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Cognitive Strategies in PAC-MAN: Insights from Macaques and Machine Learning

Lin, Z., Li, Y., & Yang, T.; arXiv (2024)

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Zhang, J., & Yang, T.; *eLife* (2022)

Changfa FU

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which our campuses are situated





Warning

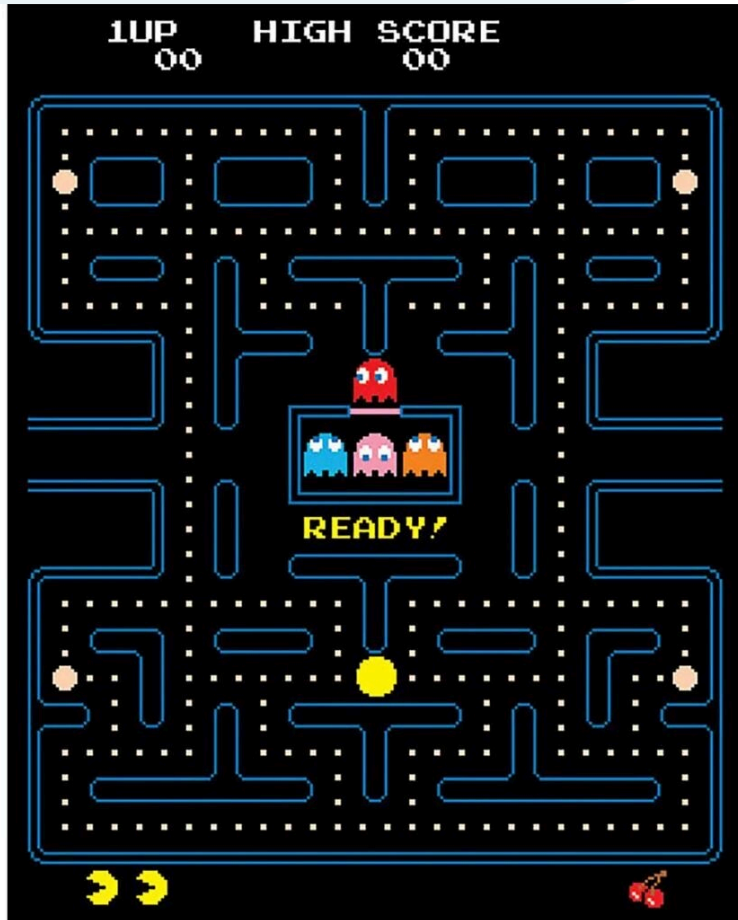
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Have you played Pac-Man?





Existing Literature

The Importance of Decision-Making:

- Survival and adaptability hinge on decision-making, influencing choices in foraging, mating, and social interaction (Stevens, 2010).
- Complex, value-based decisions require weighing multiple attributes such as risk, reward, and strategy (Padoa-Schioppa & Assad, 2006).

Why Study Macaques?

- Advanced cognitive abilities, imply human-like decision-making (Subias et al., 2024).
- Their ability to plan and adapt strategies (Beran et al., 2015; Janson, 2014; Macellini et al., 2012).

Why Pac-Man?

- Mimic natural foraging behaviours, combining spatial navigation, reward optimisation, and real-time strategy (Yang et al., 2022; Lin et al., 2024).
- Precisely control and measure decision-making variables and enable dynamics.

Use of Transformer Networks:

- Leverage attention mechanisms to model sequential data effectively (Vaswani et al., 2017).
- Predictive power of self-attention mechanism in complex, dynamic tasks (Eberle et al., 2022)



Study Aim

Paper 1

- Monkey Plays Pac-Man with Compositional Strategies and Hierarchical Decision-Making (Yang et al., 2022)

Research Gap

- Underexplored: Macaques' use of compositional strategies and hierarchical planning in dynamic tasks.
- Underexplored: Macaques' strategies adaptation in real-time spatial navigation and reward optimisation.

Research Question

- How do macaques approach decision-making in a dynamic, reward-driven task like Pac-Man?
- Can their gameplay be modelled effectively using computational frameworks?
- What cognitive strategies emerge, and how do they align with human-like decision-making processes?

Experiment Design: Subjects



Subjects:

- Two adult male rhesus macaques (O & P)
- On average 6 – 7 kg

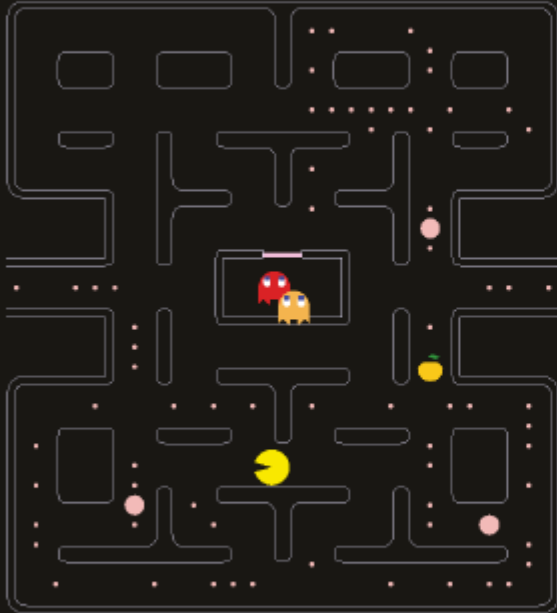
Setting:


- Facing a 27-inch monitor placed 68cm away
- Four-way joystick, sampled at 60 Hz
- Eyelink 1000 Plus sampling at 500 or 1000 Hz











Data Recorded:

- 33 ± 9 games in each session
- 4.86 ± 1.75 attempts in each game
- Dataset includes 3217 games, 15,772 rounds, and 899,381 joystick movements.

