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Directed reciprocity subverts cooperation in highly adaptive populations

Jean-Jacques Herings[1], Ronald Peeters[2]✉ & Anastas P. Tenev[3]

We examine the generally accepted hypothesis that directed reciprocity is a powerful driver for cooperation. To do so, we consider a framework where agents situated on a circle network interact with their neighbors and have the choice to be egoistic, altruistic, or partially cooperative. We study the interaction between reciprocity, the likelihood that an agent reproduces value to the neighbor who has recently produced value for the agent, and inertia, the tendency of agents to repeat their previous choices even if other strategies are more successful. On the basis of extensive simulations, we conclude that for high levels of inertia, reciprocity enhances cooperation, while for low levels of inertia reciprocity rather subverts cooperation. For intermediate levels of inertia, we find a U-shaped effect. Reciprocity therefore interacts with the level of inertia in a non-monotonic fashion.

Keywords Social dilemma, Cooperation, Reciprocity, Inertia

Understanding what motivates cooperation on the individual level and what drives cooperation on the population level, particularly within social dilemma situations, is a major topic of study across the social sciences[1–4]. Direct reciprocity, as captured by the "you scratch my back, and I'll scratch yours" or the "I scratch your back, and you'll scratch mine" principle, is generally considered to be a powerful mechanism for producing high levels of cooperation[5,6]. Direct reciprocity is listed as one of the five rules for the evolution of cooperation, together with kin selection, group selection and two other reciprocity-based rules: indirect reciprocity and network reciprocity[7].

Within evolutionary models of natural selection involving heterogeneous behavioral types, reciprocators are often implemented via (forgiving or generous) tit-for-tat play[8,9]. Experimental work[10] suggests that subjects who realize the value of cooperation would establish a punishment system to guarantee in-group cooperation and not so much to induce cooperation from others directly through cooperative actions; alternatively they could develop some kind of credible commitment devices[11]. Other literature stresses the importance of strong reciprocators who punish norm violators, even though they receive lower payoffs[12,13]. Theoretical studies have established that cooperation can be sustained in a local interaction framework, where agents are imitators[3,14–17].

The model of Herings, Peeters, Tenev and Thuijsman (henceforth, HPTT)[18] builds on the study of Eshel, Samuelson and Shaked (henceforth, ESS)[14] to investigate how sustainable cooperation can be in the presence of partial cooperators. The model has a number of agents positioned on a circular network interacting with their two neighbors, with each of the agents choosing either an egoistic, an altruistic or a partially cooperative strategy. Egoists do not produce any value for their neighbors, altruists produce value for both of their neighbors, and partial cooperators produce value for only one of their neighbors. The flip of a *fair* coin decides which of the two neighbors the partial cooperator produces value for. In *every* period, agents revise their strategies and adopt the one that was on average most successful among the strategies observed in their immediate neighborhood. In this study we report on findings obtained via extensive numerical simulations of this dynamic process, where we vary two parameters which were held fixed in the previous study: the levels of the updating inertia and the reciprocity probability.

First, *reciprocity* (captured by the parameter ρ) is used to allow partial cooperators to discriminate between the two neighbors based on the previous period's "kindness" towards them. Discriminating strategies have been found to foster cooperation[19]. The situation $\rho = 1/2$ reflects the flip of the fair coin in HPTT[18]. A value of ρ above 1/2 implements *direct reciprocity*: agents are *more likely* to produce value to the neighbor who has recently produced value for them. A value of ρ below 1/2 does the opposite: agents are *less likely* to produce value to the neighbor who has recently produced value for them. Although at first glance this seems to be in the spirit of

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indirect reciprocity as captured by the "you scratch my back, and I'll scratch someone else's" or the "I'll scratch your back, and you'll scratch someone else's" principle[7,20], within our context it is probably more appropriate to label such behavior '*antireciprocity*', and this is the nomenclature we will implement henceforth. While the latter type of behavior may appear unnatural, it aligns with the 'Pay It Forward' idea of encouraging a positive chain of altruistic acts; though, returning the favor directly remains a possibility in our framework. This type of behavior is also referred to as 'serial reciprocity'[21].

Second, *inertia* (captured by the parameter σ) refers to the agents' tendency to repeat previous decisions even after having received disconfirming information[22,23]. Such inertia can be a consequence of technological restrictions, but also result from behavioral factors such as status-quo bias, stubbornness, and procrastination[24–26]. In our simulations inertia means that agents stick to their current strategy with probability σ, even if another strategy was observed to be more successful. That is, inertia is exogenous to realized outcomes, independent of time and length of strategy usage, and homogeneous across the population. Recent research has considered implementations of inertia in the context of cooperation, where inertia is endogenous to observed payoff changes resulting from recent updates and observed payoff differences to other reference individuals[27–30], where inertia is increasing in the length a certain strategy has been used (habit formation)[31], and where inertia is heterogeneous in society[32–34] including the presence of 'zealous cooperators' who never update their strategy[35]. Partly due to the variations in how inertia has been implemented, its impact on the evolution of cooperative behavior has both been found to be positive[32–34,36–38] and to be negative[35,39]. One article[40] finds a non-monotonic relationship between inertia and cooperation; its results suggest that small inertia impedes cooperators, large inertia keeps the cooperation level the same as in the initial state, while medium inertia induces the greatest cooperation.

Although inertia produces higher levels of cooperation in our study (in line with some of the existing literature), we also document a remarkable influence in the role of reciprocity, and find the effect of reciprocity to *interact* with the level of inertia. While for high levels of inertia we find reciprocity to *enhance* cooperation, for low levels of inertia it rather *subverts* cooperation. The latter effect is caused by (i) reciprocity making the partially cooperative strategy (which is only *half* as cooperative as the altruist strategy) strong relative to the altruistic strategy (ii) while not being effective in eliminating the egoist strategy in case of low inertia.

Model setup and methods

There are $n \geq 3$ agents situated on a *circle* network (see Fig. 2). Agents interact with their two direct neighbors and exhibit either egoistic or altruistic behavior towards each of them. All agents have three possible strategies at their disposal: a fully *altruistic* strategy *A*, a fully *egoistic* strategy *E*, and a *partially cooperative* strategy denoted by *P*.

