Global versus local interaction in prisoners’ dilemma games: imitation models and experimental results.

Stéphane Bertrand, Kene Boun My, Marc Willinger

BETA-Theme, Louis Pasteur University
61 avenue de la Foret-Noire, 67085 Strasbourg, France

LAMETA, Faculty of Economics
Espace Richter - avenue de la Mer, BP 9606
34054 Montpellier cedex 1, France

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Abstract:

We study both theoretically and experimentally, an iterated prisoners' dilemma game on the basis of two different matching protocols: a local treatment (each player plays randomly with one of his two neighbours on a circle) and a global treatment (each player plays randomly with another member of a group). In the theoretical part of the paper, we show that a pure imitation rule allows the emergence of cooperation under local interaction independently of the values of the parameters, while under global interaction, the emergence of cooperation is not parameter-free. In the experimental part of the paper, we show that the experimental data collected under both matching rules does not reveal any clear difference in the levels of cooperation. Our explanation is that although cooperation can propagate throughout the network under local interaction, it does not favour cooperation more than under global interaction, where such effect neither favours nor reduces cooperative play. However, in both structures, players are significantly affected by the information they get, providing therefore some credit to the imitation rule assumption.

Keywords: prisoners’ dilemma game, local interaction, social learning, experimental economics.

JEL Classification: C72, C73, C92.

Corresponding author, e-mail: s.bertrand@cournot.u-strasbg.fr
1. Introduction.

Experiments on the prisoners’ dilemma game have provided strong evidence that subjects cooperate in the finitely repeated game (Selten & Stoecker, 1986, Andreoni & Miller, 1993). While cooperation is theoretically possible in a finitely repeated game environment with “almost” rational players (Kreps et al, 1982, Guttman, 1996), it is less obvious why cooperation would arise when players interact randomly in a dynamic environment. A possible reason is that players are backward looking and imitate the most successful action observed in their environment. Such behaviour is often justified by a natural selection argument. This kind of argument is captured in evolutionary models and has been developed among others by Axelrod (1984), Friedman (1991), Young (1993) and Nowak & May (1993). Cooperation can also emerge as a result of the structure of the interactions between agents. The likelihood of cooperation may depend on the way players interact with each other within a given population. For example, when players interact locally cooperation is more likely to be sustained than when players interact globally (Eshel et al., 1998, Nowak & May, 1993). This happens and can emerge as a general property if all the players in the population interact within small overlapping neighbourhoods. The central assumption that underlies such an outcome is that when players interact in small neighbourhoods, they believe to have a stronger influence on other players than they would believe to have in a global interaction framework. In other words, some players believe that they can induce their neighbours to cooperate by cooperating.

However, from a theoretical viewpoint the fact that some players believe to be able to generate cooperation in their neighbourhood is not sufficient for inducing cooperation at the population level. It is also necessary for the population outcome to have imitation. The general idea is therefore that some kind of strategic behaviour combined to imitation in the evolutionary sense can lead to the emergence of cooperation in contexts where interactions are mostly local.

In an experimental study, Kirchkamp & Nagel (2000, KN hereafter) tried to distinguish between “strategic behaviour”, whereby players intend to influence cooperative play in their neighbourhood, and “learning through reinforcement and imitation”. They show that strategic behaviour is influenced by the spatial structure of the interactions but that learning through reinforcement and imitation is not.

Their local interaction treatment is based on a circle design involving 18 players with a neighbourhood of four players. Each of the 18 players on the circle interacts with his two left neighbours and with his two right neighbours. The local interaction treatment is compared to a group treatment in which each player is matched with four other players for the whole duration of the experiment. The same game is played in both treatments. In each period a player’s choice is confronted to the choices of his four neighbours in the local interaction treatment and to the four other players’ choices in the group treatment (mean matching rule). At the end of each period, each player’s payoff and the choices of the other members of his neighbourhood or group are announced. KN observe a significantly higher level of cooperation in the group treatment than in the circle treatment (resp. around 40% and 30% of cooperative plays).

The only difference between the two structures used in KN is in the influence of play. In the group interaction treatment, players are only influenced by the choices made by the four other players in their group, whereas in the local interaction treatment a given player’s neighbourhood is also influenced by the choices of the neighbours’ neighbourhoods which themselves depend on further neighbourhoods and so on. While this design is well-suited for the purpose of identifying strategic versus learning behaviour, it does not allow a meaningful comparison of levels of cooperation between the two structures. The main reason is that in the
local interaction treatment eighteen subjects interact directly or indirectly with each other whereas in the group interaction treatment five subjects interact directly with each other and no indirect interaction exists.

In this paper, we consider a fixed population of eight players, with a random interaction rule. In each period, each player’s choice is confronted to the choice of a randomly selected player in his neighbourhood on an eight-players circle (local interaction), or in the rest of the population in an eight-players group (global interaction). Therefore, in both treatments, each player interacts with seven other players, directly or indirectly. In the local interaction treatment each player interacts directly only with two players: his left neighbour and his right neighbour. He might therefore be more likely to cooperate, e.g. for strategic reasons. However, the overlappings of the neighbourhoods may also increase the likelihood of defection, since one single defector can contaminate and invade the whole network by the way of local interaction.

Eshel, Samuelson & Shaked (1998) provide a very nice way to allow the emergence of cooperation in local environments, based on the idea that altruists live better among altruists than egoists do among egoists. Their model relies on a simple imitation rule. Under some restrictions on the parameter values, the population reaches many stable states composed of a large number of cooperative players. All evolutionary stable states in this context contain at least sixty percent of cooperative plays. Their results, which were obtained in a public good game environment, can be easily adapted to prisoners’ dilemma games. However these results rest on strong restrictions imposed on the parameter values; moreover, since interactions are repeated with identified neighbours (mean matching rule), strategic behaviour is largely expected, so that the assumption of a pure imitation rule may not be very credible.

To overcome these weaknesses we use a random matching rule in the local interaction treatment: in each period, each player plays randomly, with equal probability, with only one of his two neighbours. Within this setting a pure imitation assumption appears more credible, because players cannot easily adopt a strategic behaviour, since they cannot identify the neighbour with whom they play in each period. Therefore, imitation of the action that led to the highest payoff in their environment in the previous period represents a major alternative to the game-theoretic solution of defecting in every period.

In the global treatment, in the spirit of the model presented by Robson & Vega-Redondo (1996) for coordination games, cooperation can also sometimes lead to higher payoffs in groups of randomly interacting players. For example, suppose that two paired players cooperate and that all other players defect with each other. Therefore, the former get a higher payoff than the latter, and, if the entire group is given this information, all players can be led to cooperation under the evolutionary assumption of imitation. In general, the nature and the number of configurations allowing higher payoffs for cooperative players within this context depend on the precise values of the payoff matrix.