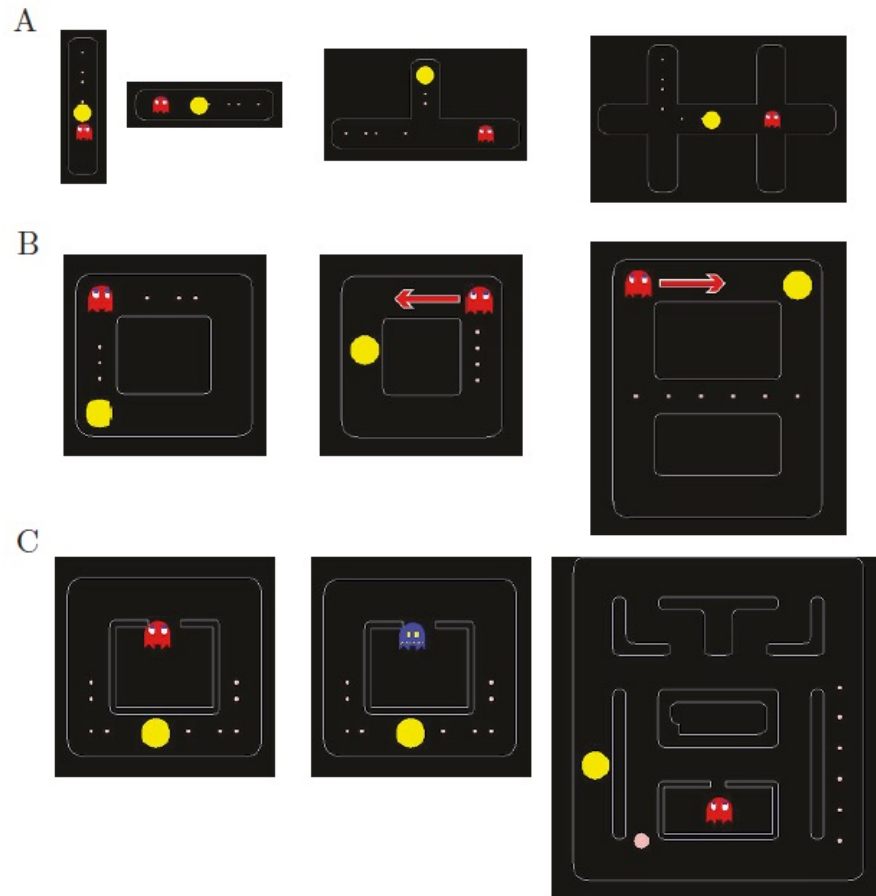
Experiment Design: Tasks



Task elements 

Ghosts		Food		
normal mode	scared mode	Energizer	Pellet	
 				
Blinky	Clyde	4 drops	2 drops	
	8 drops			
Fruits				
honeydew	apple	orange	strawberry	cherry
				
17 drops	12 drops	8 drops	5 drops	3 drops
Final Reward				
1-3 rounds	4-5 rounds	>5 rounds		
20 drops	10 drops	5 drops		

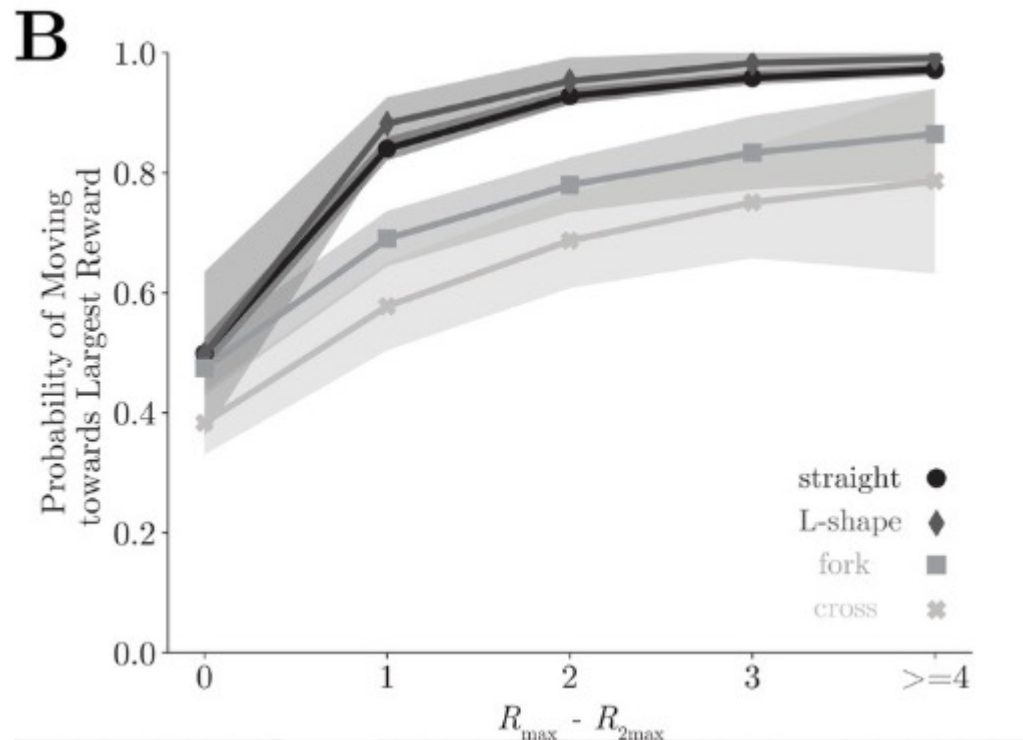
Experiment Design: Training



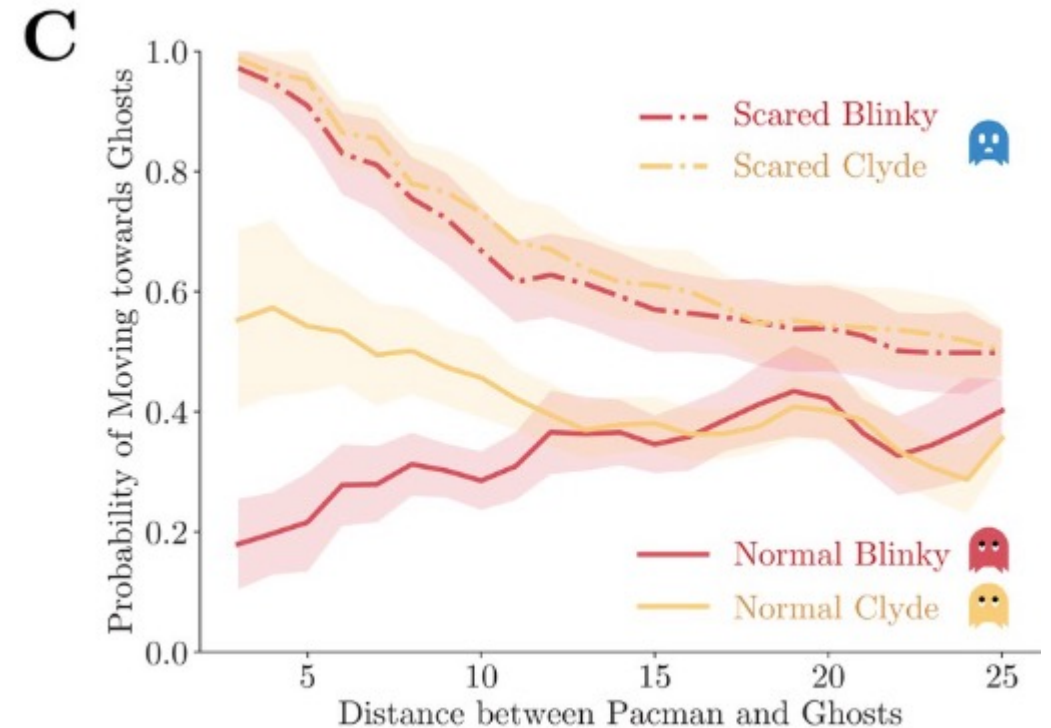
Training Procedure:

1. Trained to use the joystick to control Pac-Man to navigate in simple mazes for collecting pellets, requiring 80% accuracy
 - Linear maze
 - T-maze
2. Trained to deal with the ghosts and navigate in loops
 - Ghosts still at the corner
 - Ghosts move within arm
 - Ghosts chase Pac-Man
3. Trained to understand the energizer
 - Understand scared ghosts as compared to normal
 - Scared ghosts only triggered by energizer
 - Full maze for final gameplay

Result 1: Monkeys' reaction to elements, essentially performing a foraging task



The monkeys were more likely to move toward the direction with more local rewards.