Altruistic acts/contributions are *directed*: they produce a benefit to the contributor's neighbors these acts are targeted at, but come at a cost to the contributor. The altruistic strategy (*A*) targets *both* neighbors. In contrast, agents who have adopted strategy *E* have no costs as they refrain from altruistic contributions altogether; yet, this does not preclude them from benefiting from their neighbors' contributions targeted towards them. The partially cooperative strategy (*P*), however, enables agents to be altruistic to only *one* of their neighbors. Strategy *P* manifests itself in two possible decisions: *L*, representing altruistic behavior towards the left-hand neighbor and egoistic behavior towards the right-hand one, and *R*, representing altruistic behavior towards the right-hand neighbor and egoistic behavior towards the left-hand one. The *P*-strategy realizes as either *L* or *R*.

Without loss of generality, the value of a single altruistic contribution is normalized to 1. Hence, an agent who uses (i) strategy *A* provides value 1 to each of the neighbours; (ii) strategy *E* provides no value for the neighbours; and (iii) strategy *P* provides value 1 to only one of the two neighbors. While strategy *E* is costless, each altruistic act comes with a cost *c*, so that strategy *P* costs *c* and strategy *A* costs 2*c*. It is assumed that $c \in (0, \frac{1}{4})$. The condition $c > 0$ ensures that for all agents strategy *E* is the best reply against any play of the other agents; hence, it is the only *rationalizable* strategy. The condition $c < \frac{1}{4}$ ensures that the optimal strategy of an imitator is uniquely determined and that cooperative behavior is not impossibly costly. The level of cooperation in society is gauged by the preponderance of altruist acts, with more altruist acts corresponding to higher levels of cooperation. The socially efficient outcome is achieved when all agents use strategy *A* (with payoff $2(1-c)$ for each agent and societal payoff of $2n(1-c)$), while when all agents use the only rationalizable strategy *E*, the societal payoff is 0. Hence, the situation constitutes a social dilemma. The possible payoffs of using any of the three strategies are summarized in Fig. 1, which once again highlights the fact that on an individual level it is most beneficial to employ *E*, while on a societal level it is best to use *A*. That is, fixing a specific pair of left-

Payoffs of A

	$\{A,R\}$	$\{E,L\}$
$\{A,R\}$	$2-2c$	$1-2c$
$\{E,L\}$	$1-2c$	$-2c$

Total value for neighbors provided by A: 2.

Payoffs of P

	$\{A,R\}$	$\{E,L\}$
$\{A,R\}$	$2-c$	$1-c$
$\{E,L\}$	$1-c$	$-c$

Total value for neighbors provided by P: 1.

Payoffs of E

	$\{A,R\}$	$\{E,L\}$
$\{A,R\}$	2	1
$\{E,L\}$	1	0

Total value for neighbors provided by E: 0.

Fig. 1. The tables outline the possible payoffs for every strategy, when its left-hand neighbor uses the strategy/strategy realization in the leftmost column and its right-hand neighbor uses the strategy/strategy realization in the top row of the table. Below the table we specify the total value provided to immediate neighbors by an agent employing this strategy.

hand and right-hand neighbors, it is always individually better to use *E*, which corresponds to the lowest level of cooperative behavior, while the choice which produces the highest value *to* the neighbors (and is the most cooperative) is *A*.

The model considers recurrent interaction within the fixed circular network. The agents' behavior follows *naive imitation*, a *heuristic* decision rule, whereby at each stage they adopt the strategy that yielded the highest *average* payoff among the strategies observed in their *immediate* neighborhood; hence, only the agent's own strategy and those of the agent's immediate neighbors are in the consideration set.

In an extension of ESS[14], this setup is used by HPTT[18] who show that if strategy *P* allows contributions to *either* of the two neighbors with a strictly positive probability, there are five types of absorbing sets: (i) all-*A*, where all agents employ strategy *A*; (ii) all-*P*, where all agents employ strategy *P*; (iii) all-*E*, where all agents employ strategy *E*; (iv) mixed-*A*/*E* *singleton* absorbing sets in which *A* and *E* strategies coexist, but *E*'s exclusively appear in pockets of two adjacent agents; and (v) mixed-*A*/*E* *non-singleton* absorbing sets which cycle between two states, dubbed "blinkers"[14], with pockets of adjacent *E* strategies alternating between singletons and triples, in addition to possibly pairs of *E*'s as in (iv). For a detailed description of the blinker states' constitution, see Lemma 1 in HPTT[18]. For a description of the stationary states, see Proposition 1 there.

In choosing the topology of the circle network and the interaction structure, we follow the influential seminal paper by ESS[14]. The model as such does not correspond to a particular real-world situation, but is a metaphor for commonly occurring situations where agents interact much more with agents nearby than with agents far away and have a choice between acting more or less cooperatively. These agents can be either people living in a particular district, firms operating in geographically neighboring locations, or municipalities that interact with neighboring municipalities.

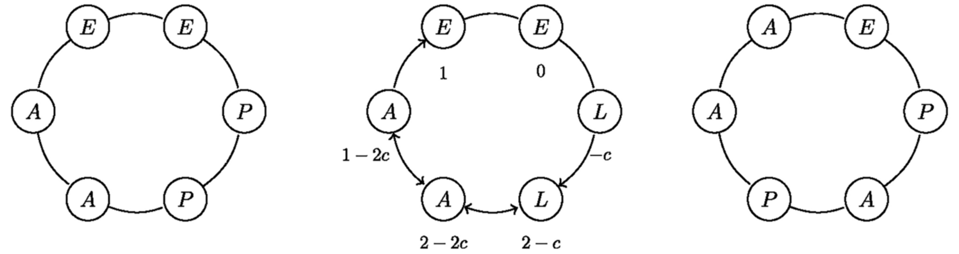
Building further on HPTT[18], the current paper considers variations along two main dimensions:

1. *Reciprocity* Whenever the partially altruistic strategy *P* is employed, reciprocity captures the probability to act altruistically towards any of the neighbors depending on the outcome in the previous stage of the process. If only one neighbor of agent *i* created value 1 to agent *i*, then a strategy *P* used by agent *i* with probability $\rho \in [0, 1]$ results in providing value 1 to this neighbor and with probability $1 - \rho$ to the other neighbor. If either *both* neighbors provided value 1 to agent *i* or *none* of them provided value 1, then strategy *P* treats both neighbors equally and results in an altruistic act towards only *one* of them as decided by a fair coin flip. Observe that the extreme case of $\rho = 1$ corresponds to *directed reciprocity*, while $\rho = 0$ can be dubbed *antireciprocity*. All cases in which $\rho > 0.5$ capture a higher probability of directed reciprocity and will be referred to as directed reciprocity, while all cases in which $\rho < 0.5$ capture a higher probability of antireciprocity and will be referred to as antireciprocity.
2. *Inertia* Inertia concerns the updating probability of all agents at every stage, i.e. how likely each agent is to implement the naive imitation rule specified above in every period of the imitation process. In every iteration, each agent keeps their strategy with probability $\sigma \in [0, 1)$ and assumes the strategy which is best according to the decision rule with the remaining probability $1 - \sigma$. This probability captures the ability to have a quick adaptive response to a changing environment or conversely the propensity to keep the status quo, hence the term *inertia*. Probability $\sigma = 1$ means no updating whatsoever, while $\sigma = 0$ implies that the agents reevaluate their chosen strategies at every stage of the process. Of course, in the latter case, the result of the process could still lead to an agent choosing the same strategy in two consecutive periods.To illustrate the imitation dynamic, consider a circular network with $n = 6$ agents. Let the agents start with the strategies (*A*, *A*, *P*, *P*, *E*, *E*). The strategies *P* played by the two middle agents can each realize in either an altruistic act towards the left neighbor or an altruistic act to the right neighbor, such that there are four possible ways in which the dynamic can progress. First, if the two middle agents' strategies realize as (*L*, *L*), the six agents receive the payoffs $(1 - 2c, 2 - 2c, 2 - c, -c, 0, 1)$ such that on average, the best-performing strategies the agents observe within their neighborhood are (*A*, *P*, *A*, *P*, *E*, *A*), which is the strategy profile the agents would move to according to our imitation dynamic. This situation is depicted in Fig. 2. Second, if the strategies realize as (*L*, *R*), the agents receive the payoffs $(1 - 2c, 2 - 2c, 1 - c, -c, 1, 1)$, and they would move to (*A*, *A*, *A*, *E*, *E*, *E*). Third, were the two strategies to realize as (*R*, *L*), and produce corresponding payoffs $(1 - 2c, 1 - 2c, 2 - c, 1 - c, 0, 1)$, the agents would move to (*E*, *P*, *P*, *P*, *P*, *A*). Fourth, if the strategies realize as (*R*, *R*), based on the payoffs $(1 - 2c, 1 - 2c, 1 - c, 1 - c, 1, 1)$ agents would move to (*E*, *P*, *P*, *E*, *E*, *E*).

As shown above, with all agents updating ($\sigma = 0$) there are four ways for the process to develop. However, positive inertia ($\sigma > 0$) can already result in as many as eight different states being reached after only the first possible realization (*L*, *L*) of the two *P* strategies in the starting state described above. When all agents update, three of the six agents change their strategy, and with positive inertia each of them can keep their current strategy with a positive probability. This means that instead of one, there are eight possible outcomes after a realization (*L*, *L*), which are summarized in Fig. 3: (i) all three change their strategy (ii) two of the three change their strategy (there are three such cases) (iii) one of the three changes the strategy (there are three such cases) (iv) all three keep their strategy.

With all agents updating ($\sigma = 0$), the realization (*L*, *L*) of the two *P* strategies leads to a total of eight altruistic acts in the next round. That is, in (*A*, *P*, *A*, *P*, *E*, *A*), there are three *A*'s, each of which provides two altruistic acts and there are two *P*'s, each of which provides one altruistic act. In contrast, the realization (*R*, *R*) only results in a total of two altruistic acts in the next round. That is, in (*E*, *P*, *P*, *E*, *E*, *E*) the two *P*'s produce one altruistic act each.

Ultimately, both parameters ρ and σ affect the probability to act altruistically to a neighbor, but while the first one does this explicitly, the second one captures a factor which has an indirect effect on that. This paper focuses on comparing the *incidence* and *efficiency* of the absorbing states of the model by means of computer



(a) Initial state – strategies.

(b) Payoffs given the realizations of the P strategy as L in both cases. The arrows show to whom a specific node provides value. No arrows mean that the node provides no value to a specific neighbor. The payoffs for every node are specified below it.

(c) Strategies after applying the heuristic decision rule.

Fig. 2. Example of the development of the imitation dynamics starting from a state (A, A, P, P, E, E) with both P strategies realizing as L under $\sigma = 0$. Nodes represent agents and edges show the connections between them.

all 3 change	two of the 3 change	one of the 3 changes	none change
$(A,\boldsymbol{P},\boldsymbol{A},P,E,\boldsymbol{A})$	$(A,\boldsymbol{A},\boldsymbol{A},P,E,\boldsymbol{A})$	$(A,\boldsymbol{A},\boldsymbol{P},P,E,\boldsymbol{A})$	$(A,\boldsymbol{A},\boldsymbol{P},P,E,\boldsymbol{E})$
	$(A,\boldsymbol{P},\boldsymbol{P},P,E,\boldsymbol{A})$	$(A,\boldsymbol{A},\boldsymbol{A},P,E,\boldsymbol{E})$	
	$(A,\boldsymbol{P},\boldsymbol{A},P,E,\boldsymbol{E})$	$(A,\boldsymbol{P},\boldsymbol{P},P,E,\boldsymbol{E})$	

Fig. 3. All possible states which can result from the initial state (A, A, P, P, E, E) for $\sigma > 0$. The positions in bold are the agents who want to revise their strategies, but might not do that due to positive inertia.

simulations. The situation $\rho = 0.5$ and $\sigma = 0$ is extensively addressed in HPTT[18], and serves as an important benchmark in the present study.

