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REGULAR ARTICLE

An evolutionary edge of knowing less (or: On the 'curse' of global information)

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Abstract Consider a population of farmers who live around a lake. Each farmer engages in trade with his two adjacent neighbors. The trade is governed by a prisoner's dilemma 'rule of engagement.' A farmer's payoff is the sum of the payoffs from the two prisoner's dilemma games played with his two neighbors. When a farmer dies, his son takes over. The son decides whether to cooperate or defect by considering the actions taken and the payoffs received by the most prosperous members of the group comprising his own father and a set of his father's neighbors. The size of this set, which can vary, is termed the 'span of information.' It is shown that a larger span of information can be detrimental to the stable coexistence of cooperation and defection, and

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that in well-defined circumstances, a large span of information leads to an end of cooperation, whereas a small span does not. Conditions are outlined under which, when individuals' optimization is based on the assessment of less information, the social outcome is better than when optimization is based on an assessment of, and a corresponding response to, more information.

Keywords Span of interaction · Span of information · Imitation · Social welfare

JEL Classifications D83 · R12 · O4

1 Introduction

Why did natural selection not eradicate cooperating behavior a long time ago? Many scientists from a variety of disciplines have posed this question and have sought to respond to it by resorting to a variety of methods. Utilizing evolutionary game theory,[1] for instance, the intertemporal development of behavioral patterns such as cooperation (or defection), can be analyzed by investigating the evolution of a population 'inflicted' with these patterns that is subject to selection (rather than by examining two rational individuals interacting with each other; Maynard Smith 1982). In particular, the evolution of cooperating and defection behavior in a population of individuals can be analyzed by drawing upon an iterated prisoner's dilemma game (cf. Bergstrom and Stark 1993). Conditions for groups of cooperators not to be removed by natural selection must thus have features guaranteeing some sort of preferential interaction as is the case, for example, when interaction is confined to a small set of (neighboring) individuals.

A setting in which cooperators form clusters in a spatial layout of the prisoner's dilemma game allows for the long-run coexistence of cooperating and non-cooperating behavior because cooperators in the interior of a cluster come off nicely as compared to defectors at the boundary of the cluster (Nowak and May 1992). Thus, the behavioral pattern of defection does not spread over to the neighborhood of cooperators. Bergstrom and Stark (1993) identify evolutionary environments that are conducive to the long-run survival of the cooperating strategy in prisoner's dilemma games. Jun and Sethi (2007) extend the model of Eshel et al. (1998), which in turn draws upon the model of Bergstrom and Stark (1993), and explore comprehensively the effect of changes in the neighborhood structure on the viability of the cooperating strategy. Jun and Sethi (2007) assume that each individual interacts with a multitude of adjacent neighbors, compared to interaction being limited to two

[1] See, for example, Weibull (1995), Samuelson (1997), Fudenberg and Levine (1998), and Hofbauer and Sigmund (1998).

adjacent neighbors, as in Bergstrom and Stark (1993), or as in Eshel et al. (1998).

Merging the economics of social structures with the economics of information can yield interesting results regarding the advantages and disadvantages of learning from others, imitating others, optimizing subject to alternative informational constraints, and the optimal layout of neighborhoods. Following Outkin's (2003) argument that in an interconnected world individual decisions are affected by socially distant people (or even by people whom we have never met), we adapt the social structure of Bergstrom and Stark (1993) by allowing information to flow in from beyond the immediate vicinity. Thus, when it comes to decision making, the individuals analyzed in this paper differ from the individuals analyzed in much of the received literature (who populate cycles,[2] or more generally, ring lattices,[3] and grids in the plane[4]) in that they draw on an informational environment that does not necessarily coincide with the social structure of exchange. Put differently, by allowing arbitrary spans of information to come into play, we extend the neighborhood structure of Bergstrom and Stark (1993), distinguishing the influence of neighbors with whom individuals interact from the influence of individuals whose good example (and 'business' success strategies) individuals could mimic. Consequently, we diverge both from the structure of Bisin et al. (2006) who study 'economies in which the distribution of information across the agents, as well as their interactions, are local' (p. 75), and from the elaborate neighborhood 'network' of Jun and Sethi (2007).