The monkeys escaped from normal ghosts and chased scared ghosts.



Models

Dynamic compositional strategy model

- Estimates the strategy weights using time windows of flexible length, assuming the relative strategy weights are stable for a period.

Static strategy model

- Uses all data to estimate a single set of strategy weights.

LARL model

- Standard Q-learning algorithm using the monkeys' actual joystick movements as the fitting target, assuming the parameterization of the utility function is linear with respect to the game features:

Linear perceptron model

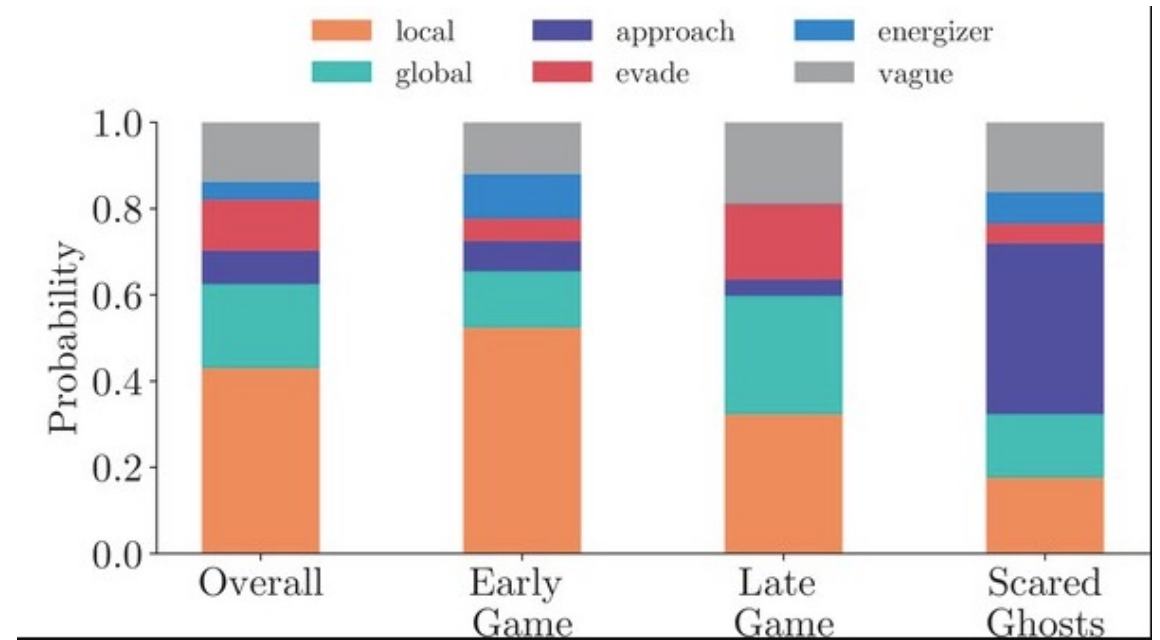
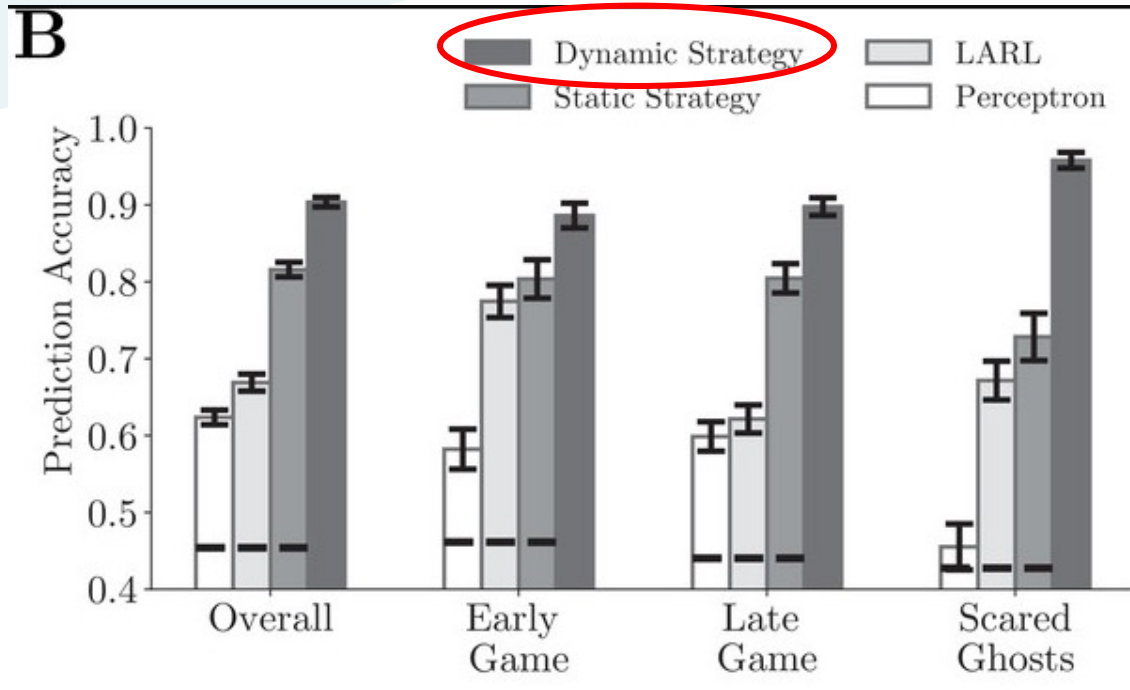
- Representative flat descriptive model to describe monkeys' decision-making based on the same 20 features included in the other models.

