CRC - Incipient Cognition

Miguel Albuquerque[1][1105828], Pedro Baptista[1][96302], and José Moniz[1][110960]

[1] Instituto Superior Técnico, Av. Rovisco Pais 1, 1049-001 Lisboa, Portugal
[2] {miguel.albuquerque,pedro.maria.baptista,jose.f.moniz}@tecnico.ulisboa.pt

Abstract. The evolution of cooperation in dynamic systems, particularly in distributed networks, is a significant focus in evolutionary game theory. These systems model agent interactions where decisions to cooperate or defect shape long-term network stability. In this study, we replicate and confirm the results of Vukov et al., demonstrating that incipient cognition—the ability of agents to adapt strategies based on prior interactions—significantly enhances cooperation in spatial networks. Through extensive simulations, we observe that incipient cognition fosters cooperation even under high temptation to defect. Our findings highlight the robustness of cooperation when agents employ cognitive strategies, and how factors like noise in strategy adoption do not prevent cooperative behavior. These results reinforce the theoretical predictions and provide strong evidence for applying these models to real-world distributed systems.
TODO:
- general problem (1 specific)
- summarize Findings (1 "here we show")
- explanation of main results (2-3)
- results in general context (1-2 broad)
- ? broader perspective (2-3)

- What is Incipient Cognition

1 Introduction

1.1 Background

- Prisioner's Dilemma
- Direct Reciprocity
- Cooperation in homogeneous worls + Spatial Reciprocity
- Different Tensions, different dilemmas
- Homogeneous VS heterogeneous networks (+ role of heterogeneity)

1.2 Motivation and Related Work

The evolution of cooperation in dynamic systems is a central question in evolutionary game theory, with implications for fields ranging from biology to social networks and distributed control systems [4]. Cooperation, though beneficial for the collective, is often undermined by defection, where individual agents seek short-term gains at the expense of collective well-being [6]. The Prisoner's Dilemma (PD) offers a fundamental framework for examining such interactions, presenting agents with a choice between cooperation and defection, and its dynamics have been widely studied to understand the conditions under which cooperation can emerge and persist [3].

Spatial structure has long been recognized as a crucial factor in promoting cooperation. When agents are embedded in spatially structured networks, such as grids or lattices, cooperative clusters can form and resist invasion by defectors. However, spatial reciprocity alone is often insufficient to ensure long-term cooperation, especially under high temptation to defect [3,5].

Recent studies, including the work by Vukov et al. [2], introduced the concept of incipient cognition to address this limitation. Incipient cognition allows agents to adapt their strategies based on previous

interactions, providing a more dynamic and flexible approach to decision-making. By allowing agents to remember and react to past experiences, cognitive abilities can significantly enhance cooperation, even in environments where defection might otherwise dominate. Vukov et al. demonstrated that incorporating these cognitive abilities into agents' decision-making processes led to robust cooperation, even under conditions of high temptation to defect.

In this study, we replicate and extend the findings of Vukov et al., confirming the impact of incipient cognition on the evolution of cooperation in spatial networks. **By introducing slight refinements in the cognitive decision-making processes and incorporating stochastic variations in strategy adoption** , we aimed to explore the robustness of cooperation in dynamic systems further. Our results align with the theoretical predictions, demonstrating that agents employing incipient cognition maintain high levels of cooperation, even under significant temptation to defect.

TODO:

– (improve) motivation & related work

2 Methods/Model

2.1 Baseline: Previous Work

The foundational work by Vukov et al. [2] explored how incipient cognition, coupled with spatial structure, promotes cooperation in a Prisoner's Dilemma setting. In this paper's model, agents occupied nodes on a network and interacted only with their immediate neighbors. Each agent's decision to cooperate or defect was influenced by prior interactions, allowing for adaptive strategies based on the last behavior. Fitness, calculated as the accumulated payoff from repeated interactions, determined strategy evolution. **Agents adopted the strategies of more successful neighbors probabilistically, with occasional mutations introducing stochasticity into the process.**

Their results highlighted the crucial role of spatial structure in facilitating cooperation. Cooperative agents tended to cluster, protecting themselves from defection and sustaining cooperation over time. Vukov et al. also found that the temptation to defect, represented by the parameter b, played a pivotal role in determining the sustainability of cooperation. Notably, their model already incorporated cognition-based strategy adaptation, where agents adjust their behaviors based on previous interactions, leading to the formation of robust cooperative clusters even under conditions of temptation.