Making these extensions, what will happen to the prevalence of the cooperating strategy in the population at large? What will the social welfare (per capita payoff) consequences be of such prevalence, or of its absence? What inferences can be drawn with regard to the existence of an equilibrium fraction of cooperators under different quantities of information? The answers to these questions can be perplexing and often differ from the views expressed in the received literature. In this regard, the present paper complements the received literature.

2 The model

In numerous settings, the fortunes and misfortunes of individuals depend on the trade that they conduct with their neighbors, and on the traits of these

[2]See, for example, Ellison (1993), Eshel et al. (1998), and Ohtsuki and Nowak (2006). Ellison (1993) studies a version of best-reply dynamics; the latter authors concentrate on imitation dynamics.

[3]See, for example, Jun and Sethi (2007) who study comprehensively the impact of the structure of a neighborhood on survival and on the stability of cooperating behavior for an arbitrary number of neighbors, when imitation is the driving force behind natural selection.

[4]See, for example, Blume (1993), Nowak and May (1992, 1993), and Nowak et al. (1994). Nowak and May (1992, 1993) and Nowak et al. (1994) concentrate on imitation rather than on dynamics based on best-reply strategies, as does Blume (1993).

neighbors. Following Bergstrom and Stark (1993), Stark (1998), and Outkin (2003), let us consider a finite population of individuals who live around a lake. Let us assume that each individual engages in trade or exchange with his two nearest neighbors. The trade is governed by a prisoner's dilemma 'rule of engagement,' and each individual's income is the sum of the payoffs from the two prisoner's dilemma games, where the payoff matrix of a single game is given by

		Column player	
		C	D
Row player	C	R,R	S,T
	D	T,S	P,P

where $S < P < R < T$. Moreover we require that

$$T + P < 2R. \tag{1}$$

To interpret assumption 1, let us think of the individuals as farmers. The exchange between the farmers arises from a need to engage in barter, say, in labor inputs or in produce, or from a need to collaborate (join forces) in production-related activities such as pest control. While an individual cannot survive on his own (exchange is mandatory to sustain life), the individual's conduct, as implied by the prisoner's dilemma structure, is subject to choice, as explained below. Assumption 1 guarantees that a cooperator surrounded by cooperators comes off better than a defector at the border of a defector cluster.

Throughout this paper we draw upon a schematic picture of a farmer community consisting of $n \in \mathbb{N}$ individuals. We introduce dynamics by postulating that when the farmers die and their n sons take over, the sons decide whether to cooperate or defect by considering the actions taken and the payoffs received by (part of) their father's generation. Whose performance would be considered? In a farmer community, it is natural to assume that while individuals are much more likely to 'trade' with adjacent neighbors (deliver or pick up begs of fertilizer, fetch or supply manure) than with farmers farther away, they receive information both about adjacent individuals and about more distant individuals. Therefore, the 'span of trade,' which for the remainder of this paper we will set equal to the two immediate neighbors, is likely to be smaller than the 'span of information,' measured by the number of individuals (in addition to one's father), r, that a descendent learns from. Thus, we require that $2 \leq r \leq n - 1$, and that r is an even (natural) number.[5]

We introduce optimization (maximization subject to an informational constraint) by postulating that when the farmers' descendents take over the farms,

[5] In an appendix available on request, we study a span of trade that is larger than that of two immediate neighbors.

they replicate the behavior of the most prosperous of their fathers, the father’s $r/2$ neighbors to the left, and the father’s $r/2$ neighbors to the right.

We know from Jun and Sethi (2007), whose analysis is based on the assessment of average payoffs, that increasing the span of trade renders the existence of a sustainable sole-cooperator equilibrium more likely given that the fathers’ trading partners are *identical* to the individuals from whom the descendents learn (that is, when the span of trade and the span of information are the same). What will happen, however, when the informational constraint under which optimization is carried out is less binding than the trading constraint? Suppose, for example, that instead of imitating the behavior of his father or of his father’s two nearest neighbors depending on who is the most prosperous (Subsection 3.1), a son who inherits his father’s farm imitates the behavior that is more successful among his father and his father’s four neighbors (Subsection 3.2) or at least six neighbors (Subsection 3.3). Does the cooperating strategy spread faster if optimization is based on the assessment of *more* information? And how is it that social welfare outcomes depend on how many the sons learn from? Subsequent subsections will thus seek to shed light on the relationship between the span of information, r, and the nature of (an intertemporal) equilibrium (Subsection 3.4), and on the relationship between the span of information and the wellbeing of the community (Subsection 3.5). A brief summary and complementary reflections that attest to the robustness of our main argument are provided in Section 4.