Transformer Network

- Standard vision transformers (ViT) on eye tracking data

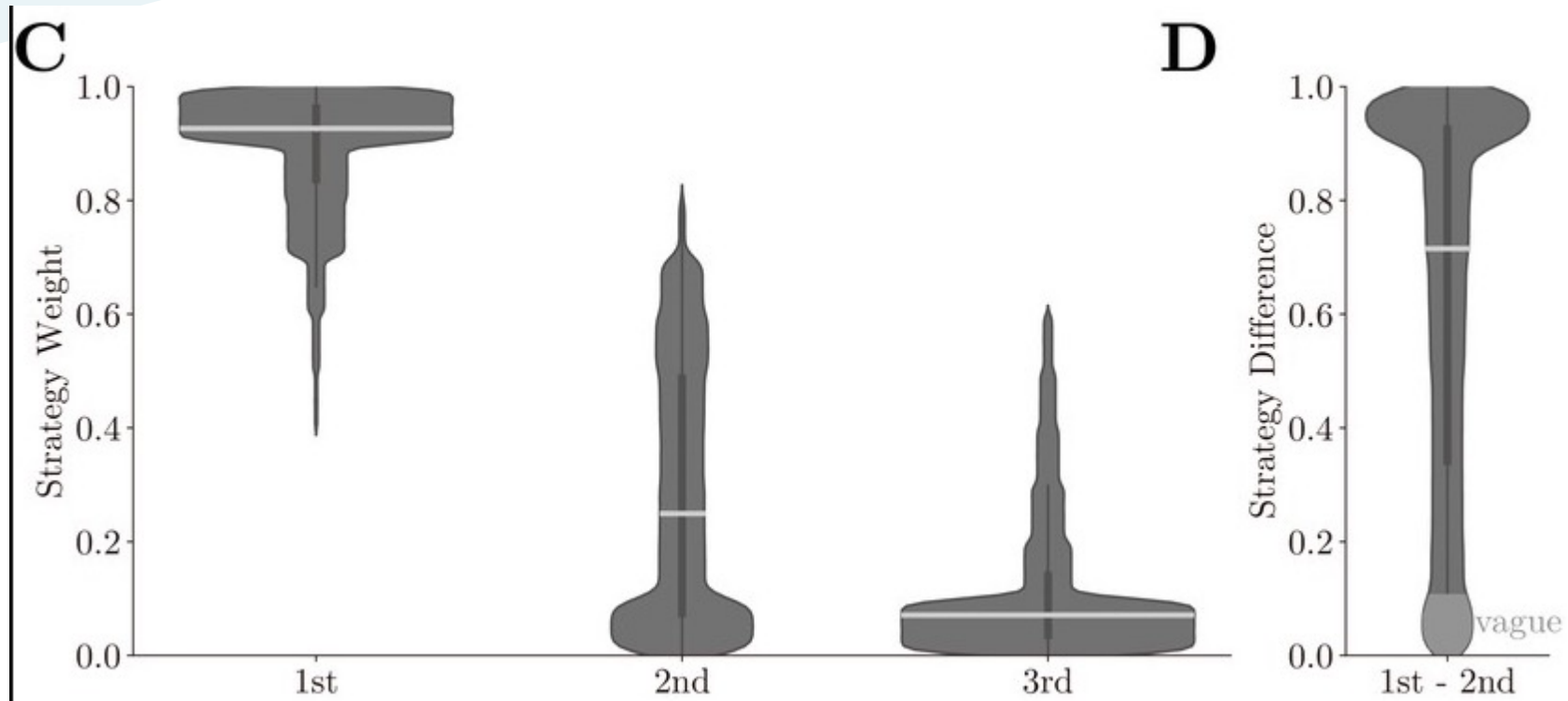
Results 2: Monkeys adopted different strategies at different game stages

Hierarchical

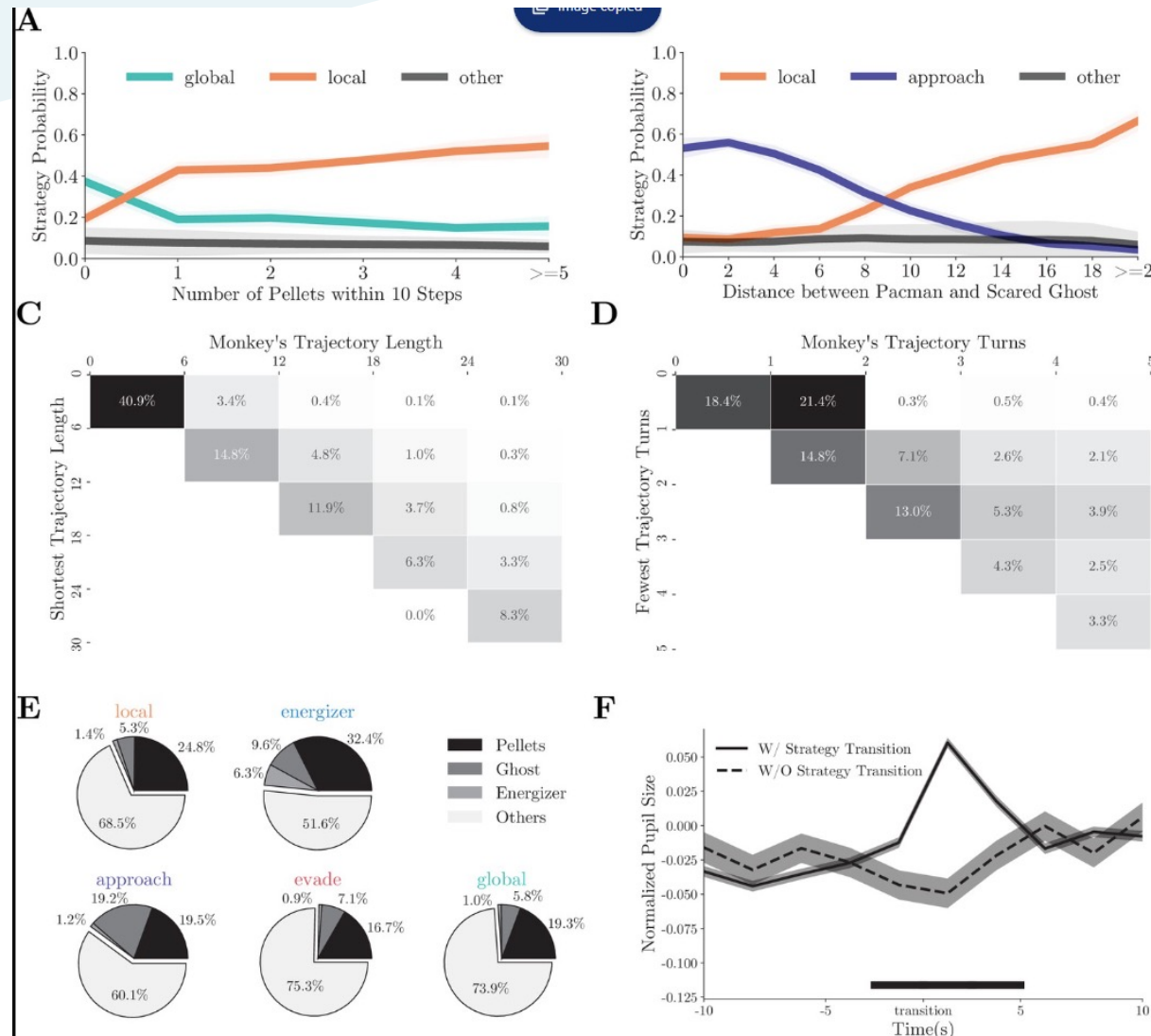


Context	Selection criteria
All stage	n.a.
Early game	Remaining number of pellets $\geq 90\%$ of total (80 for O and 65 for P)
Late game	Remaining number of pellets $\leq 10\%$ of total (10 for O and 7 for P)
Scared ghost	Any scared ghosts within 10 steps away from Pac-Man

