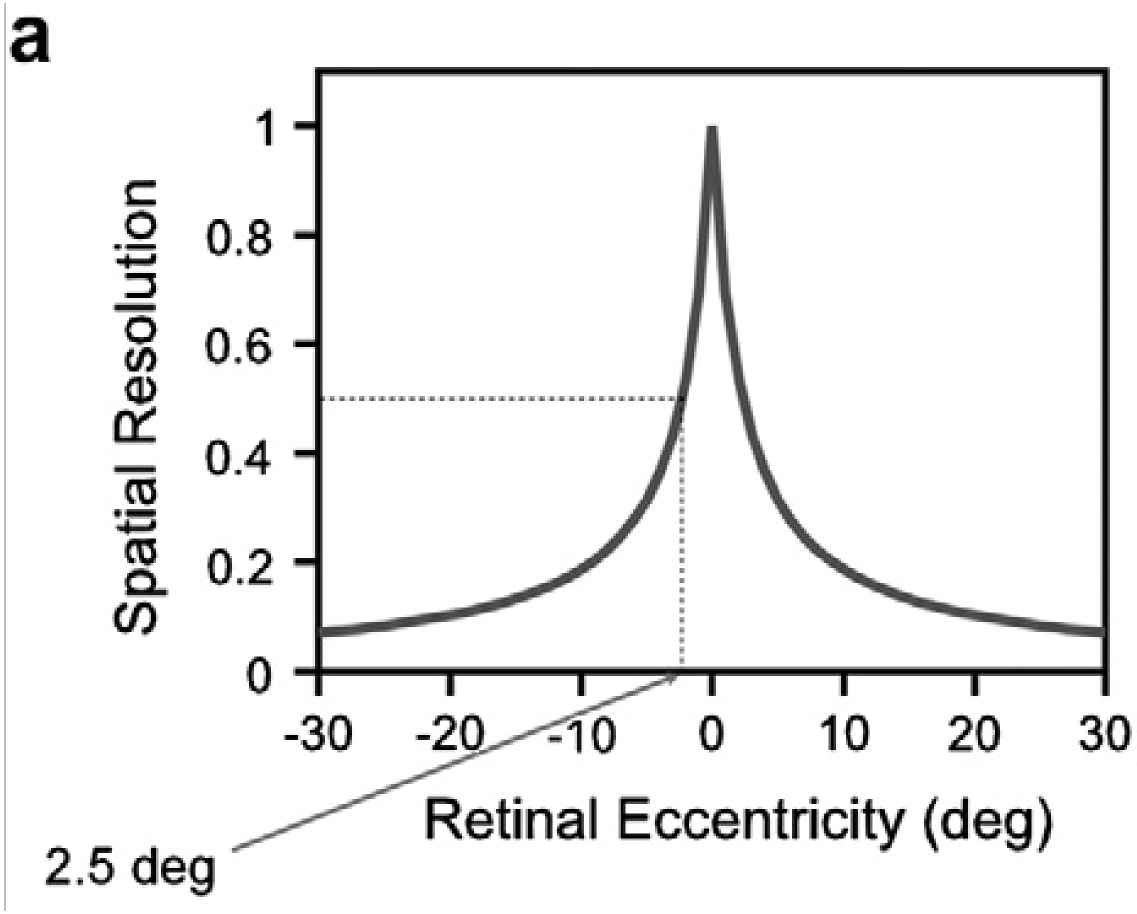
- The acuity with which we see an object is partly determined by whether the image of the object is on the fovea (high resolution) or the parafovea (relatively low resolution).
- Cones consist of three cell types, each "tuned" to a distinct wavelength response maximum centered at either 430, 535, or 590 nanometers — roughly corresponding to RGB.



