Heterogeneous Strategy Learning in the Iterated Prisoner's Dilemma

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ABSTRACT

Axelrod's work on the prisoner's dilemma is one of the most discussed models of social co-operation. While many aspects of his computer simulations have been debated, their evolutionary mechanism has not yet received the same attention. We know people do not differ only in the way they act, but also in how they change their behavior – some may like safe routines, others risk with the new. Yet in formal models cultural evolution is taken to be an homogeneous process, such as the imitation of successful peers. In this paper we challenge this view and we propose an agent-based model that takes into account heterogeneity among individuals' learning strategies. The evolutionary dynamic is an adaptation of the so-called consumat approach, originally developed by Wander Jager and Marco Janssen in order to integrate different models of individuals behavior.

KEYWORDS

Prisoner's dilemma, agent-based model, heterogeneity, consumat

1. *Introduction*

After more than thirty years from the publication of its early results, Axelrod's prisoner's dilemma tournament remains a cornerstone of evolutionary explanation of social cooperation. These explanations aim at illustrating how cooperation among rational self-interested agents may emerge even in absence of a central authority. Over the years, scholars have been testing the robustness of Axelrod's conclusions as well as extending his model to incorporate some key features that were neglected in the original work. Some notable examples are the introduction of *noise* and of *network effects*.[1] While many aspects of Axelrod's work have been discussed in details and sometimes modified, the evolutionary dynamic has been left almost untouched. Yet it

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[1] The effect of noise was taken into account as early as in 1985 by Molander [4]. On noise, see also Nowak and Sigmund [5] and Wu and Axelrod [6]. On network effects, see for example Santos and Pacheco [8].

seems unrealistic to assume that all the individuals would engage in the same learning pattern, i.e. the simple imitation of successful neighbours. It seems instead more reasonable to assume that individuals are heterogeneous even in the way they learn from experience and from others.

The aim of this paper is to propose an agent-based model that accounts for a such an heterogeneity, adapting the *consumat approach* to the prisoner's dilemma. The consumat approach, originally formulated by Wander Jager [9] [10] to model individuals behavior, is a meta-model that allows agents to choose from a pool of learning strategies, which includes imitation as a special case. The choice depends both on the agents disposition and on the circumstances.

We proceed as follows. In Section 2 we briefly introduce Axelrod's work. We then sketch the fundamental insights of the consumat approach (Section 3.1) and a possible adaptation to the prisoner's dilemma (Section 3.2). Section 4 illustrates how the consumat approach leads to different evolutionary patterns and alternative final outcomes when compared to the classic model. Section 5 will conclude our discussion with some general remarks.

2. *The prisoner's dilemma and computer simulations*

The prisoner's dilemma is the most studied game that aims at modelling social cooperation. Figure 1 illustrates the decision matrix of the game. To qualify as a prisoner's dilemma, pay-offs must satisfy the following conditions (i) *temptation > reward > punishment > sucker* (ii) *reward >* (*temptation+ sucker*)/2. Bracketed numbers are standard pay-off values that satisfy the mentioned conditions.[2]

In its simplest form, the solution of the prisoner's dilemma is straightforward. If players are rational, they both defect, obtaining the second-last preferred outcome, since mutual cooperation would lead to a better outcome for both players. In other words, the prisoner's dilemma models a situation in which two rational players are unable to coordinate their choices for mutual benefit. According to a long — and controversial — tradition, which dates back at least to Hobbes' *Leviathan*, it is then the interest of individuals to call in a third player — the State — which has the coercive power to enforce cooperation.

The solution of the prisoner's dilemma is not as immediate if the game is iterated, i.e. individuals do not play the game only once, but several times. We are now interested in knowing which is the best *strategy*, i.e. an algo-

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[2] For an introduction on the prisoner's dilemma, see Kuhn [18].

Eve		
	Cooperates	Defects
Adam — Cooperates	Eve : Reward (3) Adam : Reward (3)	Eve : Temptation (5) Adam : Sucker (0)
Adam — Defects	Eve : Sucker (0) Adam : Temptation (5)	Eve : Punishment (1) Adam : Punishment (1)

Figure 1: The prisoner's dilemma pay-off matrix

rithm that specifies which move to make at each repetition of the game. For example, one simple strategy is ALWAYS-DEFECT. Intuitively, an individual playing this strategy will defect every round of the game.