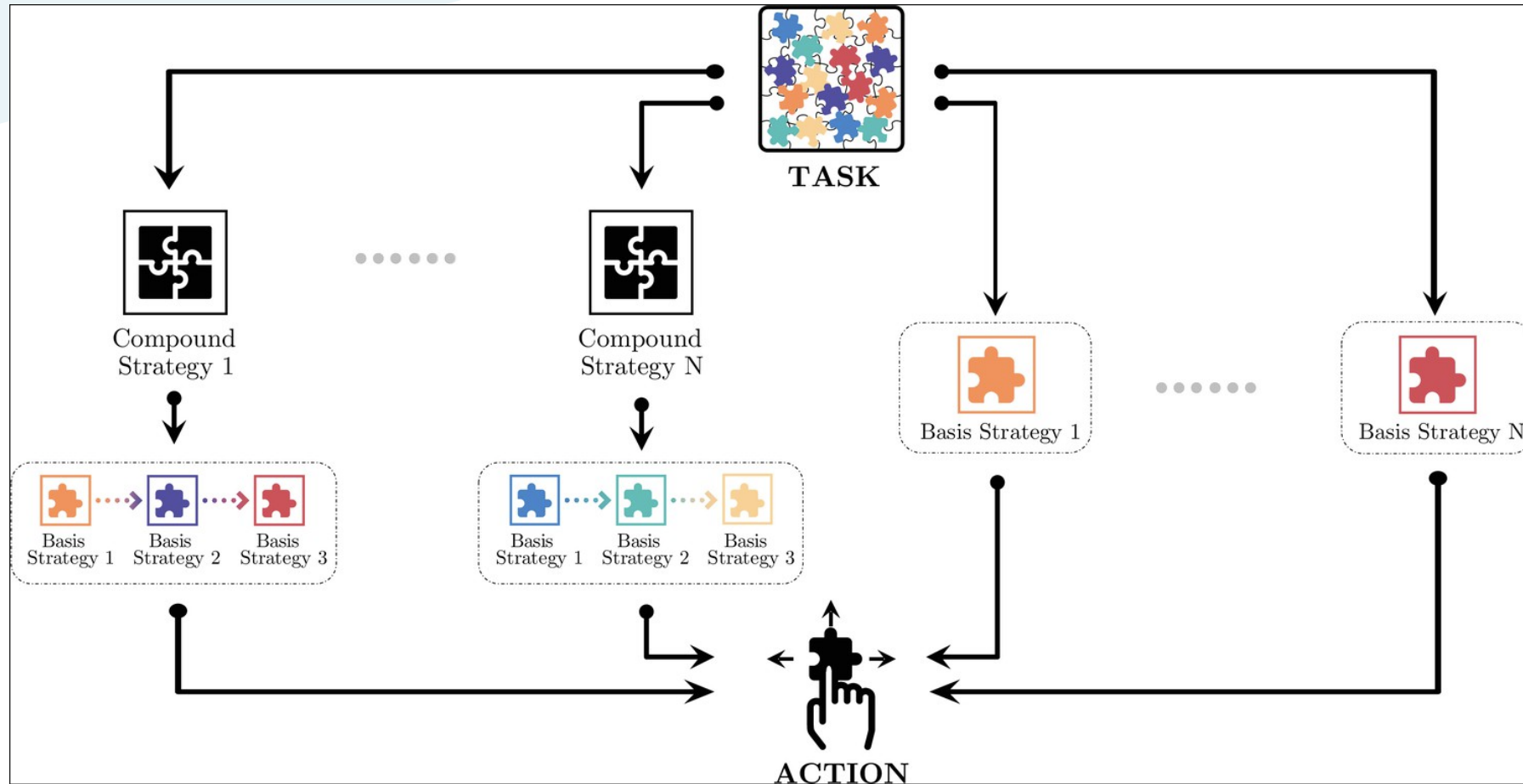
Result 3: Monkeys adopted take-the-best (TTB) heuristic



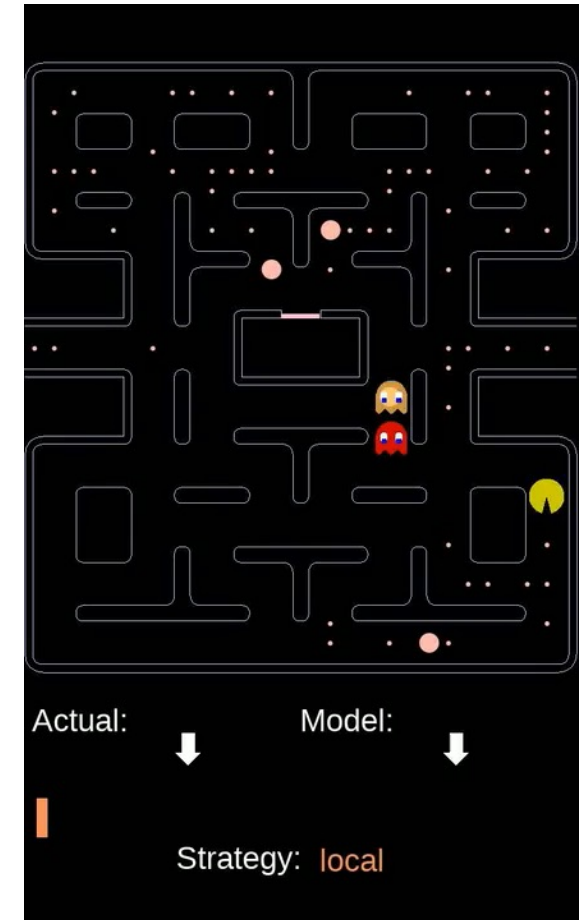
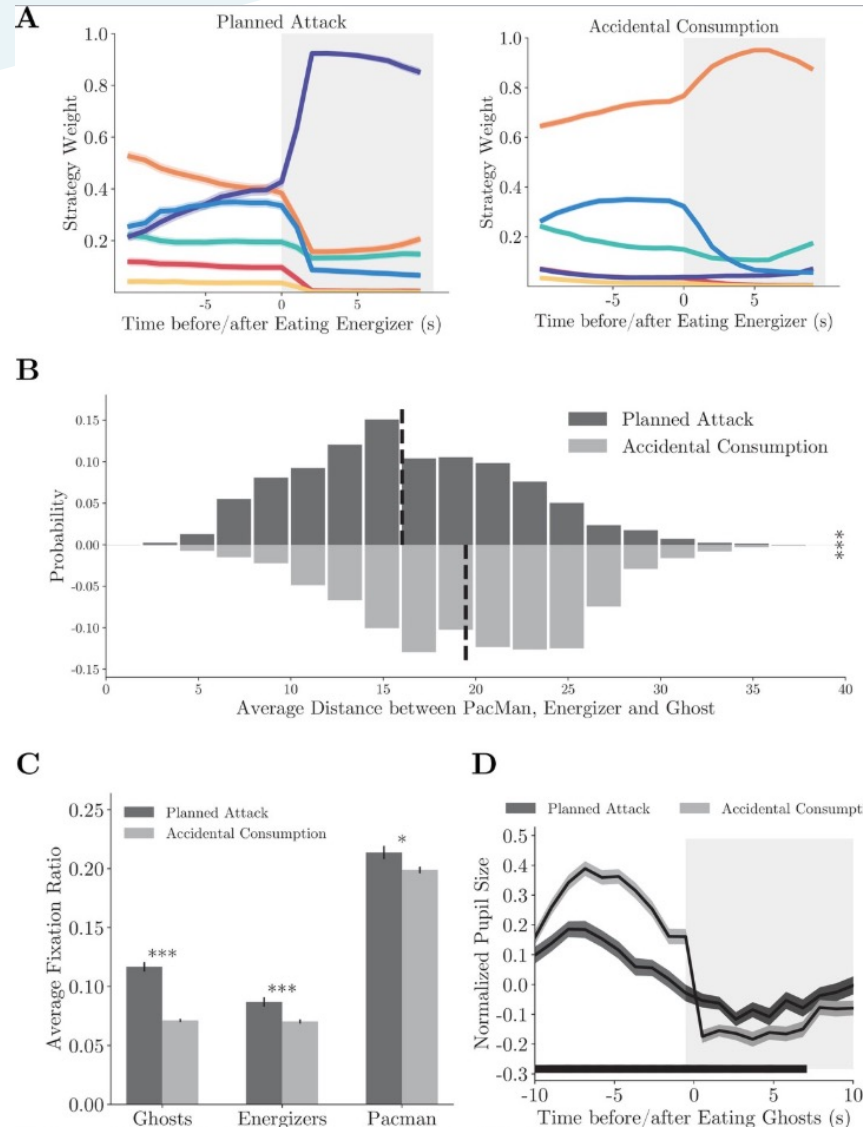
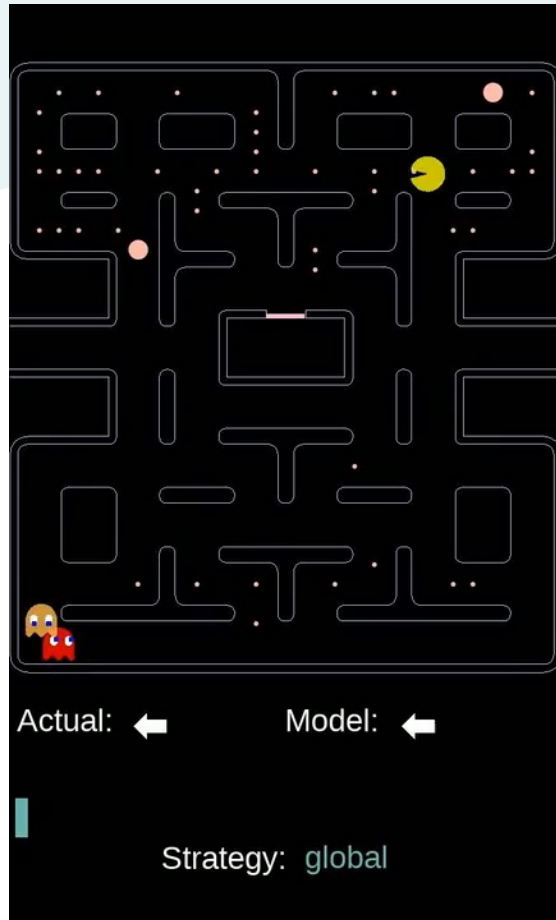
Result 4: Strategy manifested in behavior