For the simulations, the size of the circle network is taken to be $n = 60$. In HPTT[18], $n = 60$ shows the most interesting variations, which are indicative of the results for greater values of n and do not suffer from the volatility observed at very small n. We used nine different values for the reciprocity parameter ρ: 0.00, 0.05, 0.20, 0.35, 0.50, 0.65, 0.80, 0.95 and 1.00; and eight values for the inertia parameter σ: 0.00, 0.05, 0.20, 0.35, 0.50, 0.65, 0.80 and 0.95. For each pair (ρ, σ), we followed the state transition process from initial state until convergence. In order to account for potential path dependencies, we used 171 different initial conditions, related to the number of A, P and E strategies at the onset. For each strategy, the number varied in multiples of three, and was never zero. For each of the 12,312 combinations of (ρ, σ) pairs and initial conditions, we run 1,000 simulations varying in how the A, P and E strategies were initially situated on the circle network. While the total number of runs, 12,312,000, may not appear extremely high, the number of iterations required for the process to converge is very large for high levels of inertia.

Results

This section presents the simulation outcomes. The main variable of interest is *Efficiency*, which is defined as the percentage of altruistic acts within the population. Notice, in this regard, that the total number of acts is $2n$: two acts by each of the n agents. Strategy A produces two altruistic acts, strategy P one altruistic act and strategy E zero altruistic acts. In the present setting there is a one-to-one relation between the number of altruistic acts and the population's aggregate payoff.

The graphs that are presented below show averages of the specific outcome variables, which are taken over the 1,000 runs of each of the 171 initial conditions. To assess the *robustness* of the reported findings in terms of their invariance to initial conditions, we divide the initial condition parameters into *eight* categories: many-A, many-P, many-E, few-A, few-P, few-E, mixed, and equal. The first seven categories partition the full set of initial conditions. The "equal" category is included in the "mixed" category and consists of the three initial conditions where all strategies are almost evenly represented. The initial conditions and the specifics of the categories are presented in Fig. 4. Overall, the findings we report are replicated within these subsamples; the rare exceptions will be discussed in the text.

Absorbing sets: efficiency

Figure 5 shows the average efficiency of the absorbing sets as a function of reciprocity (ρ) for different levels of inertia (σ). The figure showcases the main findings of this paper, which are outlined and formulated below.

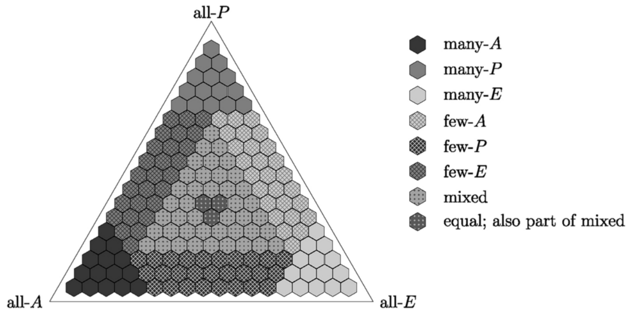


Fig. 4. Initial states and how they are categorized. Each hexagon represents one of the 171 initial conditions regarding the distribution of the initial seed of the three strategies. These initial conditions are grouped in different categories with the colors accentuating the different categories. The three categories labeled 'many-X' comprises of the 15 initial conditions where at least 42 out of 60 nodes are seeded with the X strategy. The three categories labeled 'few-X' comprises of the 27 initial conditions where at most 9 out of 60 nodes are seeded with the X strategy and there are no more than 42 nodes seeded with any of the other two strategies. The category labeled 'mixed' consists of the 45 initial conditions where for each of the three strategies at least 12 out of 60 nodes are seeded with this strategy. The category labeled 'equal' contains the 3 initial conditions in the category 'mixed' where the strategies are most evenly present. Finally, the category 'all' contains all 171 initial conditions.

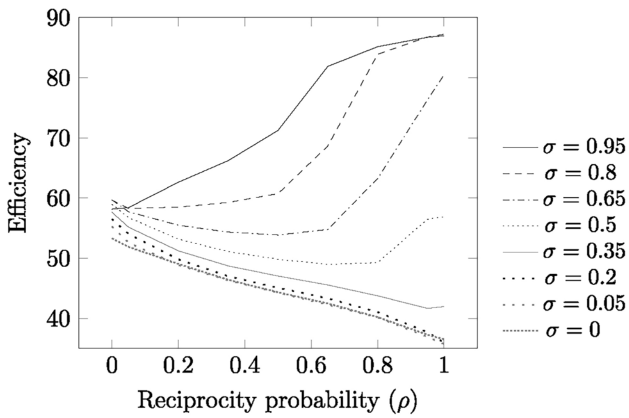


Fig. 5. Efficiency. Efficiency of the imitation process relative to the reciprocity probability ρ for some different values of the inertia parameter σ.

The analysis shows that σ and ρ have distinct effects regarding the ultimate level of cooperative behavior of the population, and that they interact in a non-trivial manner.

First, we consider the impact of inertia on efficiency. We see that, with the exception of the extreme $\rho = 0$, efficiency levels are *increasing* in σ.

Finding 1 For a given level of reciprocity, efficiency is increasing in the level of inertia.

Finding 1 implies that, for a given reciprocity level, a population *benefits* from inertia. The effect of inertia on efficiency is small at low levels of reciprocity, while it is large for high levels of reciprocity. At this stage, the reasons for this are not completely transparent, given that the same levels of efficiency can result from totally different states. For instance, a population comprising solely of partial cooperators is equally efficient as a population that is a perfect mix of altruists and egoists. The subsequent explorations will shed more light on the processes underlying Finding 1.

While there is high level of monotonicity in the relation between *inertia* and efficiency, this is not the case when considering the impact of *directed reciprocity* on efficiency. The latter relation is sensitive to the population's level of inertia. This is observed in the figure: the curves are generally decreasing for low values of σ, they are U-shaped for intermediate values, and increasing for high values of σ.

