BEYOND LOCAL INTERACTIONS: REVISITING SPATIAL EVOLUTIONARY PRISONER'S DILEMMA

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ABSTRACT

This paper examines the effects of the locality of interactions in a spatial evolutionary Prisoner's Dilemma model on several existing individual strategies, and inspects the actual cooperation levels that these strategies are able to achieve. In addition, a strategy based on the in-group/out-group concept is compared against individual strategies. The results show that the reduction in locality of interactions produces a significant reduction in the levels of cooperation among individual strategies. Furthermore, the group strategy is able to outperform individual strategies, while achieving a high level of cooperation among the population in all scenarios.

Keywords: game theory, prisoner's dilemma, agent-based modeling, social groups.

1 INTRODUCTION

This paper builds on the spatial evolutionary Prisoner's Dilemma model introduced by Nowak [1], with the aim to examine the performance of a number of existing strategies, both simple and memory-based, in environments with different levels of the locality of interactions. While interactions that take place only with immediate neighbors in a spatial environment promote cooperation between individuals [1], in real world we find many non-local, random interactions as well: grocery shopping, transit commute, and more. Therefore, it is important to examine how these one-off interactions impact the performance of various strategies. Preliminary results suggest a significant impact on the levels of cooperation among the individuals, challenging the interpretation of Tit-For-Tat and Pavlov as a cooperative strategies [1].

Furthermore, we also introduce a different strategy based on the concept of in-group/out-group dynamics and examine its performance against individual strategies across environments of varied locality. Unlike memory-based approaches, an individual using this strategy only needs to recognize whether another individual is a member of its group or not, and this strategy produces robust results.

2 BACKGROUND

Social scientists have been trying to address the challenge of simulating interaction and decision-making between people, animals, and even computer agents. Game theory presents one such approach in the form of stage games, where the interaction can be represented with a matrix that contains the payoff values for the actions that can take place, and allows one to examine interactions mathematically. This paper focuses on the Prisoner's Dilemma game, which was framed by Merrill Flood and Melvin Dresher, and later formalized by Albert W. Tucker [2]. A typical Prisoner's Dilemma illustrates a case where the rational strategy results in the worst collective outcome. In it, two individuals decide whether to confess to committing a crime (defect) or remain silent (cooperate). When prisoners examine the payoffs rationally,

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they should conclude that defection is the optimal individual choice. While defection is the rational choice in a one-shot Prisoner's Dilemma, this result does not match the observed human behavior [3], which led to further investigation into the reasons behind the discrepancy. Robert Axelrod was one of the first to explore how an optimal agent strategy changed when the Prisoner's Dilemma game was repeated with the same set of agents multiple times [4]. He collected agent strategies experts from different disciplines and conducted several computer tournaments to examine them in the Iterated Prisoner's Dilemma (IPD) scenario. The winner of the first tournament was a simple conditionally cooperative Tit-For-Tat strategy that repeated opponents moves of the previous round [5]. It is with the addition of spatial element, with agents interacting with their neighbors, that pure cooperation appeared to become a viable strategy [1]. In such models, the interactions are purely local – that is, individuals repeatedly interact with the same neighbors, which allows for islands of cooperative individuals to form at certain payoff values. However, in real world, there are numerous one-off interactions outside of one's immediate neighborhood, and it is important to consider their impact. This paper explores the performance of various strategies in the context of the spatial evolutionary Prisoner's Dilemma at various levels of locality. The evolutionary component of this model is meant to simulate the evolutionary pressure of the real world. The individuals that do not perform well die out, and are replaced by the offspring of one of the successful strategies. This has also the effect of speeding up the convergence on an equilibrium solution.

Beyond the exploration of existing strategies, this paper also introduces a group strategy. In some of the recent IPD tournaments, rudimentary group strategies have been explored and proved fairly successful. These strategies focused on entering multiple agents into the tournament and colluding to promote one agent above others, resulting in that agent taking one of the top spots [6]. While the tournament setting did not allow explicit grouping, these strategies used the first few games to identify other "teammates" and the "leader" by following a certain pattern of decisions. Given such success, this paper explores a group strategy in our model of the spatial evolutionary Prisoner's Dilemma.