TODO

– Explain what is spatial structure

2.2 Our Approach: Implementation and Simulation Setup

To replicate and further examine the role of cognitive adaptation in promoting cooperation, we implemented a model that builds upon the framework established by Vukov et al. **While their model already utilized fitness-based strategy evolution, incorporating cognitive parameters, we refined the cognitive decision-making processes to explore their impact in greater detail.**

Each agent in our model was defined by two evolving parameters:

TODO: colocar imagem de p e q descritivo como no paper

$$p : \text{Probability of cooperating after a cooperative interaction.}$$

$$q : \text{Probability of cooperating after a defecting interaction.}$$

These parameters were updated as agents interacted with their neighbors, allowing for a dynamic adjustment of strategies based on the outcome of previous interactions. **Additionally, we introduced stochastic noise in the imitation process, simulating small random fluctuations in the values of p and q. This noise added an element of variability to the agents' decision-making, reflecting more realistic cognitive decision-making processes compared to purely deterministic models.**

TODO: reformulate/add/improve on the simulations done - how much, each config, ... Simulations were conducted on a 50×50 lattice, with each agent interacting with its four nearest neighbors (Von Neumann neighborhood). We systematically varied the temptation to defect, denoted by b, across multiple simulation runs to assess the sensitivity of cooperation to this parameter. Each simulation ran for 25,000 generations, with a transient period included to allow the system to stabilize before data collection.

Our approach confirmed the results of Vukov et al., demonstrating that incipient cognition, when coupled with spatial structures, leads to robust cooperation even under conditions of high temptation to defect. **The refinement of cognitive processes in our model allowed us to further explore the nuances of how stochastic noise and adaptive decision-making contribute to the persistence of cooperation.**
TODO:

– what we added
– what we changed

3 Results and Discussion

3.1 Comparison with Baseline Studies

Previous research by Vukov et al. demonstrated that spatial structures within networks can sustain high levels of cooperation by forming clusters of cooperative agents. When the temptation to defect was low ($b = 1.1 - 1.3$), these clusters provided a buffer against defectors, allowing cooperation levels to consistently exceed 80%.

In our simulations, we were able to replicate these findings, confirming that cooperation remains robust under similar conditions ($b = 1.1$). By applying cognitive-based strategy adaptation—where agents adjust their probabilities of cooperating based on previous interactions—we observed similarly high levels of cooperation. These results confirm the effectiveness of spatial structure and cognition in promoting cooperation, **even when stochastic elements such as noise are introduced into the strategy evolution process.**

3.2 Insights from Cognitive Adaptation

One of the key findings from our simulations is the importance of cognitive strategy adaptation in sustaining cooperation, even in the presence of stochastic noise. Similar to Vukov's model, our agents adopted strategies based on their past experiences with neighbors. **The introduction of Gaussian noise** allowed agents to slightly deviate from their neighbors' strategies, introducing variability that better reflects real-world decision-making processes.

As expected, when the temptation parameter b ranged from 1.4 to 2.0, cooperation levels began to decline, **and defectors gradually overtook the network. (corr.: they did not overtake...)** While higher values of b naturally incentivize defection, the decline in cooperation was gradual and followed the trends observed in Vukov's results. **This demonstrates that cognitive adaptation, even when paired with stochastic noise, can sustain cooperation under moderate temptation but faces challenges as b increases further. (corr.: explain more about this rationale)**

3.3 Additional Findings

Our simulations also **revealed (corr.: observed)** the significance of the transient period in the evolution of cooperation. Early in the simulations, bursts of cooperation were observed before the system stabilized at higher levels of cooperation. **This transient behavior indicates that agents need time to explore and adapt their strategies before settling into more stable interaction patterns (corr.: explore this more)** , a phenomenon also noted by Vukov et al.