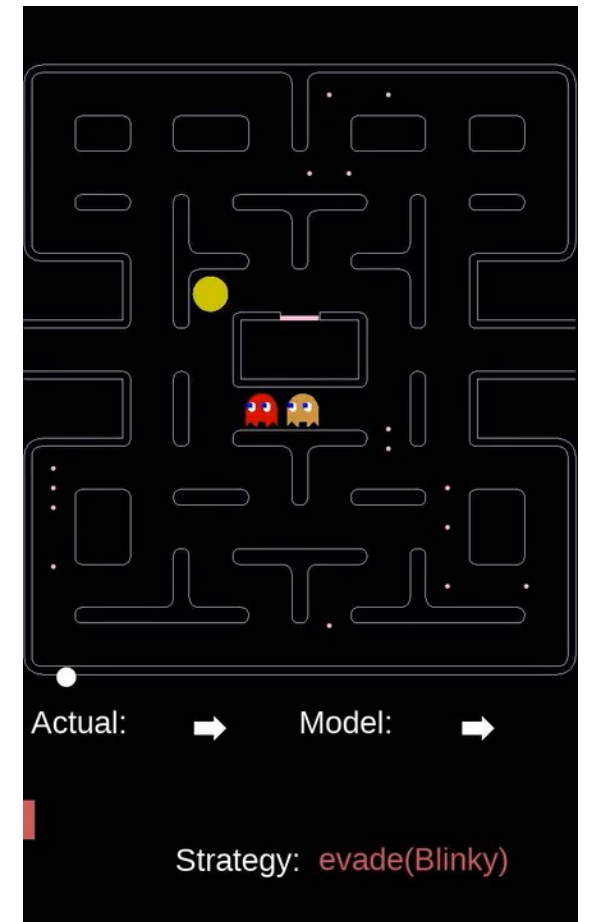
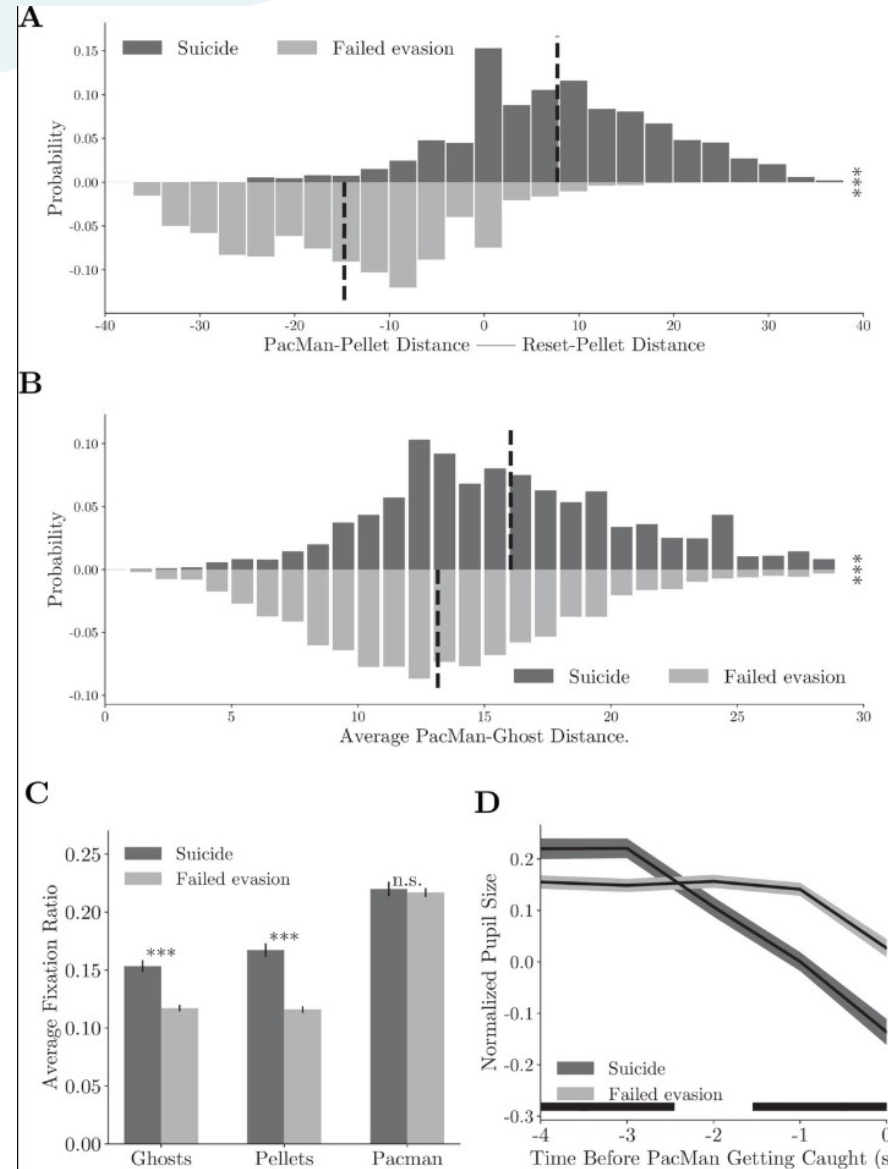
Result 5: Monkeys' decision-making in different hierarchies (Compound)