The paper is organised as follows. In section 2 we present the imitation dynamics in a local interaction model, on the basis of two different matching rules: the mean matching rule and the random matching rule. Section 3 presents the imitation dynamics in a global environment, under the two matching rules. Section 4 introduces the experimental design and describes the various treatments. The results of the experiment are discussed in section 5. Section 6 concludes and stresses the need for developing the study of interaction structures.
2. Imitation dynamics in a local interaction model.

Consider the game in figure 1:

<table>
<thead>
<tr>
<th></th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>R, R</td>
<td>S, T</td>
</tr>
<tr>
<td>D</td>
<td>T, S</td>
<td>P, P</td>
</tr>
</tbody>
</table>

*Figure 1. The prisoner's dilemma game*

Under the assumptions that \( T > R > P > S \) and \( 2R > T + S \), we obtain a symmetric prisoners’ dilemma game in which \((C, C)\) is the Pareto-optimal outcome and \((D, D)\) the dominant-strategy Nash equilibrium. \((D, D)\) is therefore the only subgame perfect Nash equilibrium of the finitely repeated game.

2.1. Mean matching rule.

Eshel, Samuelson and Shaked (1998, ESS hereafter) show that cooperation can emerge in a public good environment by the way of local interaction. In their model, each player is located along a circle and plays repeatedly with his two nearest neighbours. In each period \((t)\), each player chooses an action, which is confronted to the actions of his two neighbours (mean matching rule). At the end of each period, the player observes the mean payoff of each action within his neighbourhood – composed of himself and his two neighbours. In the next period \((t+1)\), the player imitates the action that gives the highest mean payoff in period \(t\).

Let us consider the following conditions:

(i) \( 3R + S > 2P + 2T \)

(ii) \( 2R + 2S > 3P + T \)

By applying ESS's model to a prisoners’ dilemma game, it can be shown that under conditions (i) and (ii) there exist five absorbing states: one in which all players defect, one in which all players cooperate, and three kinds of mixed stable states in which cooperative play represents at least sixty percent of all plays.

To illustrate this result, consider the following example. Let \( T = 70 \), \( R = 60 \), \( P = 20 \) and \( S = 10 \), and consider the following distribution of play in period \(t\) (for some part of the circle):

```
- - - C  C  D
D  D - - -
```

The player whose action is underlined observes in his neighbourhood (composed by himself and his two neighbours), that action D has as mean payoff of 65 and action C has a mean payoff of 70.\(^1\) If he purely imitates the most successful action observed in his neighbourhood, this player chooses "cooperate" in period \((t+1)\). Based on this principle of evolution, all stable states where cooperation exists contain at least sixty percent of cooperative play. If mutations are allowed, the stable state in which all players defect is eliminated, so that all evolutionary stable states contain at least sixty percent of cooperative agents.\(^2\)

While these results suggest that cooperation may be sustained when players interact locally, conditions (i) and (ii) are very restrictive as shown by the above example. Taken together they imply that both "greed" (\(T – R\)) and "fear" (\(P – S\)) are low, because \(R\) must be close to \(T\) and

\(^1\) Mean payoff of action D : \(((70+20) + (20+20)) / 2 = 65\), mean payoff of action C : \((60+10) / 1 = 70\).

\(^2\) See Eshel, Samuelson & Shaked, 1998, for the demonstration of all these results in a public good environment.
P must be close to S. This situation renders cooperation less risky and therefore more likely to occur; moreover the high value of \((R - P)\) reinforces this effect in favour of cooperative plays as established by previous experimental studies (Rapoport & Chammah, 1965, Ahn et al., 2001). If conditions (i) and (ii) are not satisfied, ESS’s model implies that there is a unique stable state that includes only defectors.

In the theoretical part of this paper we look for less restrictive assumptions on the parameter values for cooperation to emerge when interactions among players are organized on a circle. We show that under a random matching rule and a pure imitation assumption cooperation can emerge as a general property, i.e. the imitation dynamics can lead to stable states involving cooperative play, independently on the values of the parameters of the payoff matrix. However, there is a cost for such a generalization. First, we cannot guarantee that the level of cooperation is as large as in ESS, and second that the corresponding states are evolutionary stable (Bertrand, 2003).

2.2. Random matching rule.

Consider a group of players located on a circle. In any period, a given player interacts with only one of his two adjacent neighbours. With probability one half he is matched with his left neighbour and with probability one half he is matched with his right neighbour. While each player only encounters one of his neighbours at a time, we still assume that he is sufficiently well informed about his neighbourhood to be able to observe the mean payoffs of each action played in his neighbourhood in every period: this lies on the credible idea that people do not need to constantly interact in order to be aware about their neighbours performance. The two examples that follow illustrate how the imitation rule leads the process from one period to the next.

Example 1: the distribution of play in period \(t\) is \(-----\ C–D \ C–C \ ----\)

The player whose action is underlined interacts with his left neighbour, whereas his right neighbour interacts with his own right neighbour. Therefore, in the neighbourhood of the agent, mean payoff of action D is \(T\) and mean payoff of action C is \((S + R) / 2 < T\). Therefore, in period \(t + 1\), the player keeps on playing D under the imitation rule.

Example 2: the distribution of play in period \(t\) is \(-----\ D–D \ C–C \ ----\)

Assuming the same matching than in example 1, in the neighbourhood of the agent whose action is underlined mean payoff of action D is \((P + P) / 2 = P\) and mean payoff of action C is \(R > P\). Therefore, in period \(t + 1\), the player switches from D to C.

Consider now the particular case where \(N = 8\), as in our experiment. We show that the following proposition holds.

**Proposition 1.** Let \(N = 8\). Over an infinite number of periods, the imitation dynamics lead to four possible stable states:

(i) all players defect (allD),
(ii) all players cooperate (allC),
(iii) five adjacent players defect and three adjacent players cooperate (5D, 3C),
(iv) three adjacent players defect and five adjacent players cooperate (3D, 5C).

(Proof: appendix 1).

Once the initial configuration of play is given, the evolution is simultaneously driven by a deterministic force, the imitation process, and a random force, due to the random matching
rule. Therefore, two identical initial configurations can evolve towards two different absorbing states. For example, the configuration CCCCDDDD evolves with probability one half towards the stable state allC, and with probability one half towards the stable state allD (see appendix 2). Proposition 2 gives the mean proportion of initial configurations leading to each stable state in the case where N = 8.

**Proposition 2.** Let N = 8. Over an infinite number of periods, on average:

(i) \( 65.23 \% \) of the initial configurations converge towards the stable state allD,

(ii) \( 12.89 \% \) of the initial configurations converge towards the stable state allC,

(iii) \( 12.50 \% \) of the initial configurations converge towards the stable state (5D, 3C),

(iv) \( 9.38 \% \) of the initial configurations converge towards the stable state (3D, 5C).

(Proof : appendix 2).

If N becomes large (N has to be even, due to the random matching rule), proposition 3 applies:

**Proposition 3.** Let N be even. Over an infinite number of periods the imitation dynamics lead to the following possible stable states:

(i) all players defect (allD),

(ii) all players cooperate (allC),

(iii) several mixed stable states, denoted (nD, (N-n)C), composed of one or several strings \( s_i \); each \( s_i \) is composed of an odd number \( n_i \) of adjacent defectors, with \( 3 \leq n_i \leq N - 3 \) \( \forall i \) and \( \Sigma n_i = n \) (n is the number of defectors within the whole circle).