3 METHODOLOGY

The basic principles of our simulation are similar to those used by Nowak [1]. Our model utilizes a 101x101 square grid with horizontal and vertical edge wrapping. Agents have a fixed position in each of the cells and cannot move, but they can interact with eight other agents in their neighborhood, although the specific agents that they interact with depends on the degree of locality of the model (see Figure 1).

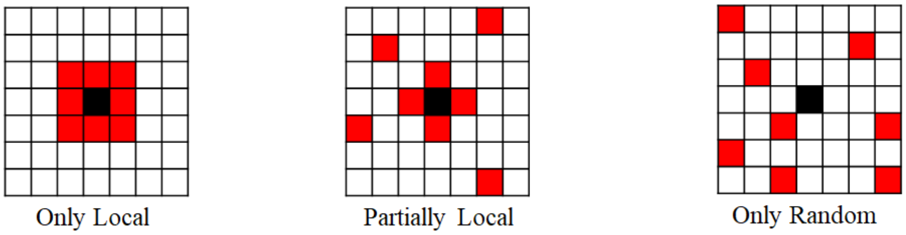

Figure 1: Three types of neighborhood frameworks used in the model.

Only Local is a typical Moore Neighborhood, and this arrangement is equivalent to a periodic lattice network with eight neighbors. In Partially Local setting, an agent interacts with four random agents as well as the four agents in its Von Neumann neighborhood, to allow for repeated interactions with the same agents. This in effect transforms this simulation into a four neighbor periodic lattice network, while maintaining the same number of interactions each step. Finally, when locality is set to Only Random, an agent interacts with eight random agents from the grid, effectively removing all local interactions or network effects. Each step of the model triggers a single round of interactions for each agent on the grid, asynchronously. This interaction consists of each agent playing a Prisoner's Dilemma with every agent in its neighborhood framework, once every step. During this interaction, each agent chooses to either cooperate or defect, as defined by the agent's strategy.

We explore four individual strategies, of which Cooperate and Defect always cooperate and defect, correspondingly. The remaining Tit-For-Tat (TFT) and Pavlov strategies store opponents' moves in memory to determine their strategy in the next round, up to last 50 individuals that they have interacted with. In Tit-For-Tat [5], an agent cooperates in the first round, and then changes its strategy to that of its opponent in the previous round. Pavlov is a "win-stay, lose-shift" strategy, [8] whereby an agent will cooperate if its neighbor used the same strategy as the agent in the previous interaction, and will defect otherwise. In the initial definition of Pavlov strategy, Nowak did not specify what the first move of the strategy should be, as "owing to noise, the initial move has no effect in the long run" [8]. After testing both cooperation and defection as the first round, we observed that starting Pavlov with defect was more robust over a variety of scenarios, particularly when non-local interactions were present. Therefore, in our implementation, Pavlov will always defect in the first round. Finally, we also explored the group strategy "In-Group Cooperate, Out-Group Defect" (In-C-Out-D), based on the concepts introduced by Henri Tajfel [7]. In it, agents always cooperate with the members of their own group, and always defect against everyone else. While this simulation aims to keep the agent behavior simple, and does not address the complexity of social identity theory and the individual desire for positive distinctness, it can still highlight what kind of benefits, if any, grouping can bring.

Every agent starts with a score of 0 at the beginning of every round. During each simulation step, agents interact once with other agents in their neighborhood using the Prisoner's Dilemma matrix shown in Figure 2, and both agents update their score based on their choices and the values used that scenario. Note that in an IPD, such as our model, the value of Defection Award X should always be between 1 and 2 [5]. The values for the choice to defect by both agents were chosen to be greater than zero to ensure that Defect strictly dominates Cooperate choice.