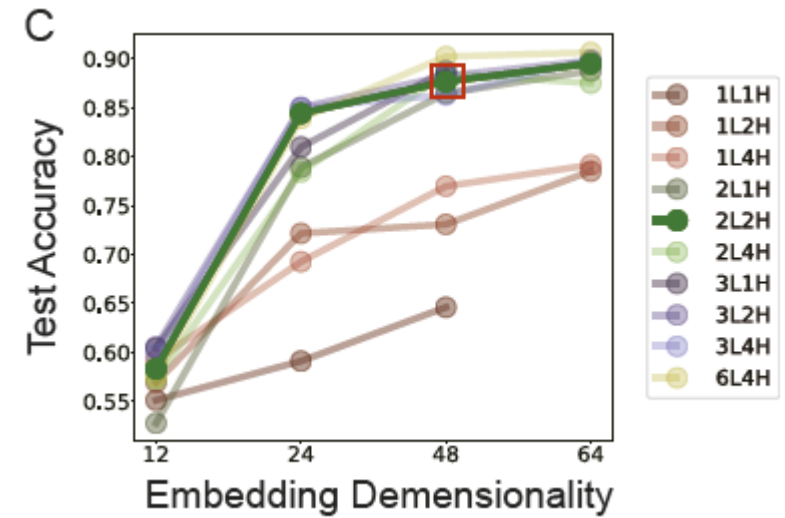
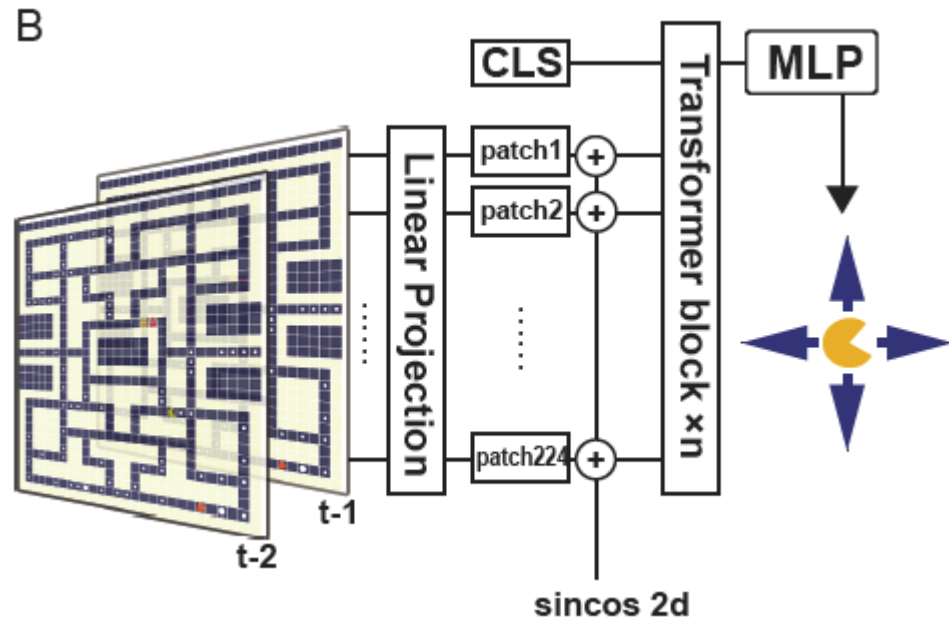
Result 6: Planned or Accidental