https://www.nature.com/articles/eye2016107

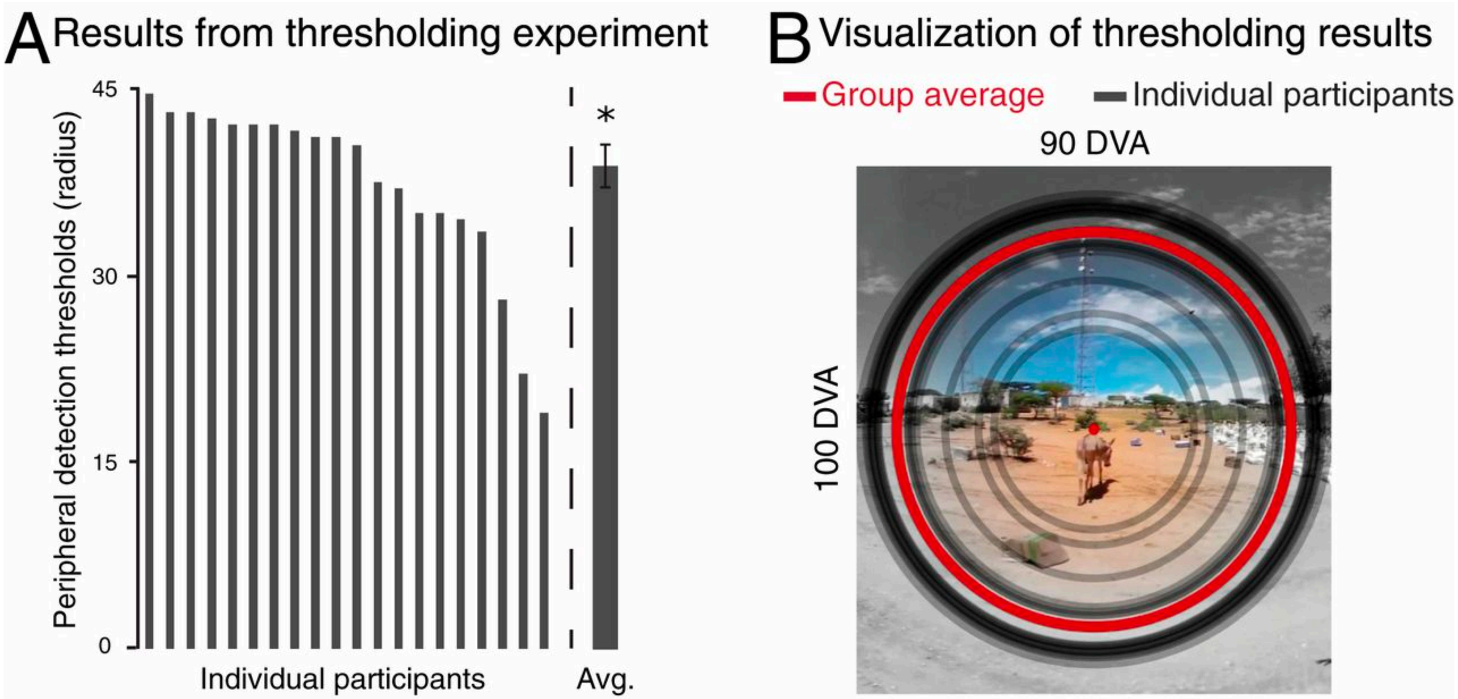
Spatial resolution with eccentricity from the fovea

- Geisler (2011)
- At 2.5 degrees of visual angle the spatial resolution has dropped to 50%.



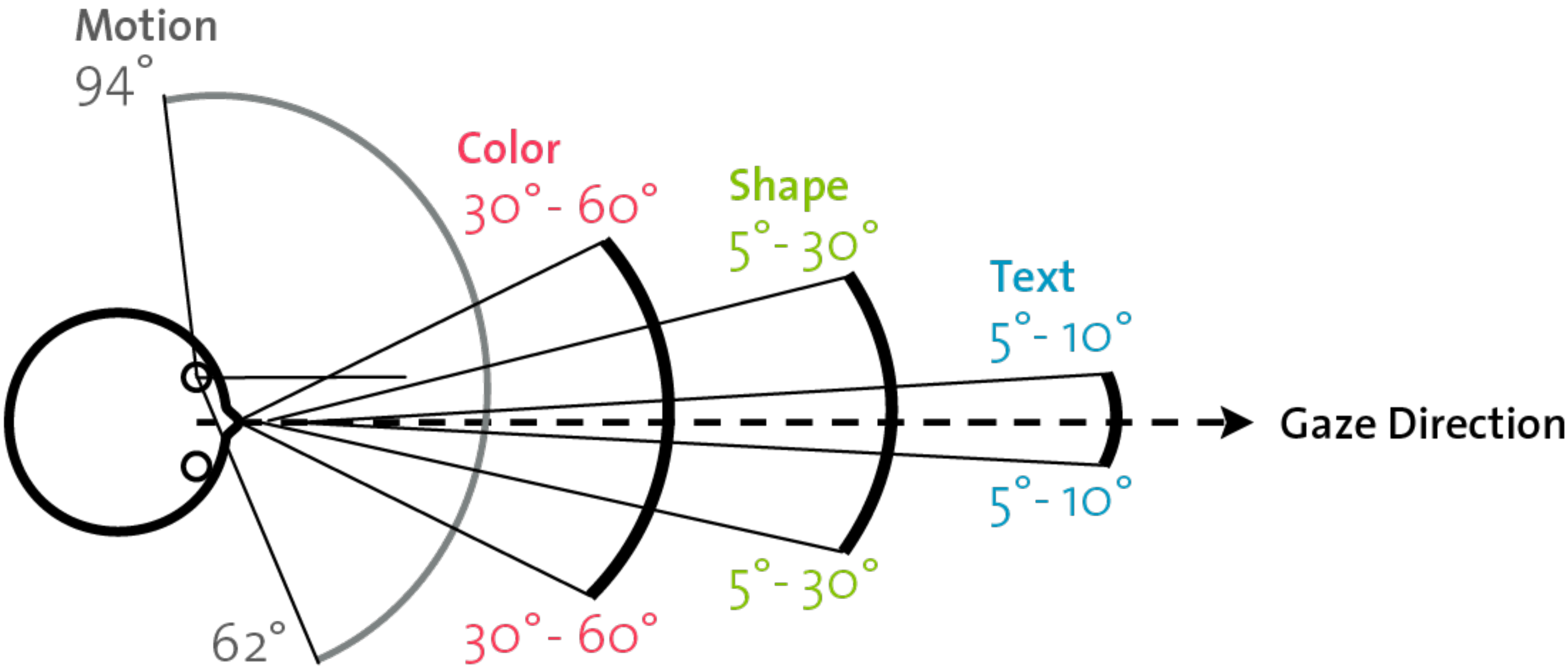
https://www.sciencedirect.com/science/article/pii/S0042698910004724