All strings \( s_i \) are separated two by two by an odd number (at least equal to three) of adjacent cooperative players.

(Proof : appendix 3 ; see also examples provided by appendix 4).

The imitation model presented in this section is ruled both by a deterministic process (imitation rule) and a random process. (matching rule). As shown in the proof of proposition 2, all initial configurations need to be studied, and, from each initial configuration, the number of possible evolutions may double in every period until a stable state is reached. The number of possible initial configurations, with N players located around a circle, is \( 2^N \). Therefore, if N = 8, 256 initial configurations have to be studied. This leads to the four possible stable states described in proposition 1. In this case, the average rate of cooperation, over all possible initial configurations and all possible consequences of the matching rule equals about 23.5 \%.

If N = 50, the number of possible initial configurations is \( 2^{50} \) and only numerical simulations allow to approximate the average rate of cooperation resulting from the evolution of each initial configuration towards one of the several possible stable states described in proposition 3. Simulations run over 1000 initial configurations, all of whom end up in a stable state in less than 500 periods, exhibit, in period 500, a global mean over all cooperation rates around 24 \%. Appendix 4 presents some examples of possible stable states for N = 50.

3. Imitation dynamics in a global interaction model.

Since all results presented in section 2 are based on an imitation assumption, we also study the possible impact of “global and imitable” information when interactions are global. Under

\[ 65.23 \times 0 + 12.89 \times 1 + 12.5 \times (3/8) + 9.38 \times (5/8) = 23.44. \]
global interaction cooperation can emerge only under the random matching rule and is not parameter-free.

3.1. Mean matching rule.

Consider a group of N players. In period t, each player chooses an action, which is confronted to the actions of the N – 1 other players. At the end of period t, all players observe the mean payoff of each action within the group. Then, in period t+1, each player imitates the action that gives the highest mean payoff in period t. The following proposition shows that cooperation survives only if all players cooperate in period t = 0.

Proposition 4.
(i) There exist two stable states: (1) all players cooperate (allC), (2) all players defect (allD).
(ii) If there is at least one defector in the initial configuration, the allD stable state is reached in period 1; otherwise, the system remains in the allC stable state.
(Proof: appendix 5).

3.2. Random matching rule.

Robson & Vega-Redondo (1996) study a global interaction model with imitation, based on a random matching rule, applied to coordination games. Adaptation to prisoners’ dilemma games is straightforward and can allow cooperation to yield higher mean payoffs than defection and therefore lead to the emergence of cooperation. Consider a group of N players where N is even. In each period (t), agents are paired randomly, so that every agent meets any other agent of the group with probability 1/(N–1). At the end of period t, each player observes the mean payoff of each action within the group. Then, in t+1, he imitates the action that gives the highest mean payoff in the group in period t.

Proposition 5 contains two specific examples related to the sets of parameters that we use in our experiment. The proposition establishes that cooperation can emerge as a general property in a group of randomly interacting players, but depends on the values of the parameters of the payoff matrix.

Proposition 5.
(i) The imitation dynamics lead to two possible stable states: (1) all players cooperate (allC), (2) all players defect (allD).
(ii) Let N = 8, T = 40, R = 30, P = 20, S = 10. If there is an even number of cooperative agents and if all are paired together (5.86% of the possible initial configurations), the stable state allC is reached in period 1, in all other cases the stable allD is reached in period 1.
(iii) Let N = 8, T = 70, R = 60, P = 20, S = 10. The stable state allC is reached in period 1 through one of the following initial configurations:
   - there is an even number of cooperative agents and all are paired (15 configurations),
   - there are three cooperative agents in the initial configuration and two of them are paired (24 configurations),
   - there are five cooperative agents in the initial configuration and four of them are paired (24 configurations).
Therefore 24.6% of the possible initial configurations lead to the stable state allC in period 1.
(Proof : appendix 6).

4. Experimental design.

The experimental sessions were run between May 2001 and October 2002 at the BETA Laboratory of Experimental Economics (LEES) at the University of Strasbourg. Subjects were randomly chosen from a subject-pool of 1200 volunteers of various disciplines. None of the subjects had previous experience of the prisoners’ dilemma game. Twelve sessions were organized, involving sixteen subjects each, yielding a total of twenty-four groups of eight players. We implemented two different parameter sets, for each of whom six of the groups played the local treatment and six played the global treatment. Each treatment involved fifty periods.

Our aim was to allow the emergence of cooperation through the imitation of "successful" strategies in each of the two interaction structures. Therefore we informed our subjects at the beginning of each round about the mean payoff of each action in their environment in the previous period. The same type of information was provided under the local and under the global interaction structure. In the local interaction groups, subjects played randomly with one of their two neighbours in each period. Similarly, each subject in the global interaction structure was randomly assigned to play against another randomly chosen member of his group. These design options were of course chosen in order to be as close as possible from the environment corresponding to the propositions introduced in the previous section.

For the local treatment subjects were told that they are located on a circle (shown in the instructions) and would interact in each period with only one of their two neighbours chosen randomly. Subjects assigned to the global treatment were told that they would interact randomly with one of the seven other members of their group in each period. At the end of a period, players were informed about the action chosen by their opponent player for the period, their payoff for the period, and the mean payoff of each action within their neighbourhood (defined as the player himself together with his two adjacent neighbours) in the local treatment, or within the whole group in the global treatment. Mean payoffs observed within the environment were kept on display in the following period.

Given that the predictions of the imitation model proposed in section 2.2 (local interaction under random matching rule) are independent of the values of the parameters, we implemented two different parameter settings in order to test for parameter independence : a "weak" setting and a "strong" setting. The “weak setting” is motivated by the fact that cardinal differences among values of the payoffs have been proved to influence agent’s cooperative behaviour, as shown for example by Ahn et al. (2001). Furthermore, when mutual defection leads to a payoff equal to zero, “zero” represents a repulsive focal point which may artificially favour more cooperation. Finally, if negative payoffs are allowed, the general pattern of loss-aversion drives play to secure strategies and therefore favours defection (Tversky & Kahneman, 1991). In an attempt to rule out all these possible biases, we chose the following parameters for what will hereafter be called our weak setting : T = 40, R = 30, P = 20, S = 10. This game is therefore played in both local and global interaction environments, and we expect, as suggested by the imitation models, a higher level of cooperation in the local treatment.
In the “strong” setting, $T = 70$, $R = 60$, $P = 20$, $S = 10$. Therefore the gain from cooperation $(R - P)$ is much higher than in the weak setting. The difference $(R - P)$ can be taken as a measure of the strength of the social dilemma. Willinger & Ziegelmeier (2001) showed, in the case of public goods games, that the stronger the social dilemma the larger the frequency and level of cooperation (see also Isaac & Walker, 1998, for a similar result). We therefore hypothesise that by increasing the dilemma in our game cooperation might be favoured. Furthermore, we expect cooperation to be more likely to be imitated than under the weak setting since the payoff superiority of cooperative play, if it is established in a neighbourhood or a group, is now larger.