Result 7: Suicide or Failed Evading

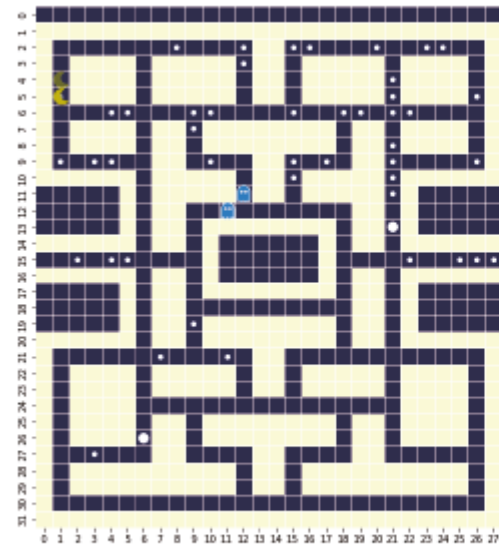


Transformer Network

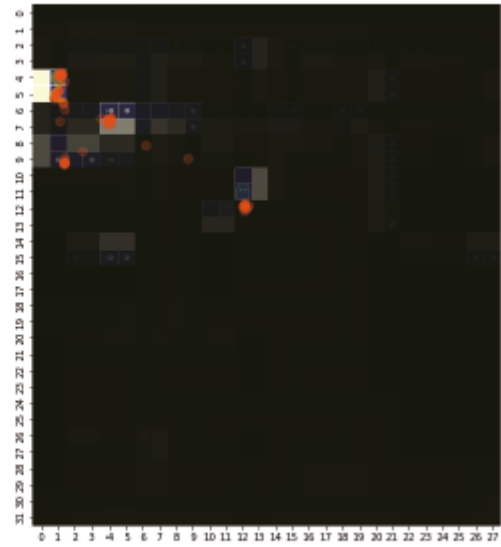


Example Scenario

A

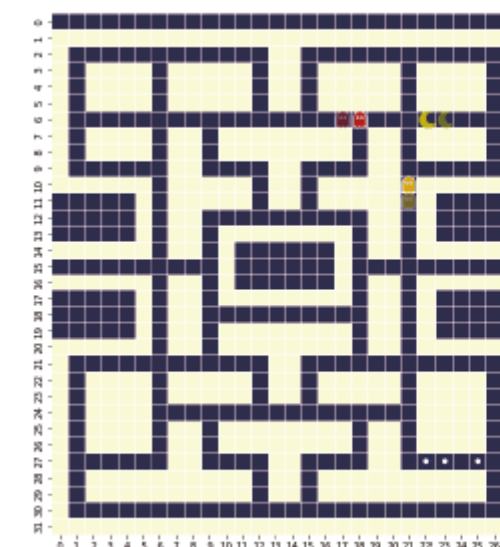


Game State

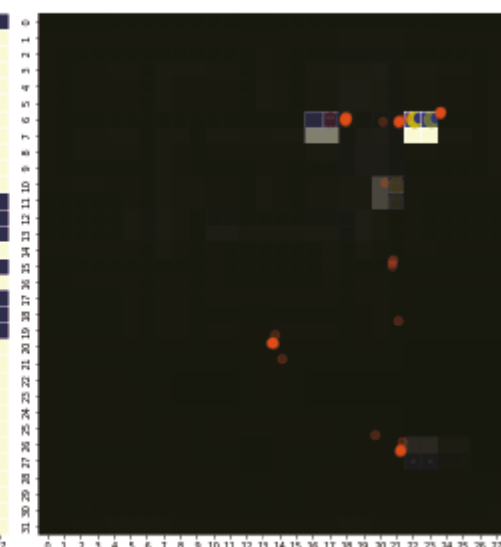


Model Attention
and Monkey Gaze

B

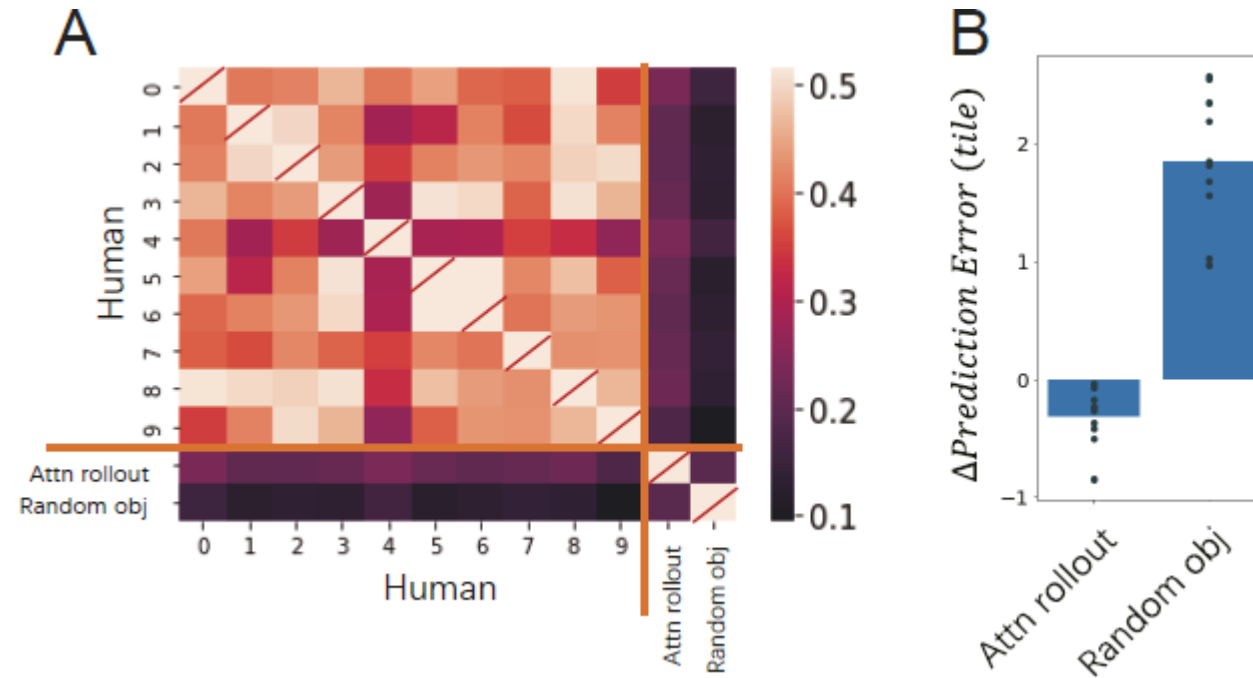


Game State

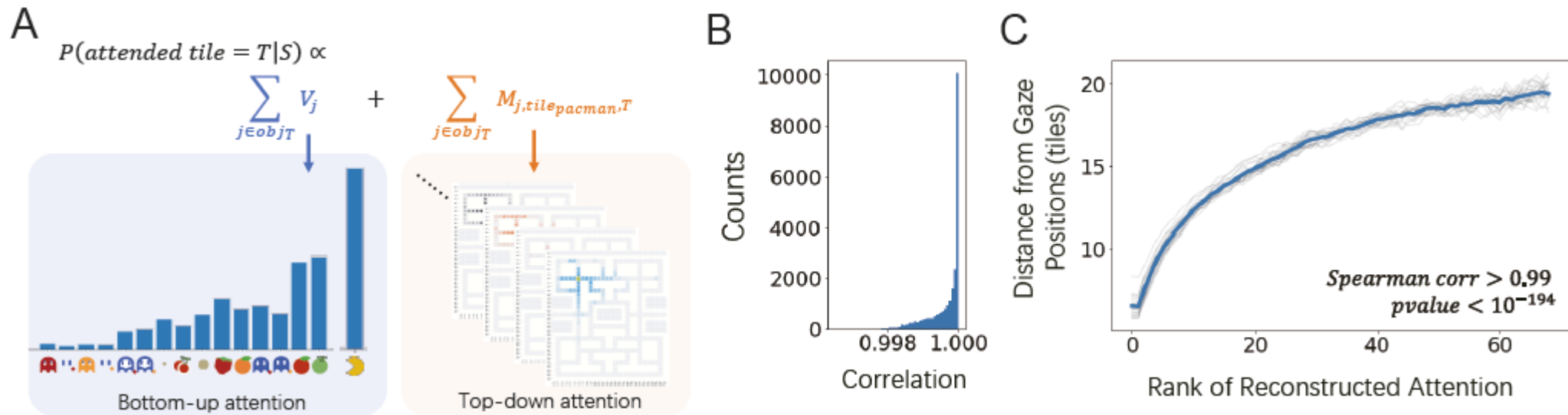


Model Attention
and Monkey Gaze

Result 8: Humans' prediction of monkeys' focus when making directional decisions at junction.



Result 10: Condensed Model of Attention





Discussion:

Paper 1

- Monkeys demonstrated compositional strategies by focusing on specific tasks (e.g., pellet collection) and adapting dynamically to game states.
- Hierarchical decision-making allowed them to prioritise strategies based on context, such as avoiding ghosts when they were nearby.

Paper 2

- Transformer networks aligned closely with the monkeys' gaze behaviours with self-attention mechanisms
- Dissected the role of value-based attention and interaction-based attention.

- How do these findings inform understanding of cognitive flexibility in macaques, and how does it compare to human cognition?
- Can transformer models be generalized to other tasks or species? What are limitations?
- What does this say about the balance between heuristic-based decisions and fully optimal strategies in animals?



Limitations & Implications

Small sample size

- Need research on biological variables such as age or sex

Neural Imaging?

- May introduce neural imaging techniques (e.g., fMRI, calcium imaging) with behavioral tasks to map brain regions associated with compositional strategies.

Validity of Transformer

- Validates transformer networks as tools to decode behavioral patterns, especially in dynamic and reward-based tasks.

Research Extension:

Investigate the cognitive and neural mechanisms underlying decision-making complexity in macaques using structured tasks inspired by the Grid-Based Traveling Salesman Problem (TSP).



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