As it is well known, Axelrod [1] [2] organized a series of virtual tournaments of competing strategies playing an iterated version of the prisoner's dilemma. Scholars from different disciplines were invited to submit a strategy. Each strategy would then play against all the others, aiming to obtain the highest pay-off. The strategy that won the tournament was TIT-FOR-TAT, submitted by the mathematician Anatol Rapoport. Axelrod's conclusion was that if a simple strategy such as TIT-FOR-TAT outperforms defection, cooperation may emerge even in the absence of a central authority.

An agent who plays TIT-FOR-TAT will cooperate in the first round and then do what the opponent did in the previous round. Hence, TIT-FOR-TAT never defects first, but is not exploitable by a defecting strategy. For example, suppose that an agent playing TIT-FOR-TAT faces another agent playing the same strategy. The two agents will keep cooperating. Suppose now the same agent faces an agent which plays ALWAYS-DEFECT. He will cooperate the first round, but defect every other (see Figure 2).

To illustrate how TIT-FOR-TAT can outperform ALWAYS-DEFECT consider the following example. Suppose a population of agents, some of which play ALWAYS-DEFECT and some TIT-FOR-TAT. In each round, agents are paired randomly and play the prisoner's dilemma. An agent playing ALWAYS-DEFECT will obtain the *punishment* pay-off every round re-

	TIT-FOR-TAT	TIT-FOR-TAT			TIT-FOR-TAT	ALWAYS-DEFECT
Round 1	Cooperate	Cooperate		Round 1	Cooperate	Defect
Round 2	Cooperate	Cooperate		Round 2	Defect	Defect
….	Cooperate	Cooperate		….	Defect	Defect
Round n	Cooperate	Cooperate		Round n	Defect	Defect

Figure 2: Iteration of the prisoner's dilemma

gardless of the kind of strategy played by the agent he is facing. An agent playing TIT-FOR-TAT will obtain the *punishment* pay-off only when facing defectors. On the other hand, he will obtain the *reward* pay-off every time he meets another agent playing TIT-FOR-TAT, as a result of mutual cooperation. As *reward > punishment*, the average pay-off of agents playing TIT-FOR-TAT will be greater than the average pay-off of agent playing ALWAYS-DEFECT.

Further computer simulations, inspired by the collaboration with the evolutionary biologist W. D. Hamilton, confirmed the success of TIT-FOR-TAT as extremely robust. TIT-FOR-TAT resulted to be the best strategy when playing in different pools of strategies, as well as in evolving populations. In the first tournament, the number of agents remained the same over time and so the strategy they played. In the following tournaments, Axelrod experimented different evolutionary mechanism, all inspired by the principle of differential reproduction: strategies which obtain a better pay-off would tend to become more common in the population, while strategies which are not successful would tend to become less common and eventually disappear.

One interesting evolutionary mechanism, which might be a good model of cultural evolution, is the imitation of successful peers in a simple network. In fact, it seems reasonable to suppose that individuals tend to copy the behavior of others if it is more successful than their own. In the computer simulation, this means that agents see only a fraction of the total population, i.e. the agents they are linked to, or their neighbours. Among those they see, they copy the strategy played by the agent with the highest pay-off. Figure 3 illustrates a simple network, a regular square lattice. In this network, each agent is linked to his four adjacent neighbours. In Figure 3 agents are represented by black dots and links by red lines.

3. *The Consumat Approach*

The consumat approach is a *meta-model* of human behaviour, originally developed by Jager [9]. The consumat approach aims at providing a unifying
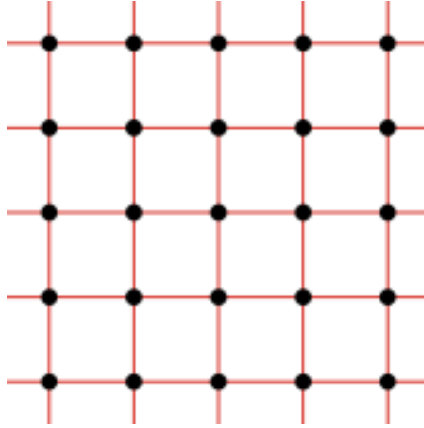
Figure 3: A regular square-lattice network

framework for partial models of individual behaviour. While a full exposition of the consumat approach is beyond the purpose of this article, we introduce its principles in the next section.