Since under the strong setting cooperation is favoured in both treatments, will it be more favoured under local interaction than under global interaction? Actually, the opposite outcome is more likely. The change in parameters does not affect the predicted outcome for the local treatment. But it affects the predicted outcome in the case of global interaction, because cooperation is more likely to yield higher payoffs (see proposition 5). We expect therefore a smaller difference in the level of cooperation between the local treatment and the global treatment for the strong setting.

5. Experimental results.

This section presents the results collected over the six groups assigned to each interaction structure and each set of parameters. Our main interests are (i) the differences in the level of cooperation between the local treatments and the global treatments (ii) the credibility of the pure imitation rule. All potential differences are tested with the use of the non-parametric Mann-Whitney test, at the level of significance of 5%. We also study conditional cooperation, as presented in Keser & van Winden (2000), to analyze alternative assumptions to the pure imitation rule, such as reactive behaviour and future-oriented behaviour.

5.1. General results.


Tables 1 and 2 provide a summary of the results for the local treatment and for the global treatment. The first column indicates the group label (“L” for local interaction, “G” for global interaction, “W” for weak setting). The second column gives the frequency of cooperative play per group, i.e. the percentage of cooperative play among the eight players and the fifty periods. The three remaining columns provide detailed information about the frequency of imitation of the previous period “highest payoff” action.

The average level of cooperation, over the six groups of eight players and over the fifty periods, is about 19.5 % in the local treatment and about 13.9 % in the global treatment. Since the models described in section 2 are based on the assumption that players purely imitate the action that lead to the highest mean payoff in the previous period within their neighbourhood or within their group, they require a rate of imitation equal to 100 %. In the experiment, the average levels of imitation are very high, equal respectively to 81.5 % and about 85.3 % for the local and the global treatment.
The non-parametric Mann-Whitney test rejects the hypothesis that the levels of cooperation in the local and in the global treatment are different, at the level of significance of 5%. We can therefore not conclude, under this set of parameter, that local interactions neither favour nor reduce cooperative play. The only difference between the two treatments that is accepted, (Mann-Whitney, 5%), is that in the local interaction treatment players are more sensitive to the information that cooperation yielded higher payoffs in the previous period, in the sense that they are significantly more likely to cooperate in the next period.

In most cases (92.5% in the local treatment and 96.9% in the global treatment), the action that leads to the highest mean payoff is defection. There is no clear way to separate pure imitation of defection from dominant strategy play. However, within each treatment, players are significantly more likely to cooperate when they observe a higher payoff from cooperation than from defection in the previous period (Mann-Whitney, 5%). We take this as evidence of the imitation rule assumption, but of course subjects might also take more than just one period into account to take their current decision: observation by a subject of a higher payoff for cooperation in one period just increases the likelihood of cooperative play, but does not make cooperation be played with probability one.

In the local treatment, over the 48 players and over the 49 periods in which imitation was feasible, cooperation yielded the highest mean payoff in the neighbourhood in 177 cases, and was played, in the next period, in 95 cases. This corresponds to a rate of imitation of cooperation of about 53.7%. For example, player LW1.2 who was informed twelve times that cooperation led to a higher mean payoff than defection in the previous period in his neighbourhood, cooperated in all twelve cases in the following period. On the other hand, player LW3.5 who was informed six times that cooperation led to a higher mean payoff in the previous period, cooperated in only three cases in the following period. More precisely, nine players always imitated cooperation as the latter led to higher payoffs in the previous period (44 observations), eleven players never imitated cooperation (33 observations), nine players never noted that cooperation led to higher payoffs, the remaining nineteen players imitated cooperation in 51 cases out of 100.
In the global treatment, cooperation led to the highest mean payoff in the previous period only in 72 cases, and cooperation was then imitated in the following period in 22 cases. This corresponds to a rate of imitation of cooperation of about 30.5%. For example, player GW2.8 was informed twice that cooperation yielded a higher mean payoff within his group, and cooperated once in the following period. More precisely, twelve players always imitated cooperation as it yielded higher payoffs in the previous period (15 observations), twenty-nine players never imitated cooperation (44 observations), the remaining seven players imitated cooperation in 7 cases out of 13.

Defection was established to lead to higher mean payoffs in 2175 cases in the local treatment, and was played in the following period in 1822 cases (83.8%). In the global treatment, the imitation rate of defection is about 87.1 % (1985 cases out of 2280). Note that eight players out of 48 chose to defect in all of the fifty periods in the global treatment, whereas only four players did in the local treatment.

5.1.2. Strong setting : T = 70, R = 60, P = 20, S = 10.

Tables 3 and 4 summarize the general results respectively for the local treatment and for the global treatment. (“S” stands for strong setting). The average levels of cooperative play are equal to about 30.4 % and 31 % for the local and the global interaction treatment respectively; the average levels of imitation are equal to about 72.3 % and 70% respectively.

The average level of cooperation is significantly higher under the strong setting, both for the local and the global interaction treatment (Mann-Whitney, 5 %). These results confirm in the case of our local and global (random) interaction structures, the previous findings that when the social dilemma becomes stronger, cooperation is reinforced (see Isaac & Walker 1988, Willinger & Ziegelmeyer, 2000).

Furthermore, in the strong setting, subjects are significantly (Mann-Whitney, 5%) less likely to imitate the previous period’s most successful action than under the weak setting. The lower sensitivity to the information reflects again the fact that subjects are more likely to cooperate (due to the parameter values) and therefore less likely to simply imitate the strategy with the highest mean payoff of the previous period. More precisely, under the strong setting, subjects are more likely to imitate cooperation within the global treatment (but not significantly), and significantly less likely to imitate defection within both the local and the global treatment.