Individual variation



- There is considerable individual variation in colour awareness during active real world vision (Cohen, 2020).

https://www.pnas.org/doi/abs/10.1073/pnas.1922294117



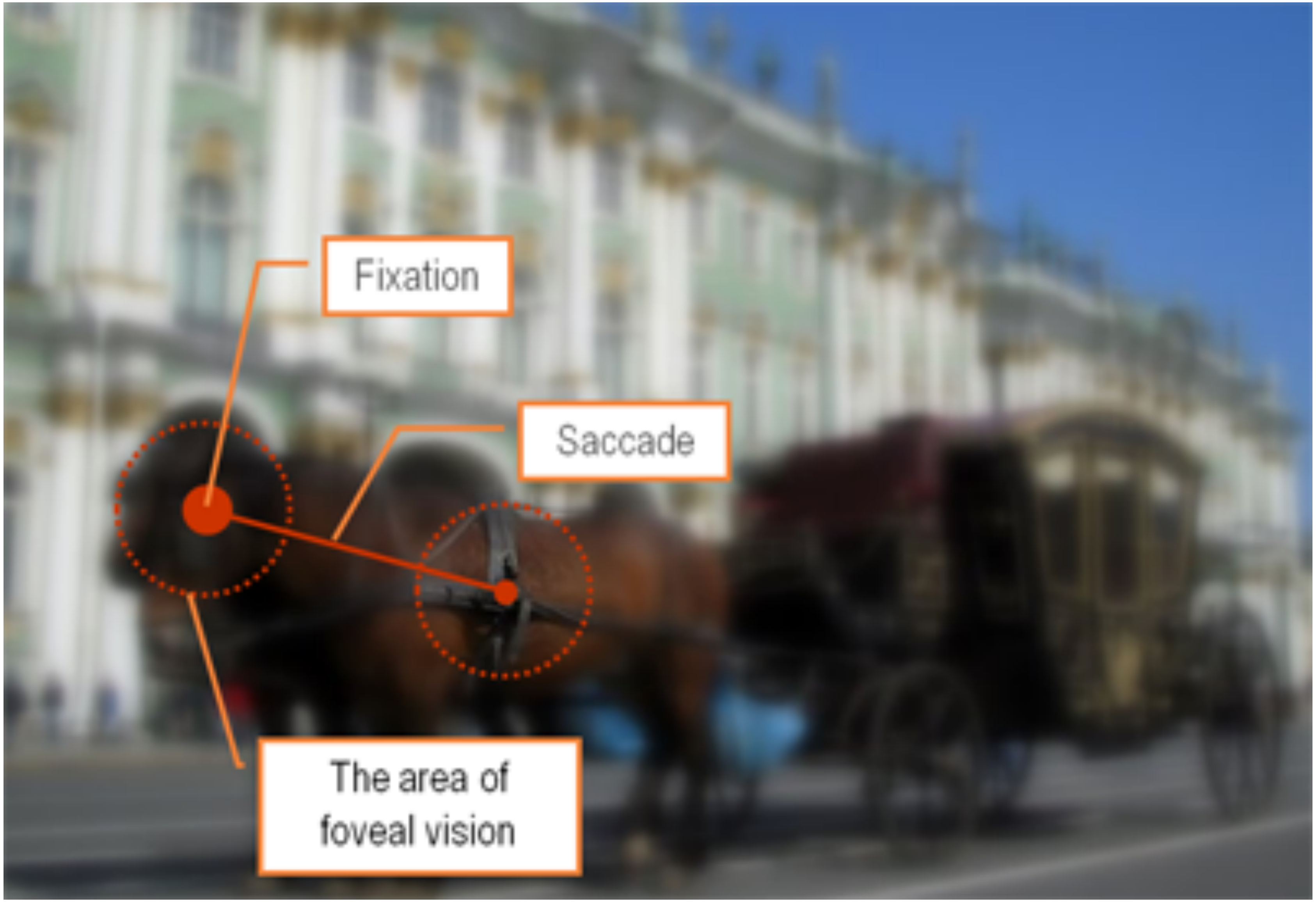
Matthies, et al. (2015). Properties of a Peripheral Head-Mounted Display (PHMD)