		Prisoner B	
		Cooperate	Defect
Prisoner A	Cooperate	**1 , 1**	**X, 0**
	Defect	**0, X**	**.33, .33**

Figure 2: Prisoner's Dilemma payoff matrix used in the simulation.

At the end of a round, if an agent has the lowest score in its neighborhood, it is replaced by a new agent with the strategy of the highest scoring agent in its neighborhood. If several agents have the highest score, one of these agents is picked at random instead. If an agent is tied for the lowest score, the agent has a proportional probability to be replaced. This ensures that strategies with the highest score will reproduce, while the strategies with the lowest scores will die out.

4 RESULTS

To test the performance of various strategies, we used the BehaviorSpace extension of NetLogo [9], which allows to automate simulation runs and to output the results externally. Each scenario in Figure 3 was repeated 50 times, and initialized with a well-mixed population of agents. The Defection Award X (from Figure 2) was varied to explore the behavior of agents in the range from weak to strong defection reward. The first set of experiments was intended to recreate the findings of Nowak [1,8] with Only Local neighborhood framework, as well as to understand the performance of individual strategies in the spatial evolutionary environment at different Defection Award values. Strategies with memory (Tit-For-Tat, Pavlov) performed quite well compared to simple strategies, although when the reward for defecting was high enough (Defection Award of 1.9), a strategy of Defect still achieves significant presence in the population (See Figure 3). With the Partially Local setting, Pavlov performs best, in large due to using Defect as its first move. In a Random Only setting, all interactions between agents turned into one-shot Prisoner's Dilemma interactions, which allowed the Defect strategy to dominate.

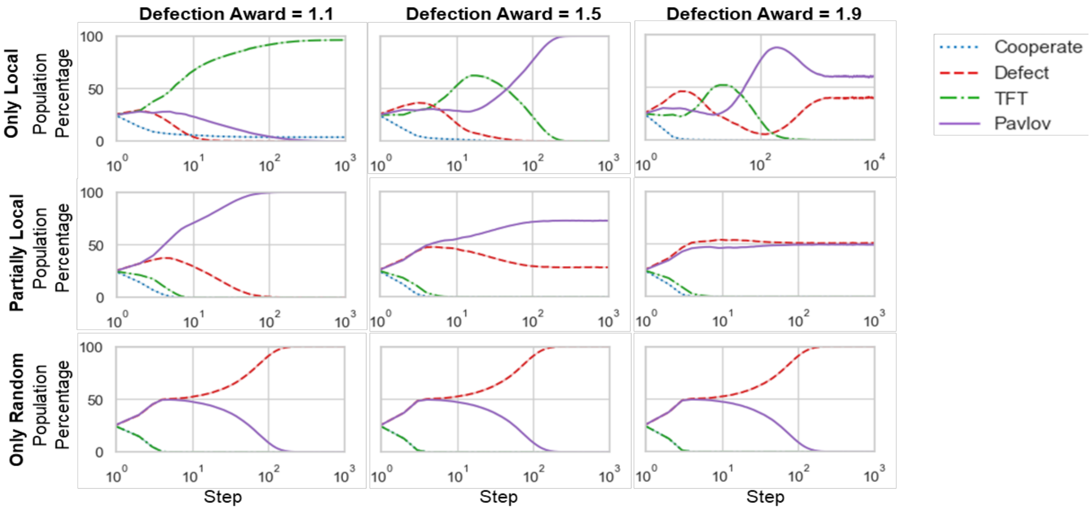

Figure 3: Populations of strategies over time with different Defection Award values and types of locality.

It is notable that while Pavlov, a conditionally cooperative strategy, dominates in the Partially Local setting, the percentage of times that agents have chosen to cooperate is surprisingly low (see Figure 4).