<table>
<thead>
<tr>
<th>Group</th>
<th>Cooperation</th>
<th>Imitation</th>
<th>Imitation of C</th>
<th>Imitation of D</th>
</tr>
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<tbody>
<tr>
<td>LS1</td>
<td>20.50%</td>
<td>77.55%</td>
<td>16/42</td>
<td>288/350</td>
</tr>
<tr>
<td>LS2</td>
<td>44.00%</td>
<td>64.03%</td>
<td>56/82</td>
<td>195/310</td>
</tr>
<tr>
<td>LS3</td>
<td>32.00%</td>
<td>72.45%</td>
<td>46/77</td>
<td>238/315</td>
</tr>
<tr>
<td>LS4</td>
<td>31.75%</td>
<td>71.17%</td>
<td>38/68</td>
<td>241/324</td>
</tr>
<tr>
<td>LS5</td>
<td>23.25%</td>
<td>78.57%</td>
<td>14/23</td>
<td>294/369</td>
</tr>
<tr>
<td>LS6</td>
<td>30.75%</td>
<td>70.15%</td>
<td>26/49</td>
<td>249/343</td>
</tr>
<tr>
<td>Mean</td>
<td>30.38%</td>
<td>72.32%</td>
<td>57.48%</td>
<td>74.84%</td>
</tr>
</tbody>
</table>

Table 3. Local treatment
According to our findings there is no difference between the local and the global treatment, both with respect to the level of cooperation and with respect to the sensitivity to the information. This result is not very surprising from a theoretical viewpoint since the strong setting allows more initial configurations leading to cooperation under global interaction (see proposition 5). The stronger cooperation observed under global interaction in the strong setting could therefore be the result of more frequent imitations of the more successful strategies. Indeed, in the global interaction treatment, on average, cooperation yielded higher payoffs than defection about 8 times per group under the strong setting, but only 1.5 times per group under the weak setting. Note that the proposition that the strong setting allows more frequent cooperative outcomes applies only to global interaction. The higher mean payoffs also observed under local interaction for the strong setting are not theoretically justified.

Like for the weak setting, information provision about the mean payoff significantly affects (Mann-Whitney, 5%) the likelihood of cooperative play, under both interaction structures. More precisely, after having observed a higher mean payoff for cooperation than for defection, subjects were more likely to cooperate.

In the local treatment, over the 48 players and over the first 49 periods, cooperation yielded the highest mean payoff in the neighbourhood in 341 cases, and was imitated, in the next period, in 196 cases. The rate of imitation of cooperation is therefore about 57.5 %. For example, player LS.6 who was informed 15 times that cooperation led to a higher mean payoff than defection in the previous period and cooperated in the next period in all 15 cases. On the other hand, player LS.4 was informed 10 times that cooperation led to higher payoffs but never cooperated in the following period. More precisely, six players always imitated cooperation as the latter led to higher payoffs in the previous period (65 observations), nine players never imitated cooperation (37 observations), two players never noted that cooperation led to higher payoffs, the remaining thirty-one players imitated cooperation in 131 cases out of 239.

In the global treatment, cooperation led to the highest mean payoff in the previous period 392 times, and was then imitated in the next period in 202 cases, yielding a rate of imitation of cooperation about 51.5 %. For example, player GS.5 cooperated in the next period in each of the seven cases he was informed that cooperation gave a higher mean payoff in the group. More precisely, six players always imitated cooperation as the latter yielded higher payoffs in the previous period (37 observations), six players never imitated cooperation (37 observations), the remaining thirty-six players imitated cooperation in 165 cases out of 318. Defection was established to lead to higher payoffs in 2011 cases in the local treatment, and was played at the next period in 1505 cases (74.8%). In the global treatment, the imitation rate of defection is about 73.7% (1444 cases out of 1960). Note that two players defected in all of the 50 periods in the local treatment, whereas only one did in the global treatment.
5.2. Evolution over time.

5.2.1. Weak setting.

Figure 2 shows the evolution of the average rate of cooperation in both the local and the global treatments. As already established by many experiments on repeated prisoners’ dilemma games (Selten & Stoecker, 1986, Andreoni & Miller, 1993, Ledyard, 1995), the average level of cooperation decreases over time. As underlined by the tendency curves, in both treatments the level of cooperation decreases sharply. For example, the average level of cooperation falls from 40% to less than 20% in the local treatment. The trends show that cooperation decreases at a faster rate in the global than in the local treatment (slopes equal –0.48 and –0.36, respectively).

Table 5 summarizes the evolution of the level of cooperation and imitation into five sequences of 10 periods. The decline in the level of cooperation appears clearly, but for the local treatment it seems to be somewhat “regular” whereas in the global treatment there is particularly steep fall in the third sequence. While the levels of cooperation are comparable over the two first sequences, they differ strongly for the remaining ones. The imitation rates are increasing in both treatments, reflecting the fact that players defect more and more often, reducing therefore the probability that cooperation can be established as the better action in a neighbourhood or in a group. This induces an increase of the imitation rate, mainly due to the imitation of defection. Note also that both levels begin around the same value, but the imitation rate increases faster in the global treatment, because of the stronger decline of the level of cooperation.
5.2.2. Strong setting.

As shown by the tendency curves in figure 3, the level of cooperation decreases sharply in the local treatment (from above 50% to less than 20%, slope of the trend equals −0.67), whereas in the global treatment the decline proceeds at a lower pace (slope of the trend is only −0.31). This is in clear contrast with the weak setting.

<table>
<thead>
<tr>
<th>Period</th>
<th>Cooperation</th>
<th>Imitation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Local</td>
<td>Global</td>
</tr>
<tr>
<td>1 to 10*</td>
<td>26.46%</td>
<td>23.96%</td>
</tr>
<tr>
<td>11 to 20</td>
<td>23.12%</td>
<td>19.79%</td>
</tr>
<tr>
<td>21 to 30</td>
<td>18.96%</td>
<td>11.67%</td>
</tr>
<tr>
<td>31 to 40</td>
<td>16.04%</td>
<td>8.75%</td>
</tr>
<tr>
<td>41 to 50</td>
<td>12.71%</td>
<td>5.42%</td>
</tr>
</tbody>
</table>

Table 5. Evolution over time
* Imitation rates are computed for periods 2 to 10

With table 6 one can see that the decline of the level of cooperation in the local treatment is particularly important over the first ten and the last ten periods. In the global treatment, the rate of cooperation remains relatively stable over the first thirty periods, and begins really to decline only over the last twenty periods. Therefore, despite the important difference between the two treatments over the first sequence, the overall level of cooperation is nearly the same in the two treatments. Since the rate of defection increases, cooperation gives more and more scarcely a higher payoff, and this explains the parallel increase of the imitation rate, since it corresponds mainly to the imitation of defection. In the global treatment for instance, the rate of imitation is globally stable over the first thirty periods, and only increases over the last
twenty periods, reflecting the parallel increase in the level of defection. Therefore, in contrast to the weak setting, the rate of imitation increases faster in the local treatment.

As already established, the level of cooperation is larger under the strong setting, where fear and greed are low compared to the large difference between R and P. However, within the strong setting, there is no difference in the global levels of cooperation between the local and the global interaction treatments. There are two reasons for that. First, in the global treatment, these parameter values (70-60-20-10) allow for much more configurations to yield higher mean payoffs for cooperative play. Some of the players’ behaviours therefore reflect imitation of cooperation. Second, within the local treatment, one single defector can strongly reduce cooperation over the whole circle, because all players are indirectly connected and players cannot identify each other. Therefore, the neighbour of an always-defecting player will always defect too, infecting his own neighbourhood, and defection propagates further. In the global treatment, players who try to induce cooperation may be more confident in finding another cooperative agent, since if a single always-defecting player belongs to the population, the other players will be matched with him only with probability 1/7, and a propagation effect such as in the local interaction treatment does not built up. Moreover, since each player knows that each other player is given the information about mean payoffs in the whole group, each player knows that by being matched with another cooperative agent he may influence the whole group towards cooperative play by showing that cooperation can give higher payoffs. Under the weak setting, only few cases led to a higher mean payoff for cooperative play within the global treatment.