https://www.researchgate.net/publication/278302885_Properties_of_a_Peripheral_Head-Mounted_Display_PHMD

Saccades

- Important actions include: saccade and fixation.
- There are minimum time requirements for how long it takes to make eye movements
- For reading,
- Saccade duration is between150 and 175ms (Rayner, 2008).
- Fixation durations vary between 100 and over 500ms.
- where a millisecond (ms) is 1/1000th of a second.

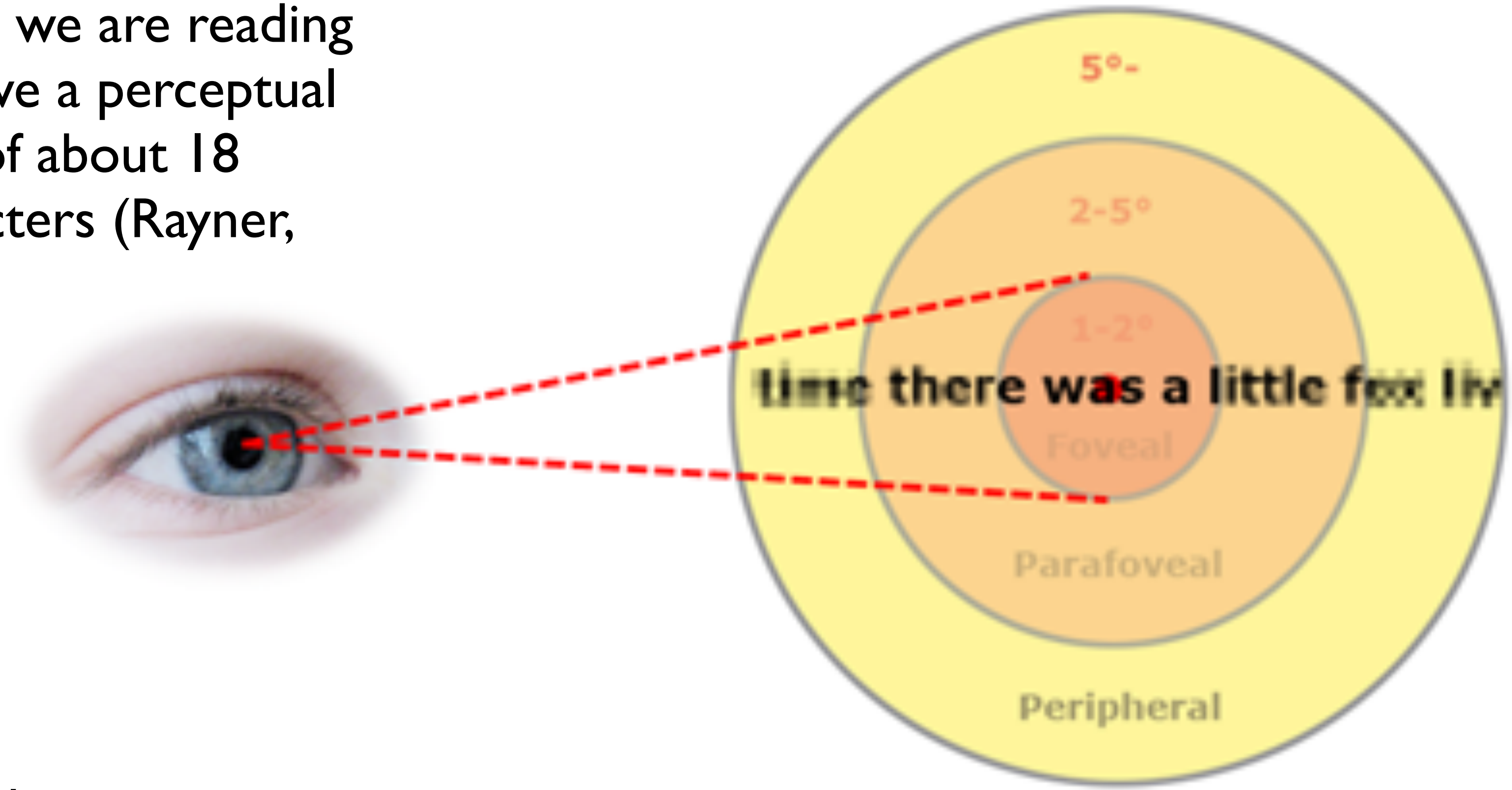
fixations and saccades



http://eyetracking.me/?page_id=9

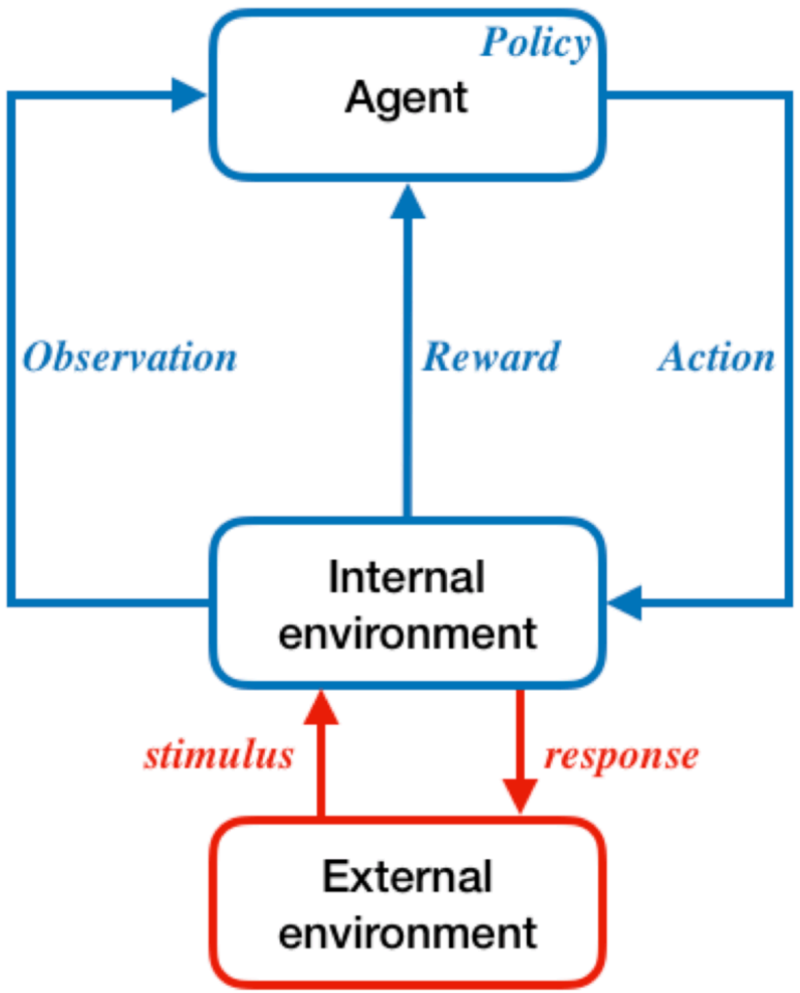
letter perception

- When we are reading we have a perceptual span of about 18 characters (Rayner, 1998).



- we make a sequence of fixations and saccades in order to read a sentence.

http://eyetracking.me/?page_id=9


Policy
Agent
Observation
Reward
Action
Internal environment
stimulus
response
External environment

Practical exercise 1:
foveated vision

Closing comments

- Very simple model of *bounds.*
- No difference between colour, shape, size. No spatial smearing.
- Look no data.
- No programming of heuristics — e.g. no rule for “inhibition of return”. No “salience”.
- Next: (1) Bayesian state estimation (Kalman Filter) and (2) learning an optimal policy with RL.
- How might Bayesian inference help?