3.1. *Fundamental insights*

Social imitation or rational deliberation are just two possible examples of the many cognitive processes that people may engage in. According to the consumat approach, it is reasonable to suppose that

- cognitive processes have different costs, in terms of the amount of information they need to compute. For example, rational deliberation appears to be the most expensive in terms of cognitive resources.

- cognitive processes can be more self-oriented or more socially-oriented. Rational deliberation falls in the former category, while social imitation in the latter.

- the same individual tends to choose different cognitive processes in different circumstances. For example, one would engage in an expensive cognitive process only if one expects a great improvement in his condition and if one has relevant information at hand. On the other hand, if the decision does not seem important an individual would tend to engage in less expensive cognitive processes, such as repeating a routine behaviour.

- different individuals have a different tendency in engaging in one particular cognitive process, at the expenses of the others. For example, some individuals are more prone to follow what others do, rather than deliberate on their own.

What makes one cognitive process more relevant in comparison to others depends on two factors: the perceived satisfaction and the uncertainty level. Satisfaction expresses the fulfilment of the different needs that individuals might have. It is reasonable to assume that individuals engage in expensive cognitive behavior only if highly unsatisfied, thus expecting that it is worth to invest a great amount of resources to improve their condition. Uncertainty refers to the confidence one has in his ability to understand the environment and act in an efficient way. If an individual does not feel confident, he would tend to imitate successful behavior of others, rather than deliberate on his own.

Ideally, there is a *continuum* of cognitive processes, which differ for cognitive effort and degree of deliberation. For simplicity, the consumat approach includes four different cognitive processes, which correspond to different models of individual behavior

1. Repetition of one's last action. Repetition is cheap in cognitive effort and individually determined. Hence, it is the choice of satisfied and confident individuals. Repetition of routine behavior is inspired by the Classic Conditioning Theory, made popular by the experimental findings of Pavlov [11].

2. Rational deliberation. Rational deliberation aims at optimising one's utility, considering all the possible options and weighting all the available information. For this reasons, deliberation is cognitively expensive and individually determined. Hence, it is the choice of unsatisfied, but confident individuals. The classic work on rationality is Von Neumann and Morgenstern [12].

3. Imitation of successful peers. Imitation is cheap in cognitive effort and socially determined. Hence, it is the choice of satisfied, but not confident individuals. Imitation refers to social learning theory, developed by Bandura [13].

4. Inquiry. Inquiry involves deep social research. It is then cognitive expensive and socially determined. Agents who choose to inquire will consider the behaviour of all other individuals and imitate the most successful one.[3]

We can now introduce a decision matrix that illustrates the previous discussion (Figure 4).

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[3] The inquiring process was not present in the first formulation of the consumat approach. It has been introduced by Jager and Janssen [15] in 2012 and is inspired by sophisticated forms of social learning, such as the one introduced by Festinger [14].

Cognitive effort (determined by satisfaction)		
	Low	High
High Repetition Conditioning theory	**Repetition** Conditioning theory	**Rational deliberation** Decision theory
Low	**Imitation** Social learning theory	**Inquiry** Social comparison theory

Figure 4: Consumat decision matrix

3.2. *Adapting the consumat approach to the prisoner's dilemma*

The consumat approach has been introduced to model consumer behavior, but it has been successfully applied to a number of different context. For example, Speelman et al. [16] models farmers deciding which crop to grow and Jager and Janssen [17] models demographic dynamics. In this section, we propose a new application of the consumat approach to the prisoner's dilemma.

In this new application, the different cognitive processes modelled by the consumat approach translate in alternative ways to choose a strategy for the iterated prisoner's dilemma. For example, suppose that at time t agents i's strategy is ALWAYS-COOPERATE and agent j's strategy is ALWAYS-DEFECT. If at time $t+1$ agent i *imitates* agent j, then i's new strategy becomes ALWAYS-DEFECT. Until his strategy changes again, agent i will act according to his new strategy and defect in every interaction.

In the prisoner's dilemma, the four cognitive processes translate as follows

1. Repetition — don't change your strategy.

2. Rational deliberation — adopt the strategy ALWAYS-DEFECT. Here we assume that rational agents analyse the prisoner's dilemma in the

classic way, hence recognizing defection as the dominant move in each round of the game.