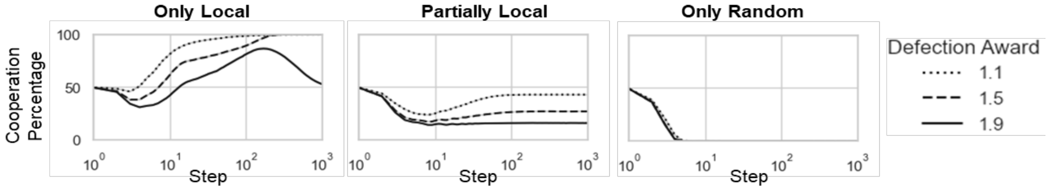

Figure 4: Total cooperation percentages for each scenario with individual strategies only.

Even with the Defection Award set to 1.1, where Pavlov was able to take over the entire simulation, the rate of cooperation is below 50%. We have observed similar performance when simulating only Tit-For-Tat and Defect strategies against each other – the level of cooperation in a Partially Local scenario remained lower than expected.

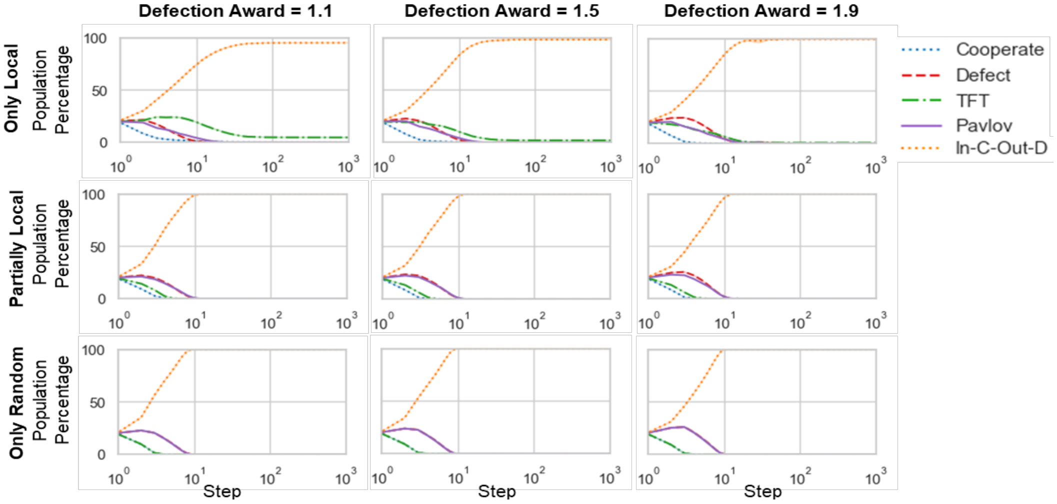

Figure 5: Populations of strategies over time with different Defection Award values and types of locality with the addition of the In-Group Cooperate, Out-Group Defect group strategy.

We then introduced the group strategy In-C-Out-D, and repeated the tests for all the combinations that were examined for the four individual strategies. The results show that this strategy is able to dominate other individual strategies at all values of Defection Award and levels of locality (see Figure 5). Only Tit-For-Tat is able to maintain some presence against In-C-Out-D strategy at small Defection Award values with Only Local interactions, which in our simulation is realized as clusters of Tit-For-Tat agents.

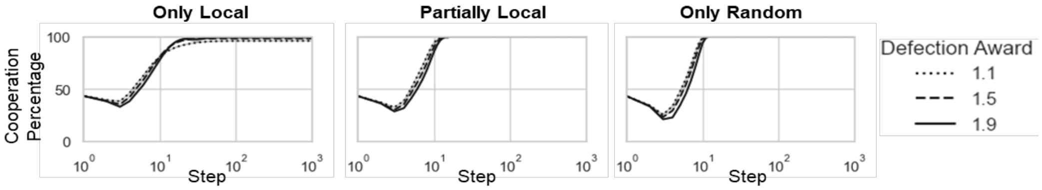

Figure 6: Total cooperation percentages for each scenario with the addition of the group strategy.