The larger difference in the level of cooperation within the global treatment, compared to within the local treatment, even if it is not significant, can therefore be explained by imitation of successful choices of cooperation. Indeed, under the strong setting and the global interaction treatment, cooperation yielded much more often higher payoffs than under the weak setting, the strong increase in cooperative play therefore reflects that imitation occurred. In the local interaction treatment, since the results of the model presented in section 2.2 are independent of the parameter values, no such effect occurs. The only influence of the change in the parameter values is the increase in the strength of the social dilemma. While this change increases the level of cooperative play, one must take into account the fact that, first, the number of configurations allowing a higher payoff for cooperation remains the same, and second, one single defector can still invade the whole circle. Therefore, in the strong setting, the increase in the level of cooperative play is larger within the global interaction treatment, and only the use of an imitation rule could theoretically predict this outcome.

### 5.3. Conditional cooperation.

<table>
<thead>
<tr>
<th>Period</th>
<th>Cooperation</th>
<th></th>
<th>Imitation</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Local</td>
<td>Global</td>
<td>Local</td>
<td>Global</td>
</tr>
<tr>
<td>1 to 10*</td>
<td>46.25%</td>
<td>34.37%</td>
<td>65.51%</td>
<td>67.13%</td>
</tr>
<tr>
<td>11 to 20</td>
<td>31.67%</td>
<td>33.75%</td>
<td>68.12%</td>
<td>67.50%</td>
</tr>
<tr>
<td>21 to 30</td>
<td>32.29%</td>
<td>36.46%</td>
<td>66.87%</td>
<td>66.04%</td>
</tr>
<tr>
<td>31 to 40</td>
<td>25.21%</td>
<td>26.87%</td>
<td>75.83%</td>
<td>72.71%</td>
</tr>
<tr>
<td>41 to 50</td>
<td>16.46%</td>
<td>23.33%</td>
<td>84.58%</td>
<td>76.20%</td>
</tr>
</tbody>
</table>

Table 6. Evolution over time

* Imitation rates are computed for periods 2 to 10
As in Keser & van Winden (2000) we define conditional cooperation as a combination of two aspects of subject's behaviour: future-oriented behaviour and reactive behaviour. Future-oriented behaviour inclines subjects to cooperate in order to induce other members from their group to cooperate as well. A future-oriented behaviour is more likely to be adopted by subjects in the early periods of the repeated game and tends to disappear towards the end of the repeated game. Such behaviour might therefore lead subjects towards cooperation even when other subjects do not cooperate, as a kind of persuasion tool. While future-oriented behaviour is expectation-based, reactive behaviour on the other hand is more memory-based and refers to the reciprocity principal.

We identify future-oriented behaviour in period $t$ as the choice of cooperative play after having been confronted to defection in period $t-1$. Similarly we identify reactive behaviour as the choice of defection after having been confronted to defection in period $t-1$. We limit ourselves to these categories, because the choice to cooperate in period $t$ after having experienced cooperation in period $t-1$, could be both due to future-oriented or reactive behaviour. We expect to observe more future-oriented behaviour under local interaction than under global interaction since the environment of each agent is composed of a smaller number of agents under the former than under the latter.

Table 7 presents the percentage of cooperative plays in period $t$ depending on the different cases resulting from plays in period $t-1$, both under the weak and the strong setting.

<table>
<thead>
<tr>
<th>Play in $t-1$</th>
<th>Weak setting</th>
<th>Strong setting</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Local</td>
<td>Global</td>
</tr>
<tr>
<td>C</td>
<td>41.92%</td>
<td>41.57%</td>
</tr>
<tr>
<td>D</td>
<td>13.52%</td>
<td>8.86%</td>
</tr>
<tr>
<td>Opponent player's play in $t-1$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>28.60%</td>
<td>14.16%</td>
</tr>
<tr>
<td>D</td>
<td>16.74%</td>
<td>13.37%</td>
</tr>
<tr>
<td>Payoff in $t-1$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>72.03%</td>
<td>62.50%</td>
</tr>
<tr>
<td>10</td>
<td>31.47%</td>
<td>38.03%</td>
</tr>
<tr>
<td>40</td>
<td>13.53%</td>
<td>5.99%</td>
</tr>
<tr>
<td>20</td>
<td>13.51%</td>
<td>9.33%</td>
</tr>
</tbody>
</table>

Table 7. Conditional cooperation.

For example, in the local treatment under the weak setting, 72.03% of the socially optimal outcomes (30) were followed by cooperation from the subject who get it, whereas only 31.47% of the situations where one player was exploited (and get 10) were followed by cooperation from this player; therefore, 41.92% of the cooperative plays were followed by a cooperative play from the same player in the following period, whereas only 28.60% of the cooperative plays of the opponent players induced cooperation in the following period. Within the strong setting, these last two values respectively equal 55.82% and 38.09%.

Future-oriented behaviour is more frequent under the strong setting (around 27%) than under the weak setting (around 15%), but does not differ depending on the interaction structure: under the weak (resp. strong) setting, the percentage of cooperative play after being confronted to defection is around 17% (resp. 26%) within the local interaction structure and around 13% (resp. 28%) within the global interaction structure. However, future-oriented
behaviour is dependent on the precise payoff obtained by a subject when he is confronted to defect. A subject is much more likely to cooperate, under both interaction structures and both sets of parameters, if he cooperated in the previous period (and therefore get a payoff of 10) than if he defected too (and get a payoff of 20). This surprising result shows the strength of future-oriented behaviour, which leads to persistent attempts to avoid to get locked in mutual defection, a situation for which attempts to favor emergence of cooperation are much less likely. For example, under the strong setting and the global interaction treatment, a subject cooperating and being confronted to defection keeps on cooperating with probability one half in the following period, whereas when mutual defection is reached the probability of cooperative play in the next period is only around 19%.

Furthermore, as shown by table 7, general features emerge from both interaction structures and both sets of parameters:

(i) subjects are more likely to cooperate in period $t$ if they already cooperated in period $t-1$, in order to sustain cooperation or to make it emerge,
(ii) subjects are more likely to cooperate in period $t$ if their opponent player in period $t-1$ cooperated, combining therefore future-oriented behaviour and reactive behaviour,
(iii) not surprisingly, subjects are more likely to cooperate in period $t$ if they got the socially optimal outcome (30 or 60) in period $t-1$ then in all other cases, which shows that mutual cooperation can be sustained,
(iv) surprisingly, subjects are more likely to cooperate in period $t$ if they have been exploited in period $t-1$ (payoff of 10) then if they get one of the two possible payoffs of defection (40 or 20, or 70 or 20), which shows the persistence of future-oriented behaviour,
(v) finally, subjects are more likely to switch to cooperation if they get the mutual defection payoff (20) then if they get the maximum payoff (40 or 70), which shows that the likelihood of future-oriented behaviour after mutual defection overcomes the likelihood of cooperative reaction to a cooperative play by the opponent player, reducing therefore the latter mainly to the cases in which mutual cooperation was reached.