3. Imitation — among your neighbours, i.e. the agents you are linked to, consider the one with the highest pay-off. If his pay-off is greater than yours, abandon your old strategy and adopt his.

4. Inquiry — the same as imitation, but consider all agents, rather than your neighbours only.

While in the consumat approach individuals have different kinds of needs, in the prisoner's dilemma the fitness of one agent simply corresponds to his average pay-off per interaction E. Each agent is defined by a satisfaction threshold ST [0,1]. Agent i is satisfied if

$$Ei > TP * STi$$

where TP stands for temptation, which is the maximum pay-off obtainable (see Figure 1).

Intuitively, an agent with a very high ST is ambitious. For example, suppose $STi = .9$. This means that agent i is satisfied only if he obtains on average at least .9 TP. This could be possible if agent i's strategy is ALWAYS-DEFECT and most of his neighbours, with which he interacts every round, play the ALWAYS-COOPERATE strategy. Since this is very unlikely, Ei will normally be far below .9 TP and agent i will be unsatisfied. This means he will often change his strategy, engaging in the two expensive cognitive processes — rational deliberation and social inquiring.

On the other hand, an agent with a low ST is unmotivated. For example, suppose $STj = 0$. Agent j is always satisfied and has no interest in investing resources in cognitively expensive processes. He will always repeat his last strategy or imitate his successful neighbours.

Each agent is also defined by a confidence threshold CT [0,1]. CT simply stands as the chance of being confident at a given time. For example, suppose $CTi = .5$. This means that agent i has equal chances of engaging in the individually driven processes and in the socially driven ones.

Agents have different threshold values. Hence, they evolve heterogeneously. For example, suppose $STk = .2$ and $CTk = .9$. Agent k tends to repeat because easily satisfied and often confident — he rarely changes his strategy. On the other hand, suppose $STl = .7$ and $CTl = .3$. Agent l tends to engage in social inquiry, because he is hard to satisfy and often confident. Figure 5 provides a graphical illustration of the characters of agent k and agent l. It is evident how they would respond differently given the same

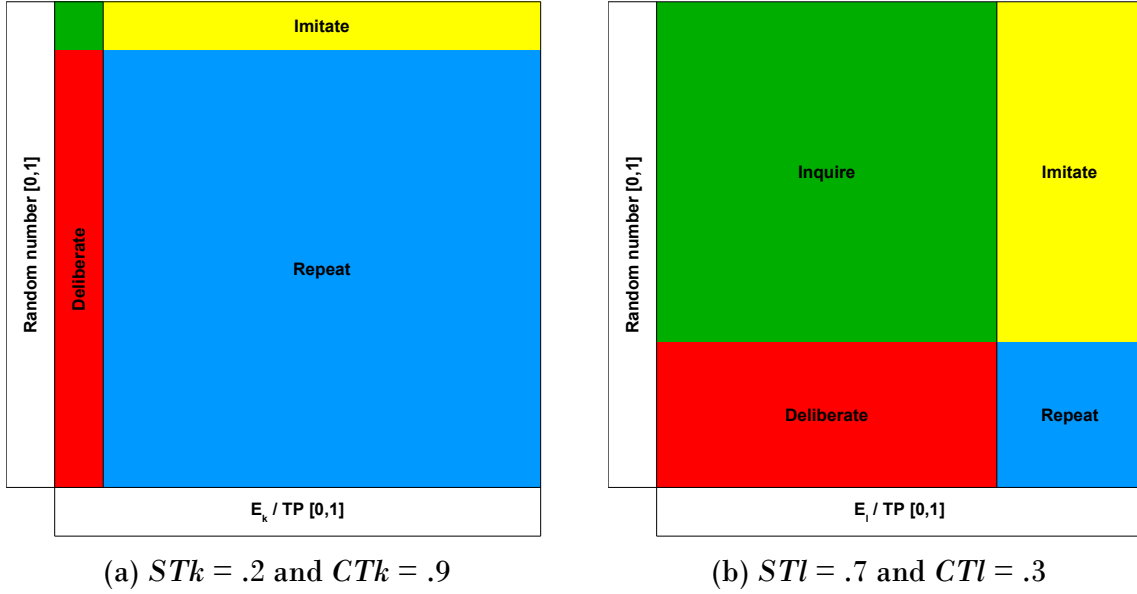(a) $STk = .2$ and $CTk = .9$ (b) $STl = .7$ and $CTl = .3$

Figure 5: Graphical representation of two possible agents, agent k (a) and agent l (b)

conditions — a given level of uncertainty (on the y axis) and of satisfaction (on x the axis).