Notably, it is only when other strategies are still present, such as during Local Only scenarios with Defection Award set to 1.1, that we see the cooperation percentage below the 100% level (see Figure 6).

5 DISCUSSION

Overall, with Only Local interactions, our results aligned with Nowak’s findings, where Pavlov strategy is able to perform better than other strategies at most Defection Award levels, except it should be noted that Tit-For-Tat is able to outperform Pavlov when the benefit of defection was low. This likely could be explained by the fact that our variation of Pavlov starts off by defecting, rather than cooperating: at the Defection Award of 1.1, defection only provided a marginal benefit over cooperation, allowing more cooperative strategies to win. At higher Defection Award values, Pavlov was the more dominant strategy, as it is able to benefit not only from cooperation, but also from the initial defection.

When it comes to dealing with non-local interactions, strategies with memory – such as our variation of the Pavlov strategy, which starts off by defecting – are also able to perform relatively well. With the neighborhood framework set to Partially Local and all four individual strategies present, Pavlov is able to deal well with the one-off interactions by defecting on the first move, preventing the Defect strategy from overwhelming it. However, higher Defection Award values allow Defect strategy to eventually overwhelm all others. In a cooperation-friendly environment with the Defection Award set to 1.1, Pavlov was able to completely dominate other strategies, and even at higher Defection Award values it is able to survive against Defect strategy. We also verified that with only Tit-For-Tat and Defect present, Tit-For-Tat was also able to survive in Partially Local scenarios. Finally, in the Only Random framework, Defect strategy was able to dominate other strategies at all Defection Award settings of the Prisoner’s Dilemma matrix. We can conclude that individual strategies, as they are defined, can perform well with some non-local interactions, but as the amount of non-local interactions grows, their survival against pure Defection strategy eventually becomes unsustainable, and notably, their levels of cooperation drop. This is contrary to the observed behavior in real world [3], where people cooperate even in one-off Prisoner’s Dilemma interactions. There are alternative ways through which such cooperation may have emerged, as summarized by Nowak [10], however they remain outside of scope of this paper.

As we examine the results from the introduction of the group strategy, our implementation of it at the individual level is able to show the power of coordination and highlights one of the reasons why individuals tend to group, even when the distinction between groups is minimal – grouping can be extremely effective for survival compared to individual performance. By having a reliable way of identifying other individuals that will cooperate, and in turn defecting against everyone outside of that collective, the In-C-Out-D strategy is able to benefit from the higher cumulative cooperation payoff, while reducing the payoffs available to everyone else through defection. We can observe similar effects in real world, where people tend to group up when dealing with uncertain circumstances: gangs in rough neighborhoods, nomadic tribes throughout history, and even religious cults can attribute their success to strong internal support and hostility to outsiders. Further exploration of the performance of groups across a variety of game scenarios using this modeling approach can help explain the formation and internal workings of groups. One caveat that should be noted is that a group strategy requires a strong adherence to its principles. If members of the group start defecting against each other, the performance of the group will drop. However, exploration of these enforcement methods is also outside of the scope of this paper.

6 CONCLUSION AND FUTURE WORK

Our initial results of simulating individual strategies against each other confirm the importance of local repeated interactions to survival of cooperation among individuals. However, another way that cooperation can thrive in a population is by allowing individuals to group up and act uniformly against individuals outside of their group. When we compare these results to human behavior, we can find that cooperation is often exhibited in the context of groups, families, and other organizations, much like the agents in this simulation performed the best when they were part of the group strategy.

In the future we would like to look beyond the Prisoner's Dilemma interaction and towards an environment that contains multiple potential types of interactions, such as Stag Hunt or Hawk-Dove, to achieve a better approximation of the diversity of the real world. To help with this, we are developing decision-making approaches that are agnostic to the scenarios they encounter and can operate in an environment containing any number of game types. It should also be noted that our simulation does not address whether a group strategy can invade others, which we would like to examine in the future. The ability to invade other strategies would give a pathway to the emergence of grouping as a social behavior.

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