Furthermore, the cognitive memory mechanisms in our model—where agents adjust their strategies based on previous interactions—introduced a level of complexity that goes beyond simpler models. (corr.: this is not ours, is taken from the paper) Cooperative bonds were maintained for longer periods in environments with lower temptation values, but as b increased, the accumulated noise began to affect these bonds. This finding emphasizes the trade-off between adaptability and stability, where cognitive mechanisms allow for flexible decision-making but can also introduce new challenges in maintaining long-term cooperation.
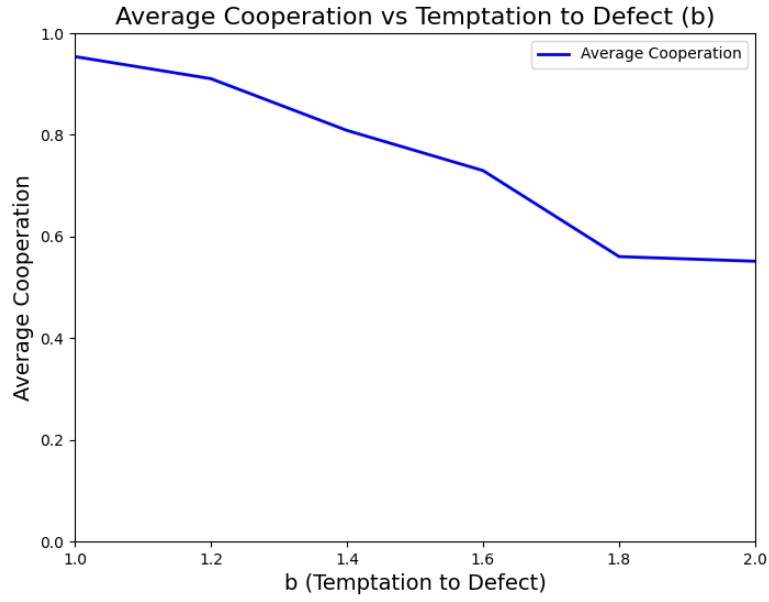
Fig. 1. Average Cooperation as a function of the temptation to defect (b). The plot shows how cooperation levels decrease as b increases, with significant drops when $b > 1.4$.
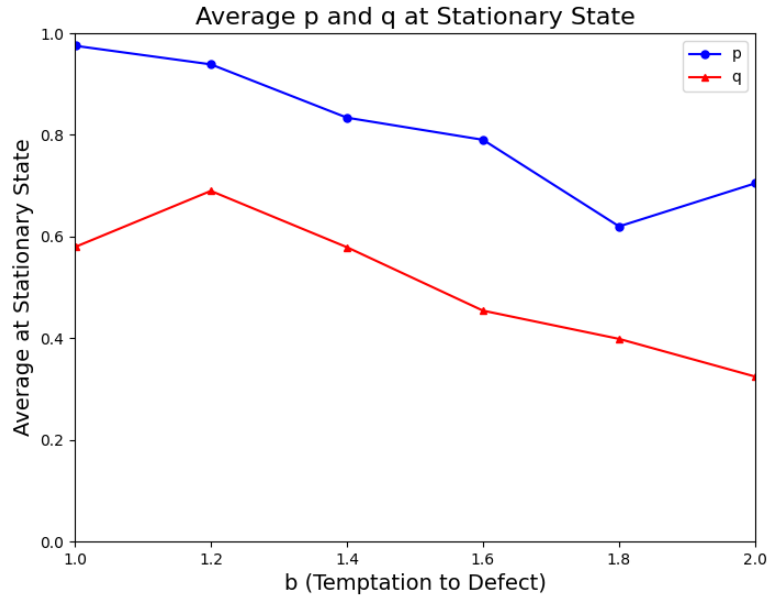

Fig. 2. Average values of p (probability of cooperating after cooperation) and q (probability of cooperating after defection) as a function of b. As b increases, both p and q decrease, reflecting a reduction in cooperation likelihood.

3.4 Context and Broader Implications

Our results, consistent with those of Vukov et al., reinforce the critical role of cognitive mechanisms in **sustaining cooperation within spatial networks.Adding elements such as memory-based decision-making and stochastic noise provides a more realistic simulation of real-world dynamics, where agents do not always behave deterministically. While Vukov et al. demonstrated that spatial structure alone can promote cooperation, our findings suggest that cognition-based strategy adaptation further enhances these effects, making cooperation more resilient to variations in temptation to defect.**

However, this realism comes with increased complexity. Cognitive adaptations introduce variability that may hinder cooperation under certain conditions, particularly when noise levels are high or temptation values exceed certain thresholds. These insights highlight the importance of balancing cognitive flexibility with strategy stability and underscore the need for further research into the interplay between noise and cognition in models of cooperation.