Suppose now agent k and agent l are the only two agents of a given society. The pay-off are temptation $= 5$, reward $= 3$, punishment $= 1$ and sucker $= 0$. At time $t = 1$, both agents' strategy is ALWAYS-COOPERATE. Agent k and agent l cooperate and each of them gets a pay-off of 3, the reward. Agent k is satisfied as

$$Ek > TP * STk$$

$$3 > 5 * 0.1$$

On the other hand, agent l is not satisfied as

$$El < TP * STl$$

$$3 < 5 * 0.7$$

We draw now a random number for agent k and for time t. Suppose we draw .4. As $.4 < CTk$, agent k is confident. We do the same for agent l and draw .1. This means agent l is confident, as $.1 < CTl$.

In this example, agent k is satisfied and confident. He repeats his strategy, which remains ALWAYS-COOPERATE. On the other hand, agent l is not satisfied, but confident. He deliberates and his strategy changes from ALWAYS-COOPERATE to ALWAYS-DEFECT.

4. *Consumat agents play the prisoner's dilemma*

Adapting the consumat approach to the prisoner's dilemma would be trivial if it did not lead to different results when compared to an homogeneous evolutionary dynamic, such as simple imitation. We introduce an agent-based model that runs both the simple imitation mechanism and the consumat one (Section 4.1). We run the same experiment varying only the evolutionary dynamic and show that — at least for a reasonable parameter set — the final population is different (Section 4.2).

4.1. *The agent-based model*

The agent based model runs an iterated prisoner's dilemma. Pay-off are the usual ones — temptation = 5, reward = 3, punishment = 1 and sucker = 0. Each round, agents play one match of the prisoner's dilemma with all their neighbours. Evolution takes place every 100 rounds. The simulation can run with

- different noise values, which stand for the chance to misunderstand one of your neighbours' move.

- two different networks, a regular square lattice network and a scale-free network. One agent's neighbourhood is defined as the agents he is linked to.[4]

- two different evolutionary dynamics, the simple imitation and the consumat approach. In case the latter mechanism is chosen, the user of the simulation has to choose the average ST and CT of agents. Generate thresholds follow a normal distribution, with a default standard deviation of .25. For example, setting a very high average ST leads most agents to be ambitious (see Section 3.2).

The population consists of thirteen equally represented strategies, listed below. The first seven strategies were submitted by colleagues and include both popular ones, such as TIT-FOR-TAT, and original ones, such as HYSTERIC — which is a stochastic version of TIT-FOR-TAT. The eigth strategy, called BAYESIAN, was developed by the present author for the purpose of this simulation. Finally, the last four strategies, such as ALWAYS-COOPERATE and RANDOM, are classic ones that we added for completeness. Here follows a list of the thirteen strategies and a intuitive description of each of them:

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[4] Intuitively, a scale-free network is a network in which nodes do not have the same number of links. The number of links per node follows a particular distribution. For an introduction to complex network, see for example Barabasi [7].

1. ALWAYS-DEFECT. Agents playing this strategy always defect.

2. TIT-FOR-TAT. Agents playing this strategy cooperate the first round. They then copy the opponent's move in the previous round.

3. PATIENT. Like TIT-FOR-TAT, but agents playing this strategy defect only if the opponent has defected in more than half of the previous round.

4. HYSTERIC. Like TIT-FOR-TAT, but agents playing this strategy change their move to the opposite one with a chance of 0.2.

5. LUNATIC. Like TIT-FOR-TAT, but agents playing this strategy will change their move to the opposite one every 5 turns.

6. GRIM. Agents playing this cooperate until the opponent defects for the first time. They then defect for the rest of the game.

7. CHAMELEON. Agents playing this strategy start playing random and ten adjust the chances of defecting and cooperating according to the success of others agents playing the same strategy.

8. DIEKMANN. Like TIT-FOR-TAT, but agents playing this strategy play two unconditional cooperation every 10 rounds.

9. BAYESIAN. Agents playing this strategy try to understand what kind of strategy their opponents are playing and act accordingly. For example, they defect if they think that their opponent is likely to keep cooperating. On the other hand, they cooperate if they think their opponent is likely to retaliate after a defection.