Finding 2 For levels of inertia which are:

1. Low, efficiency is decreasing in directed reciprocity;
2. Medium, the relationship between efficiency and directed reciprocity is U-shaped;

3. High, efficiency is increasing in directed reciprocity.

Finding 2 implies that the impact of an increase in directed reciprocity on efficiency depends on the population's level of inertia, and, if this is at medium level, it also depends on the level of directed reciprocity. The naive assumption that directed reciprocity boosts cooperation does not hold universally in our model. This is found to be true only for high levels of inertia, or at medium levels of inertia and already high levels of directed reciprocity. Otherwise, we observe an increase in directed reciprocity to be harmful. The next section explores this in more detail.

Findings 1 and 2 are not sensitive to changes in the initial conditions; the supporting graphs are presented in Fig. 6.

Absorbing sets: strategies

In order to understand better the findings related to efficiency, it is useful to consider the composition of the absorbing sets in terms of the strategies that are adopted. For instance, this helps identifying differences between

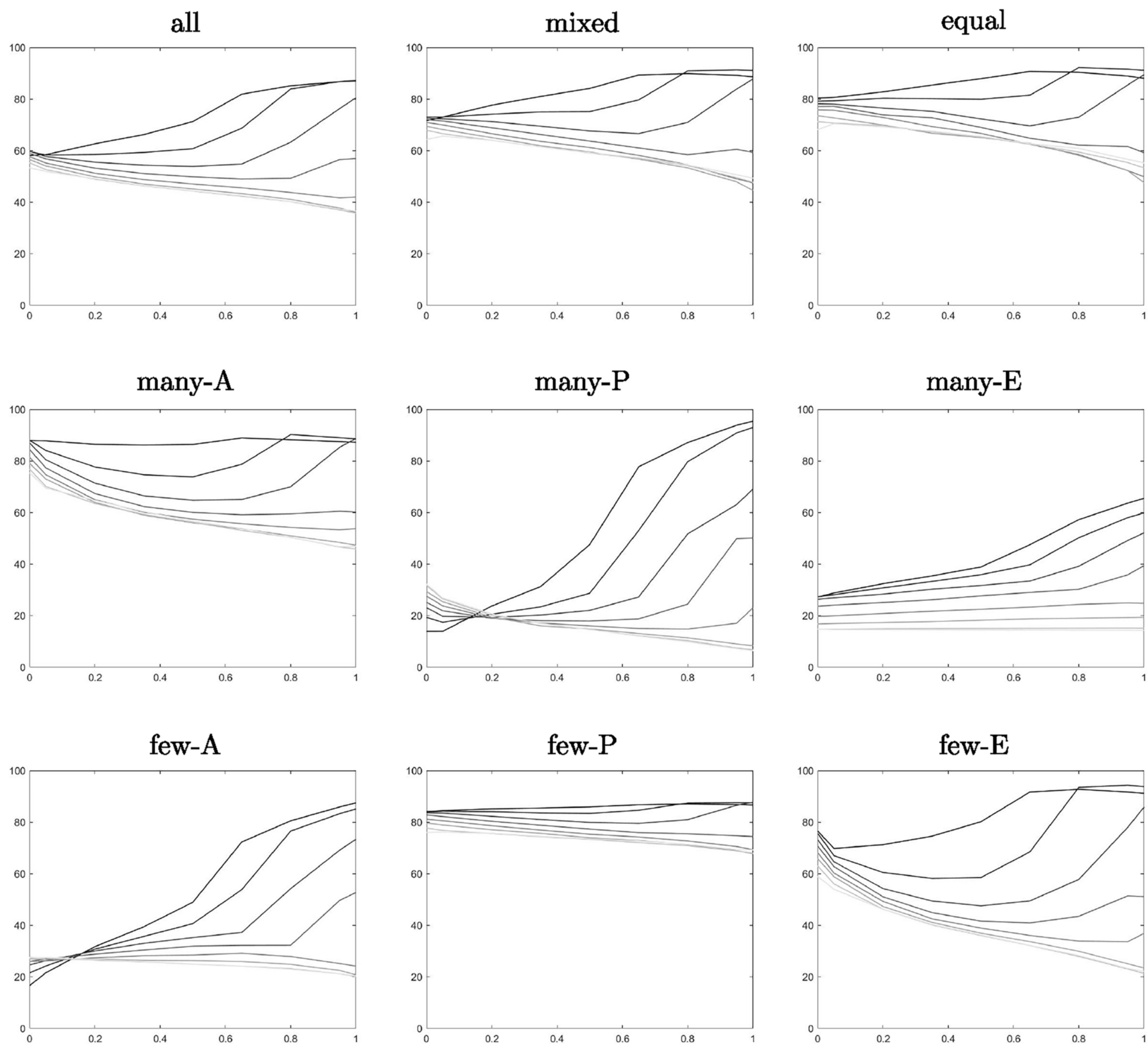


Fig. 6. Efficiency for different initial states. The graphs plot, for each of the nine categories of initial conditions shown in Fig. 4, the average efficiency obtained in the absorbing set starting from initial states within the respective category as a function of ρ for various values of σ, where lighter colors refer to lower values of σ. That is, the figures replicate Fig. 5 for different initial conditions. This helps us understand if the observations reported in the paper are robust to (particular) initial conditions. The figures reveal that the observations formulated on the basis of Fig. 5 are not specific to any particular initial condition, nor are they an artefact of aggregation over many different initial conditions.

the situation where all agents play P and the equally efficient situation where only half of them play A and the other half play E. Figure 7 presents the average percentage of the population that is using a particular strategy for the various levels of inertia and reciprocity, where each of the plots relates to one of the three different strategies. Again, the percentages presented are aggregated over all different initial conditions.