Our findings suggest that these models have significant potential for application in real-world systems, such as distributed networks and social platforms, where cooperation between agents is essential for system stability. **Future research should focus on exploring how adaptive noise levels and more complex cognitive strategies can be applied to enhance cooperation in increasingly dynamic environments.**

4 Conclusion

4.1 Limitations of Our Model and Methods

While our model successfully replicated the results of Vukov et al. and confirmed the role of cognitive mechanisms in promoting cooperation in dynamic networks, several limitations remain. A key limitation is the simplification of agent memory and decision-making processes. In our model, agents base their strategies only on the most recent interaction, which may not fully capture the cumulative effects of multiple interactions or long-term relationships. This simplification may underestimate the potential for the formation and stability of cooperative clusters over extended periods.

Furthermore, the use of Gaussian noise to introduce random mutations in strategy imitation, while valuable for adding variability, may overestimate the frequency and impact of random fluctuations in real-world systems. In practice, agents may not experience mutations as frequently or as randomly as modeled here, potentially leading to an overemphasis on instability in our results. Additionally, our model was limited to a lattice structure, which constrained our ability to explore more complex network topologies, such as small-world or scale-free networks. These structures could offer deeper insights into how different topological arrangements affect cooperation dynamics.

Lastly, our simulations were confined to a specific range of temptation values (b) and fixed noise levels. While this range provided valuable insights, expanding the parameter space or introducing adaptive noise could provide a more comprehensive understanding of how these factors influence cooperation.

4.2 Future Work and Potential Applications

Despite these limitations, our model opens several avenues for future research. Incorporating more sophisticated memory mechanisms into agent decision-making could offer a richer understanding of how long-term interactions shape cooperation. Future studies could explore how agents accumulate trust or mistrust over multiple rounds of interaction, influencing their probability of cooperating or defecting in subsequent games. Moving beyond the single-interaction memory used in our model, the introduction of "reputation," where agents base decisions on both direct interactions and the reputations of their neighbors, could provide deeper insights into the persistence of cooperation in more complex environments.

Moreover, extending our model to heterogeneous networks, where agents differ in both their initial strategies and their connectivity, would provide an important next step. Studies have shown that heterogeneous structures, such as those found in social and biological networks, can significantly affect the persistence of cooperation. Investigating how cognitive agents behave in such environments, especially when some agents hold more influence, could yield valuable insights into how network topology fosters cooperation.

Another promising area for future work is the study of adaptive noise levels. In our simulations, the noise level in strategy imitation was fixed throughout the generations, but in real-world systems, individuals may adjust their sensitivity to noise based on environmental factors or prior experiences. Allowing agents to modify their noise tolerance dynamically could reveal how agents balance exploration (trying new strategies) and exploitation (maintaining successful strategies) in evolving networks.

Finally, practical applications of this model could extend to distributed systems and social networks, where cooperation between individuals or agents is critical for maintaining system stability. Understanding how cognitive mechanisms influence cooperation can help inform the design of distributed decision-making algorithms and provide insights into encouraging cooperation in online platforms, organizations, and decentralized systems. By further exploring the interactions between cognition and network topology, future research can offer more robust strategies for fostering cooperation in a variety of real-world settings.

References

1. Francisco, A, et al.: IST - Ciência de Redes Complexas - Class slides Lisbon (2024)
2. Vukov, J., Szabó, G., Szolnoki, A.: Cooperation in the noisy case: Prisoner's dilemma game on two types of regular random graphs. Physical Review E, 72(6), 067107 (2005)
3. Nowak, M. A., May, R. M.: Evolutionary games and spatial chaos. Nature, 359(6398), 826-829 (1992)
4. Nowak, M. A.: Five Rules for the Evolution of Cooperation. Science, 314(5805), 1560-1563 (2006)
5. Szabó, G., Fáth, G.: Evolutionary games on graphs. Physics Reports, 446(4-6), 97-216 (2007)
6. Axelrod, R., Hamilton, W. D.: The evolution of cooperation. Science, 211(4489), 1390-1396 (1981)
7. Szolnoki, A., Perc, M., Szabó, G.: Evolutionary dynamics of cooperation in neutral populations. Physical Review E, 87(5), 051101 (2013)
8. Tanimoto, J.: Evolutionary Games with Sociophysics: Analysis of Traffic Flow and Epidemics. Springer (2015)