10. ALWAYS-COOPERATE. Agents playing this strategy always cooperates.

11. TIT-FOR-TWO-TATS. Like TIT-FOR-TAT, but agents playing this strategy defect only after a series of two defections.

12. RANDOM. Agents playing this strategy, randomly choose to cooperate or defect with equal probability.

13. WIN-STAY-LOSE-SHIFT. Agents playing this strategy defect the first round. They then repeat the last move if they obtain the *temptation* or *reward* pay-off, or choose the opposite move if they obtain *punishment* or *sucker* pay-off.

4.2. *Simulation results*

To test if consumat agents evolve differently from simple imitating ones we run the same experiment varying only the evolutionary dynamic. The common parameters are noise level (.05), kind of network (scale-free), size of population (about 340 agents) and length of the simulation (50 generations). The following results are averages of 100 repetitions for each experiment.

If the chosen evolutionary dynamic is simple imitation the population becomes strongly dominated by the DIEKMANN strategy, while 10 of the 13 initial strategy disappear (see Figure 6). DIEKMANN agents, which represent about the 91% of the final population, play just like TIT-FOR-TAT, but every 10th and 11th move cooperate unconditionally.

If we chose the consumat evolutionary dynamic the results are greatly influenced by the threshold parameters. It should be clear that pure imitation is a special case of the consumat approach and can be obtained if all agents are satisfied and not confident — e.g. for all agents, setting ST = 0 and CT = 0.

As no empirical data are available to suggest exact values for the thresholds, for the following example we have arbitrary chosen the plausible values $ST = .2$ and $CT = .8$. $ST = .2$ means that, on average, agents are satisfied if they get at least the punishment pay-off.[5] $CT = .8$ means that, one average, agents are confident four rounds out of five. Combining these two values, we obtain that each round about half of the agents repeat, one-fifth imitate and deliberate and one-tenth inquire.

The resulting population after 50 generation is illustrated in Figure 7. A striking difference is that this time neither strategy disappears nor dominates the population. The fact that no strategy disappears can be easily explained by the number of agents that repeat at every generation, resisting to change. ALWAYS-DEFECT is the most played strategy despite a poor average pay-off, because it is the choice of all the agents who deliberate, plus the ones resisting to change. The remaining four most common strategies are those who cope well with noise and which all get about the same average pay-off — BAYESIAN, DIEKMANN, PATIENT and TIT-FOR-TWO-TATS.

Finally, the BAYESIAN strategy, which disappeared in the first experiment, outperforms all other strategies. This asymmetry can be explained by the fact that in the first experiment all the surviving strategies are not exploitable. Hence, exploring opponent's behavior with occasional defections does not pay. On the other hand, in the second experiment a few individuals of each strategy survive and BAYESIAN agents gain a little extra pay-off playing against them.