Notice that for the P strategy, the plotted percentage is identical to the percentage of times the process converged to the all-P absorbing state, since the strategy P never co-exists with the other strategies in an absorbing set. For the A and E strategies, reported percentages are an aggregation over the all-A, all-E absorbing states respectively, and the two types of mixed-A/E absorbing sets. Figure 8 presents detailed information regarding the fraction of times a particular absorbing set has been reached. Comparing Fig. 8 with Fig. 7 makes clear that the mixed-A/E absorbing states are overall dominated by a greater number of A's, while the all-A absorbing states are relatively infrequent. Therefore, the plot for strategy A in Fig. 7 shows a high correlation with the fraction of times the mixed-A/E absorbing set was reached, and the plot for strategy E is indicative of the fraction of times the all-E absorbing state was reached.

We do not find a relationship between the level of inertia and the presence of a specific strategy that consistently applies to all reciprocity probabilities. However, we concisely report on some general tendencies below.

Finding 3 At most levels of directed reciprocity, inertia works against the spread of the egoist strategy and fosters the spread of the altruist strategy.

Next, we consider the impact of reciprocity. Like for efficiency, this impact varies across the different levels of inertia.

Finding 4 For levels of inertia which are:

1. Low, the spread of the altruist strategy is decreasing, and the spread of the partially cooperative and the egoist strategies are increasing in the reciprocity probability;
2. Medium, the spread of the altruist strategy is U-shaped in the reciprocity probability, while the presence of the partially cooperative/egoist strategy is increasing/decreasing;
3. High, the spread of the altruist/egoist strategy is increasing/decreasing in the reciprocity probability, while the spread of the partially cooperative strategy is inverse-U-shaped.

Overall, the observed impact of directed reciprocity on efficiency is mainly driven by the impact on the altruist and egoist strategies at all levels of inertia. Only at medium levels of inertia combined with high levels of directed

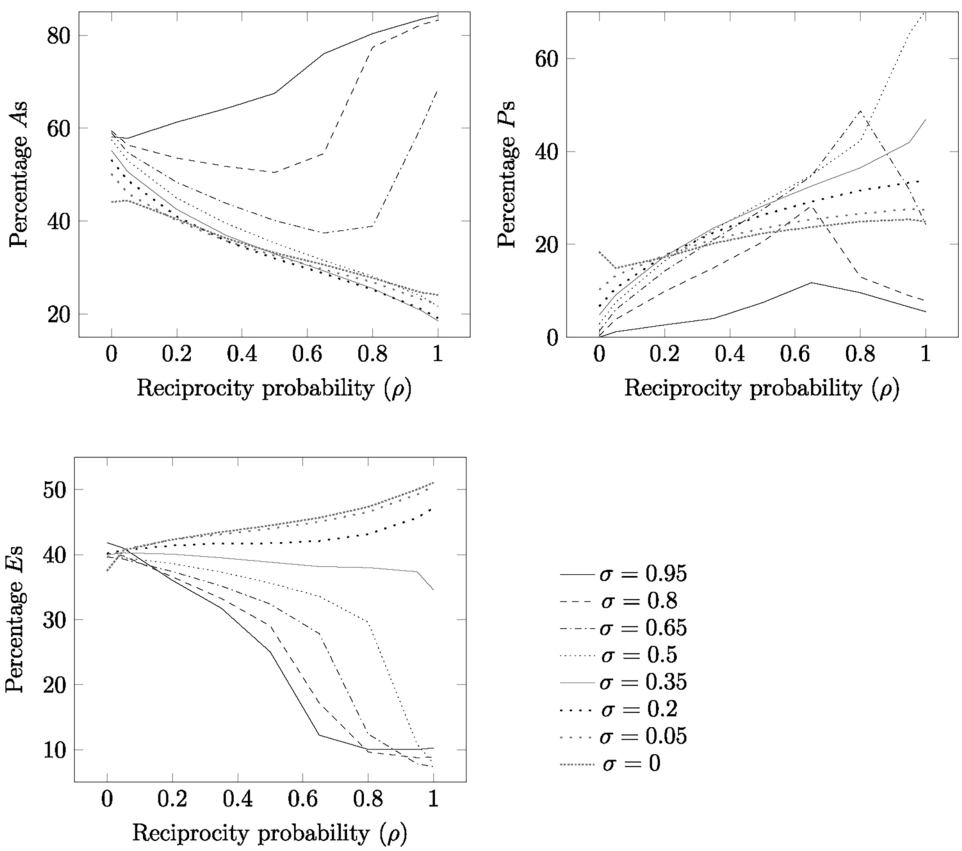


Fig. 7. Absorbing sets: strategies. Percentage of strategies A, P and E in absorbing states.