5.4. First period behaviour.

To conclude we compare the behaviour of subjects who cooperated in the first period to the one of subjects who defected in the first period. Subjects who started with cooperation can be considered as strategic or basically more cooperative, and may have wished to induce cooperation in their neighbourhood or group. On the other hand, subjects who started by defecting are more likely to be selfish, or to adopt a passive and “safe” option, waiting to see whether the nature of their environment or if cooperation leads to higher payoffs in their neighbourhood or group, before possibly switching to cooperation.

Table 8 gives the average levels of cooperation, imitation of cooperation, and imitation of defection, among players who first cooperated (19 players out of 48 in the local treatment and 17 players in the global treatment) and among players who first defected, both in the local and the global treatments, under the weak setting. Table 9 gives the same information under the strong setting, for which 27 players in the local treatment and 25 players in the global treatment cooperated in the first period.
In both treatments and under both settings, clear differences appear: players who cooperated in the first period are more likely to cooperate over the whole game, more likely to imitate cooperation when the latter was established as leading to higher payoffs, and less likely to imitate defection as the latter was established as leading to higher payoffs. In this last case, they are therefore more likely to cooperate, in order to make cooperation emerge or emerge again in their neighbourhood or in their group. Therefore, the behaviour of a player in the first period already indicates significant differences in the approach of the social dilemma. Basically, this kind of “cooperative” player can for example have a key role in a more complex environment, for example if players are allowed to have an influence on the precise form of the interaction structure in which they are involved.

6. Conclusion.

We investigated the behaviour of subjects engaged in a prisoners dilemma game within a group of subjects. The experiment is based on a strangers design and compares two interaction structures: a global interaction structure and a local interaction structure. In the global interaction structure each subject is randomly matched in each period with a member of his group. In the local interaction structure subjects are spread around a circle and in each period, each subject is randomly matched either with his right or with his left neighbour. Neighbourhoods are overlapping so that subjects are indirectly connected with all the members of the group.

Theory predicts that the emergence of cooperation is achieved more easily when interactions are local rather than global. This result is based on the simple intuition that cooperation emerges more easily in subsets of agents than in global environments. Most of the previous research relied on repeated games arguments to derive predictions about emergence and persistence of cooperation. In the models presented in this paper such arguments are partly ruled out by the random matching rule: players are not able to identify the neighbour with whom they interact, and therefore cannot really play strategically, since if they try to play strategically simultaneously with the two neighbours they risk to be exploited by an opportunistic neighbour. Similarly, the opportunities to exploit neighbours are larger because players benefit from a kind of impunity, due to the fact that defectors cannot be clearly identified by their neighbours. The only information that players are given are mean payoffs of each action within their neighbourhood (they can therefore infer the actions played by their
two neighbours in each period), but this knowledge does not allow them to behave strategically. The theoretical models are therefore based on a simple imitation rule, which is the main alternative to playing the dominant strategy in this partly random context and allow the emergence of cooperation.

Our experimental results are surprising, in the sense that they exhibit no clear differences in the levels of cooperation between local and global environments. As established, in the local environment, one single defector can infect the whole network, since he cannot be clearly identified by his neighbours; the latter therefore have strong incentives to defect too, and the phenomenon propagates. Conversely, local cooperation can be achieved among cooperative agents. Therefore, local interaction can be an advantage as well as a disadvantage for achieving cooperation. In the global environment, no such evolution can occur, each cooperative agent can hope to reach mutual cooperation in each period, since his environment is larger and the probability of matching another specific agent is weaker. In a world of “globalization”, this may be interpreted as a hope by each player to meet another player with whom interaction could be very efficient, and the probability of this “ideal matching” increases in a global environment. Conversely, local interactions restrict the number of possible opponent players, and, even if they interact more often and can therefore have incentives to cooperate, it is not sure that they would consider their neighbourhood as “perfect” enough. To take an example, many young people spend more and more time (randomly) “chatting” on the Internet with people about whom they know practically nothing but who seem to be very interesting, and reduce therefore the time that they spend with their “real” neighbours or friends…

Our results allow us to study more specifically the imitation assumption. Despite no player perfectly follows this rule during all fifty periods, a significant difference in the behaviour of the players has been established, depending on whether they observe a more profitable result from cooperation or from defection in their neighbourhood or group in the previous period. This tendency to imitate cooperation as it led to a higher payoff in the previous period, combined with some strategic attempts, by several players, to make cooperation emerge in their neighbourhood or group, allows the cooperation level to be significantly high, despite the random matching rule. In the global environment, strategic behaviour opportunities are clearly weaker, and payoff superiority of cooperation in one period is rare, so that explanations of cooperation may be attempts to make the group react and cooperate more, for example in the hope that mutual cooperation can be reached with the opponent player, and that the whole group would then be informed about the possibility of getting higher payoffs by cooperating.

The imitation rule plays a key role in the models described in this paper. Combining it with strategic behaviours would reinforce the possibility of the emergence of cooperation. For example, if we apply the model presented in section 2.2 with replacing the random matching rule by a rule in which each players alternatively interacts with each of his neighbours, the imitation dynamics would lead to the same four stable states, but the percentage of initial configurations evolving towards the allC and allD stable states would respectively grow to 23% and fall to 55% (the percentage of initial configurations evolving towards the two other stable states would remain constant). Using repeated games arguments, many couples would try to achieve cooperation for strategic reasons, and players always choosing the dominant strategy (defection) would be identified quickly, suffer defection from their neighbours, and, if they are surrounded by two couples of cooperating agents, would constantly observe higher payoffs from cooperation, and therefore have stronger and stronger incentives to cooperate.
If we go further in this direction and try to stick to real world situations, we should take into account, first, that most interactions for agents are local, and second, that agents can have an influence on the structure in which they evolve. By local interaction some kinds of norms can propagate and make the neighbourhood become “friendly”, and if it does not agents may change their neighbourhood. Indeed, agents are not simply set in a network with some fixed links, but can also act on these links, by cutting the less profitable ones and establishing new ones. In this kind of context, opportunistic players would end up more and more isolated, and, noting that cooperative players do better together than defectors do together, especially in a context where means of information spread, would have stronger and stronger incentives to imitate cooperation, that is, to have behave cooperatively.
Appendix 1. Proof of proposition 1.

Let N = 8.

(i) The configurations allD and allC are stable states, because the imitation dynamics do not allow to get out of them (if all players play D, mean payoff of playing C is unknown, so that all players keep on playing D; the argument is the same for C).

(ii) The configuration CCDDDDDC evolves with probability one half towards the configuration CCCDDDDD and with probability one half towards the configuration CDDDDDDCC. Therefore, in every further period there will be five adjacent defectors and three adjacent cooperative agents.