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[5] In fact, *temptation* $* ST = 5 * 0.2 = 1 = punishment$.
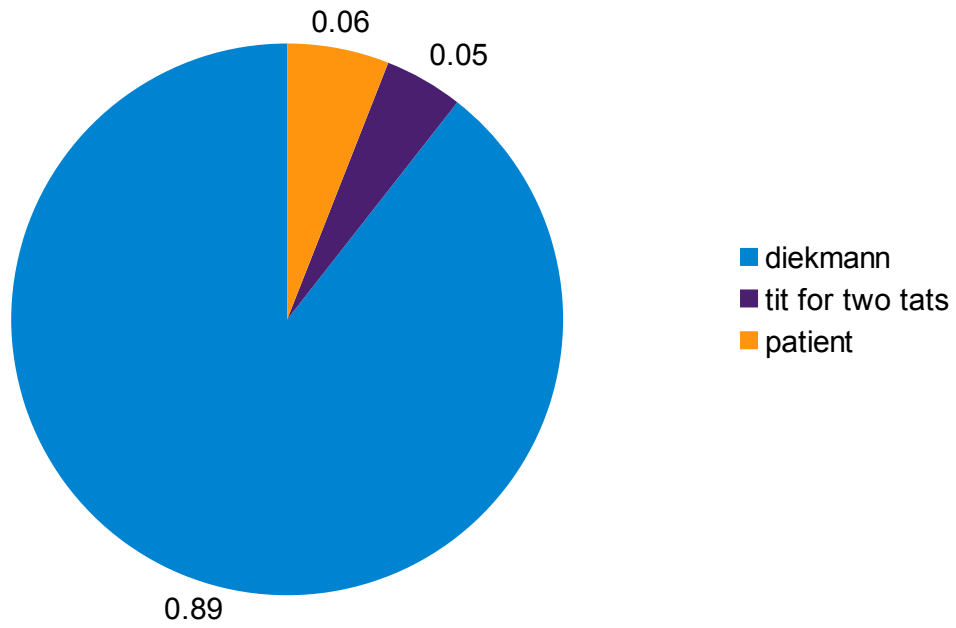
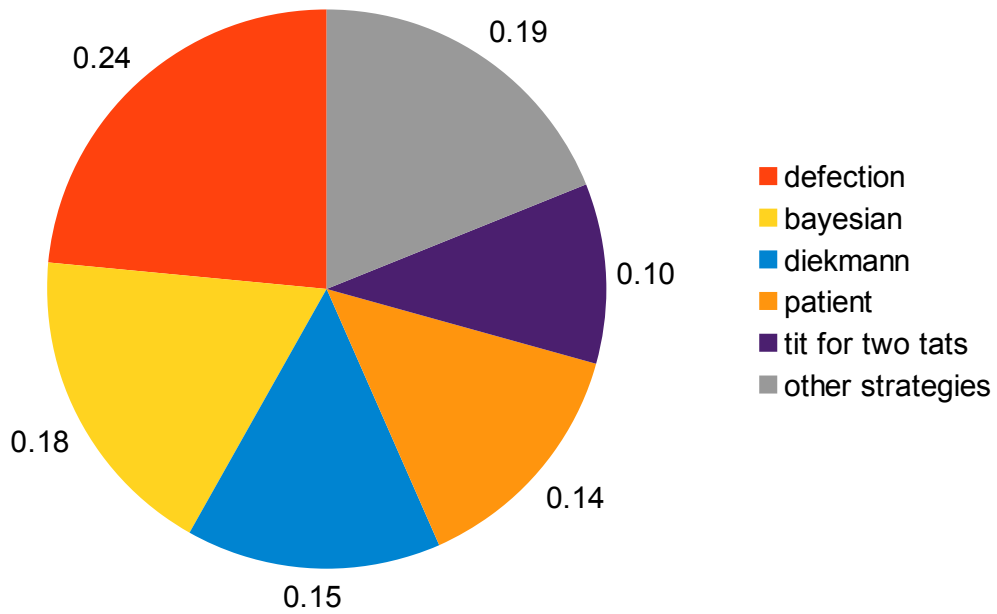Figure 6: Simulation results for imitating agents

Figure 7: Simulation results for consumat agents, with average ST=.2 and average CT=.8

5. *Discussion*

Some people like routines, others enjoy trying new ways to do things. Some are ambitious, others easily satisfied. Moreover, the same individual can adopt different strategies depending on the context. However, most formal models of cultural evolution ignore such heterogeneity and assume that a uniform mechanism fits all individuals at all times. The aim of this paper is to challenge what we think is a poor representation of cultural evolution in the iterated prisoner's dilemma, which is typically modelled as the simple imitation of successful peers.

We have proposed a first tentative application of the consumat approach. The formalization we introduce takes into account both the heterogeneity among individuals — which can be more or less prone to undertake one of the possible evolution patterns — and the fact that the choice of an individual can vary according to the circumstances.

To test the consumat prisoner's dilemma against the traditional simple imitation, we have developed an agent-based model and run an experiment. Even if this experiment is meant to be only an example, we are satisfied with the results. They show that it is possible to obtain significantly different final populations with alternative evolutionary mechanisms.

We also think the consumat results are qualitatively more similar to the empirical data obtained from laboratory experiments, in which only a fraction of the individuals defect — in our example it is about half. Game theory and evolutionary models of the prisoner's dilemma make very different predictions. In fact, according to game theory we should expect an equilibrium of pure defection. If this forecast is clearly too pessimistic, evolutionary models — such as Axelrod's — suggest we should expect everyone to be nice unless provoked — playing some variant of TIT-FOR-TAT. Reality lies somewhere in between — just like the consumat approach seems to suggest.

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