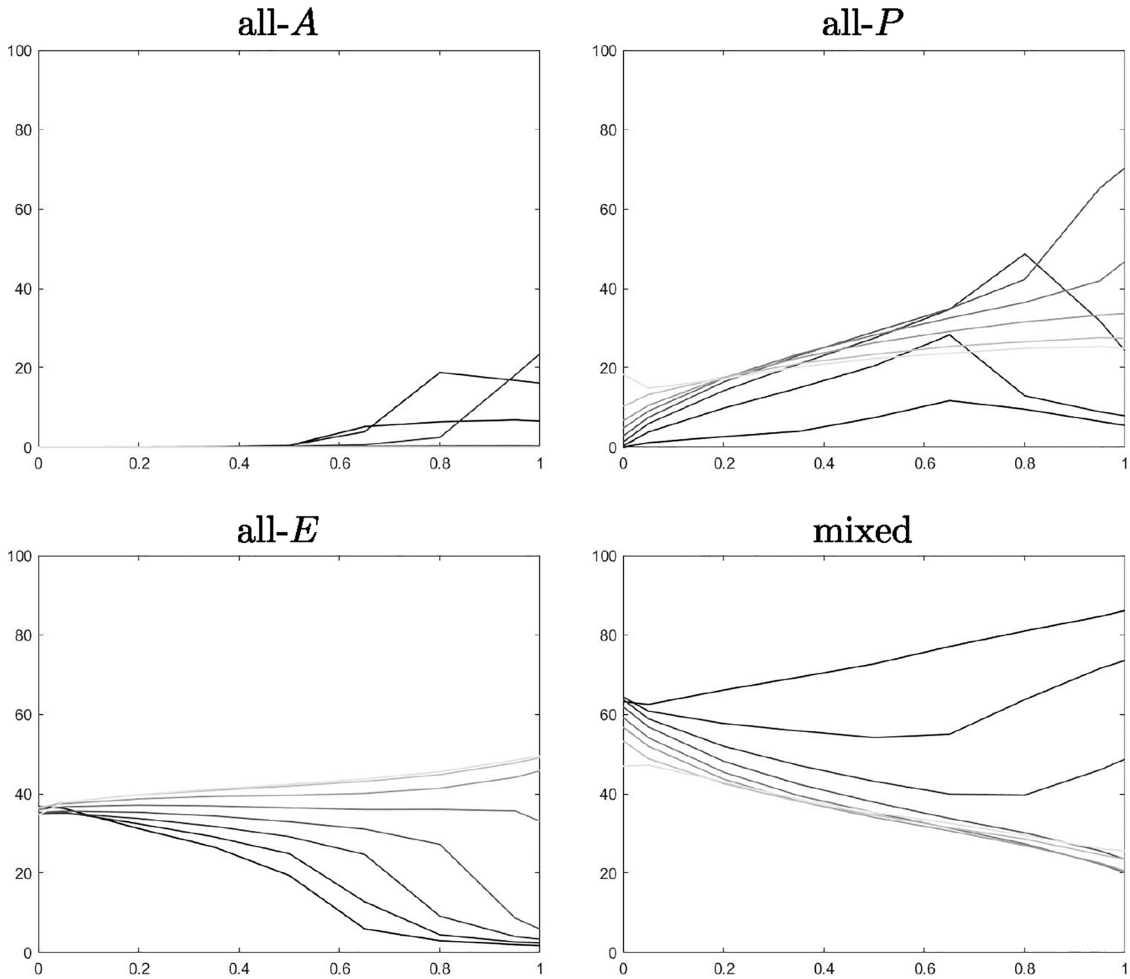


Fig. 8. Frequencies of absorbing states. The graphs plot the fraction of times a certain type of absorbing set is reached. These fractions are plotted as a function of ρ for various values of σ, where lighter colors refer to lower values of σ. The fractions are based on averages over all 171 initial conditions. The mixed-*A*/*E* singleton and non-singleton absorbing sets are pooled in one graph (labeled 'mixed').

reciprocity does the partially cooperative strategy have a substantial contribution to the generated efficiency (there is also a smaller positive effect for high levels of inertia and middle range of reciprocity probability).

The only negative effect of reciprocity on the likelihood to converge to an all-*P* state is for high level of inertia at high levels of reciprocity. Since the all-*P* states are not very efficient (overall, they achieve 50% of the potential efficiency), this is another channel through which inertia combined with directed reciprocity boosts efficiency.

Dynamics

To enhance the understanding about the full dynamics of the imitation process and how this is influenced by reciprocity and inertia, Fig. 9 presents the development of the proportions of every strategy from initial states with equal initial shares of the three strategies over the course of 1,000 iterations. The figure presents this for three values of the directed reciprocity parameter: low ($\rho = 0.20$; top graphs), medium ($\rho = 0.50$), and high ($\rho = 0.80$; bottom graphs); and three levels of inertia: low ($\sigma = 0.20$; left graphs), medium ($\sigma = 0.50$) and high ($\sigma = 0.80$; right graphs). Each of the graphs is based on aggregated data from 1,000 independent simulations of the dynamic process. Graphs for all values of σ and ρ are available as *Supplementary Information*.

Beyond the unsurprising fact that an absorbing set is reached faster with lower levels of inertia, the imitation process is characterized by three phases.

Phase 1 attack of the egoists in the first phase, the *E* strategy eliminates the isolated *A* and *P* strategies. For all three reciprocity levels, we see this effect is larger at *lower* levels of inertia. Intuitively, inertia makes the *A*'s and *P*'s more resistant in this phase. This is because this gives them a time window with more opportunities to consolidate and form larger clusters, which are more resistant to the *E*'s. Further, for each of the three levels of inertia, we see that the *E* strategy is less successful for higher levels of reciprocity. Reciprocity helps small clusters of *P* and *A* strategies retain their cooperative attitudes.

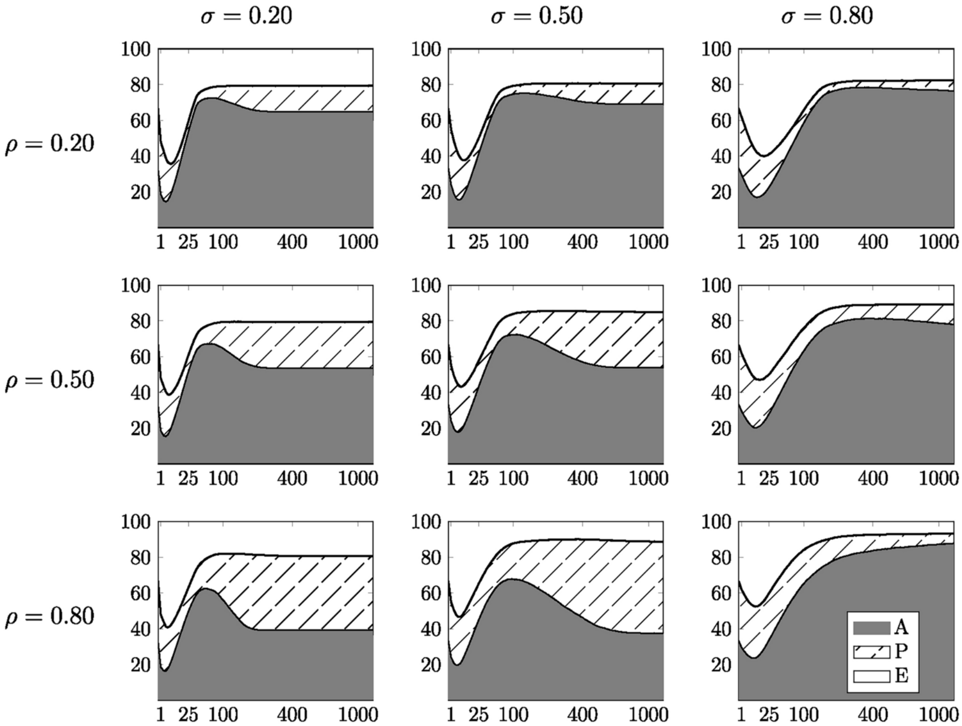


Fig. 9. Dynamics. Share of strategies A, P and E in the dynamic development of the imitation process starting from initial states with equal shares of the three strategies. The reciprocity probability increases vertically from top to bottom with $\rho \in \{0.20, 0.50, 0.80\}$. The inertia probability increases horizontally from left to right with $\sigma \in \{0.20, 0.50, 0.80\}$.