(iii) The configuration CCCDDDCC evolves with probability one half towards the configuration CDDDDCCC and with probability one half towards the configuration CCCCCCCC. Therefore, in every further period there will be three adjacent defectors and five adjacent cooperative agents.

(iv) There is no other stable state, as can be seen in table 11 in appendix 2.

Appendix 2. Proof of proposition 2.

If N = 8, there are 256 initial configurations. Table 11 below shows the evolution of the 26 initial configurations that include all of them, since many of the configurations are identical by translations. Some configurations evolve quickly towards a stable state, whereas some other ones only converge when t goes to infinity. Two examples clearly show the kind of dynamics that occur and therefore the principle that leads to the proof of proposition 2.

Example 1. Consider that the distribution of play in the initial configuration is the following: CCDDDDCC. With probability one half, it evolves towards CDDDDDDCC, and with probability one half it evolves towards CCCDDCCC. The former evolves with probability one half towards DDDDDDDD and with probability one half towards CCDDDDCC. The latter evolves with probability one half towards CDDDDDDC and with probability one half towards CCCCCCCC. So, every two periods, with probability one quarter the stable state allD is reached, with probability one quarter the stable state allC is reached, and with probability one half we get back to the initial configuration. The process then goes on, so that finally the probability of convergence towards the stable state allC is \((1/2)^2 + 2.(1/2)^4 + 4.(1/2)^6 + \ldots = 1/2\). The probability of convergence towards the stable state allD is then 1/2 too.

Example 2. Consider that the distribution of play in the initial configuration is the following: CCDDCDCC. With probability one half, it evolves towards CCCDDCCC (and so further it converges with probability one half towards allC and with probability one half towards allD), and with probability one half it evolves towards CDDDDDDC. The latter evolves with probability one half towards allD, and with probability one half towards CDDDDDDC (and so further it converges with probability one half towards allC and with probability one half towards allD). So, the probability of convergence towards allC is \((1/2)^2 + (1/2)^3 = 3/8\), and therefore the probability of convergence towards allD is 5/8.

Table 11 summarizes all possible dynamics. It is organized as follows. Column 1 gives the number nC of cooperative agents in the initial configuration. Column 3 gives the different representative configurations (in t = 0) for each value of nC, and column 2 gives the number nIC of initial configurations that corresponds to each representative one, i.e., by permutations. Columns 4 and 5 give the two possible configurations in t = 1; each one occurs with
probability one half – according to the random matching rule. Columns 6 to 9 give the probability of convergence of the initial configuration towards each stable state, by applying the same principle than in the two previous examples: \( p(\text{allD}) \) denotes the probability of convergence towards the stable state allD; \( p(\text{allC}) \) denotes the probability of convergence towards the stable state allC; \( p(5D) \) denotes the probability of convergence towards the stable state \((5D, 3C)\); \( p(3D) \) denotes the probability of convergence towards the stable state \((3D, 5C)\).

Finally, on average, 167 initial configurations evolve towards the stable state allD, 33 evolve towards the stable state allC, 32 evolve towards the stable state \((5D, 3C)\), and 24 evolve towards the stable state \((3D, 5C)\).

**Appendix 3. Proof of proposition 3.**

The configurations allD and allC are stable states, because the imitation dynamics do not allow getting out of them.

By extension of the results obtained in appendix 1, all strings of 3, 5, 7, up to \(N - 3\) adjacent defectors, surrounded with cooperative agents, move to the right or to the left in the next period. If the circle is large enough, several so groups can exist.

For example, consider the following configuration: \(C\ldotsCDDDC\ldotsCDDDC\ldotsC\). Over an infinite period time, two cases are possible:

(i) if there is an even number of cooperative agents between the two strings of defectors, the latter meet, leading to the formation of one single string composed of 6 adjacent defectors. The latter then increases or decreases (according to the matching rule) and converges towards allC or allD.
(ii) if there is an odd number of cooperative agents between the two strings of defectors, the latter never meet. By applying the same principle to all configurations with several strings of an odd number of adjacent defectors, we conclude that the only possible mixed stable states are composed of one or several strings of an odd number of adjacent defectors, all of them being separated two by two by an odd number of adjacent cooperative agents (see also appendix 4).

Appendix 4. Examples of stable states for N = 50.

Figure 4 presents seven examples of stable states for N = 50. Cooperative play is displayed by a “C”, defection is displayed by a “d”. In each row, the left neighbour of the first player is the last player in the row. The column on the left gives the percentage of cooperation in each one of these stable states.

Strings of an odd number of adjacent cooperative agents move to the left or to the right from period to period, depending on the random matching rule. If several strings exist, they move in the same direction (because they are separated two by two by an odd number of adjacent defectors) and therefore never meet (in that sense, it is a stable state: the proportion of cooperative agents is constant, evolution from period to period simply represents a translation).


(i) If there are \( n \) cooperative agents and \( N - n \) defectors in the initial configuration \( (0 < n < N) \), the mean payoff of each action is the following:
- mean payoff of playing D : \( T \cdot n + P \cdot (N - n - 1) = T \cdot n + P \cdot (N - n) - P \),
- mean payoff of playing C : \( R \cdot (n - 1) + S \cdot (N - n) = R \cdot n + S \cdot (N - n) - R \).

Since \( T > R > P > S \), we conclude that the mean payoff of playing D is always higher, so that all players play D in period 1 and are therefore locked in the allD stable state.

4 In case (i) (resp. (ii)) there is therefore also an even (resp. odd) number of cooperative agents between the two groups on the “other side” of the circle, since \( N \) is even, so that the studied side does not matter.
(ii) If n = 0, the system is and remains in the allD stable state ; if n = N, the system is and remains in the allC stable state.

Appendix 6. Proof of proposition 5.

(i) Let n be the number of cooperative agents, and c the number of meetings between a cooperative agent and a defector. The mean payoff of each action (with 0 < n < N) is the following:

- mean payoff of playing D : \( \frac{(P (N - n - c) + T c)}{(N - n)} \)
- mean payoff of playing C : \( \frac{(R (n - c) + S c)}{n} \)

Mean payoff of playing C is then greater than mean payoff of playing D if:

\[
c < \frac{((R - P)n(N - n))}{((R - S)N - (R - S + P - T)n)}.
\]

(ii) If N = 8, T = 40, R = 30, P = 20, S = 10, the above condition holds only for c = 0, whatever the value of n (0 < n < N). So, only initial configurations with an even number of cooperative players paired together (15 initial configurations out of 256) lead to the stable state allC. If n = 0, the system is and remains in the stable state allD.

(iii) If N = 8, T = 70, R = 60, P = 20, S = 10, the condition holds only for c = 0, or for c = 1 and \(2 \leq n \leq 6\). Therefore, the stable state allC is reached if there is an even number of cooperative players paired together in the initial configuration, or if there are three or five cooperative players in the initial configuration and only one of them plays against a defector. These cases represent respectively 15, 24 and 24 initial configurations out of 256 (24.6 %).
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