Phase 2 the altruists strike back after the first phase, strong clusters of A's and P's have survived the attack of the egoists, and strike back. In this part of the process, the A and P strategies again benefit from a *high* level of inertia. Inertia ensures that during the slow but long march no losses are incurred and the E's are whittled down. Overall, this happens because in this setup, clusters of identical strategies only change at their edges, and if one edge of a cluster of P's or a cluster of A's is preserved, this can help the whole cluster survive. Similarly, the A and P strategies again jointly profit from a *high* level of reciprocity. However, this benefits the P's more than the A's.

Phase 3 return of the partial cooperators after the E's are decimated, the P's find potential to combat the A's. In this process the P's again benefit from higher levels of reciprocity. At *low* levels of reciprocity, the A's benefit from inertia; at *high* levels, the P's benefit. Intuitively, in this case they can be locked into a mutually beneficial relationship longer. The only exception is the situation in the bottom-right of Fig. 9: high levels of inertia in combination with high levels of reciprocity prevent the tipping point for this phase being reached. Given the strategies found in the absorbing sets (see Fig. 7) this appears not to be an artefact from the dynamics only being displayed for the first 1,000 iterations.

In Finding 1 we report inertia to positively impact efficiency for (almost) all levels of reciprocity. Comparing each row of graphs in Fig. 9, we see that inertia leads to a less extreme drop in the A's and the P's during the first phase of the dynamics, and less E's to survive the second phase of the dynamics. While the latter effect is smaller at lower levels of reciprocity, this is compensated by the A's being stronger than the P's in the third part of the process (where E's remain constant).

In case of low levels of inertia, we document in Finding 2 that reciprocity negatively impacts efficiency. Looking in the first column of graphs in Fig. 9 we see that higher reciprocity leads to more A's and P's surviving the first phase, which would suggest the reversed impact. However, we find the share of E's at the end of the second phase, and throughout the remainder of the process, not to be different for different levels of reciprocity. The negative impact of reciprocity on efficiency is caused by reciprocity making the P's stronger relative to the A's, and this effect being highly visible throughout the second and third phase of the process.

For medium levels of inertia, we found the impact of reciprocity on efficiency to be non-monotonic. This refers to the second column of graphs. Again, like for low levels of inertia, reciprocity makes the P's stronger relative to the A's, in particular throughout the second and third phase of the process. However, in the current case reciprocity unambiguously reduces the share of E's that survive the first two phases. For low levels of reciprocity, the latter effect only dominates the former effect at higher levels of reciprocity, which explains the U-shaped effect on efficiency. We note that the U-shaped effect is, compared to Fig. 5, less prominent for medium level of inertia in Fig. 9. The notable difference is that Fig. 5 is based on averages over all initial states, while Fig. 9 is based on averages from the three initial states in the category "equal".

Finally, for high levels of inertia, we found reciprocity to impact efficiency unambiguously positively. The third column of graphs represents this situation. Here we see that reciprocity has a negative impact on the *E*'s. Opposite to that, we find reciprocity to positively effect the *A*'s. There is a non-monotonic effect on the fraction of *P*'s, with a larger fraction of *P*'s surviving at intermediate levels of reciprocity (an effect that is better visible in Fig. 7). Nevertheless, this non-monotonic effect has no differential impact on efficiency given that it is dominated by the effect on the *E*'s and the *A*'s.

Discussion

We study the repeated interaction between agents situated on a circular network who have to choose between altruistic, egoistic, and partially cooperative actions. We examine the influence of two crucial parameters on the amount of cooperation in society: inertia and reciprocity. Inertia reflects the probability that agents in a given period do not consciously choose their action, but simply repeat the action they chose in the previous period. With the remaining probability, they take the action that generated the highest average payoffs in the previous period, where the choice is restricted to actions played by themselves and their neighbors in the previous period. Reciprocity corresponds to the probability that an altruistic action of their neighbors is responded to by an altruistic action in case of partially cooperative agents.

We find that inertia is always favorable for cooperation. However, contrary to conventional wisdom, reciprocity does not always stimulate cooperative behavior. The interaction between inertia and reciprocity is complicated. For low levels of inertia, reciprocity is harmful for cooperation, for intermediate levels of inertia the effect of reciprocity on cooperation is U-shaped, whereas for high levels of inertia, reciprocity is beneficial for cooperation. To better understand these effects, we subdivide the dynamic process in three stages: attack of the egoists, the altruists strike back, and return of the partial cooperators. We explain how inertia and reciprocity affect the behavior of agents during these stages.

Our model of interaction on a circular network is very stylized and invites further research on the effect of different network topologies on cooperation. Moreover, a further generalization could be to distinguish between the agents whose actions one observes and the agents who are affected by one's actions.

Another avenue for further research concerns the extension of our framework to other forms of moral behavior[41,42]. Recent works in social physics explore the evolution of trust[43] and honesty[44]. A natural research question is therefore to study how inertia and reciprocity affects these types of behavior.

Data availability

The study reports on data generated via simulations in Matlab. Matlab codes and the generated output are available for download from the OSF repository at https://doi.org/10.17605/osf.io/8jyeg.

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Author contributions

J.J.H., R.P., and A.P.T. conceived the setup. R.P. conducted the simulations. All authors analysed the results and reviewed the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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