3 On the long-run survival of cooperation

In the next three subsections we depict and explore a specific stylized example. In Subsection 3.4 we generalize for an arbitrary population size, n, and for an arbitrary span of information, r. In Subsection 3.5 we trace out the social welfare repercussions of changes in the long-run composition of the modeled population. This we obtain without resorting to parameter specifications.

3.1 Imitating the behavior of the more successful of an individual’s father and the father’s two adjacent neighbors

Let the community consist of $n = 12$ farmers. Each of these farmers trades with his immediate neighbors. In the diagrams that follow, a number by the side of a letter representing the selected strategy, C or D, is the farmer’s total payoff, which can be conceived to measure the output of some agricultural good.

We calibrate the prisoner dilemma’s payoffs in line with assumption 1: $S = 0$, $P = 1/4$, $R = 3/4$, and $T = 1$. Initially, all the farmers are cooperators playing C, as depicted in Fig. 1. When a farmer’s son takes over, he imitates the most prosperous of his father and of the father’s two adjacent neighbors ($r = 2$). Consequently, generation after generation, all farmers are cooperators who have each a payoff of $2R = 1\frac{1}{2}$ units of farm goods.

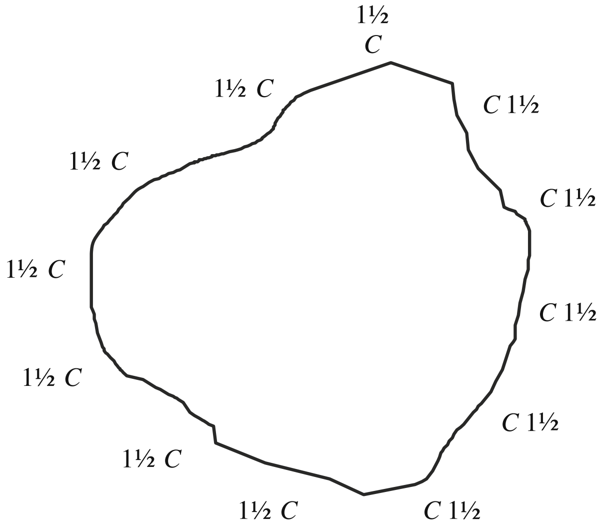

Fig. 1 A community of twelve cooperating farmers (generation 1)

Suppose, alternatively, that one of the $n = 12$ farmers is a defector[6] (playing D), who thereby exploits the cooperating nature of his two adjacent neighbors, gaining a payoff of $2T = 2 > 1\frac{1}{2} = 2R$, as in Fig. 2. Let the fraction of cooperators in the i-th generation of the population be given by x_i, where $x_i \in [0, 1]$ for $i = 0, 1, 2, \ldots$. Then, $x_1 = \frac{11}{12}$.

In the next generation, cf. Fig. 3, there will be three defectors, as the sons' of the 'ripped-off' farmers become defectors as well (due to a simple comparison of payoffs; one such comparison is illustrated by the dashed arrows in Fig. 2). The payoff of each of these two descendents will, however, be only $T + P = 1\frac{1}{4}$, as they are neighboring the initial defector's offspring (from whose father he has learned the seemingly successful D-strategy). The descendent of the initial defector fairs, however, worse than any other member of the community since both his neighbors are defectors. His payoff is a mere $2P = \frac{1}{2}$. If we measure social welfare by output (payoff) per capita, then due to the reaction to the mutant defector, the whole community is worse off in generation 2 than in generation 1, when the fraction of cooperators is $x_2 = \frac{3}{4}$.

Since, according to Eq. 1, the two defectors at the border of the *DDD*-cluster[7] (Fig. 3; north of the lake) receive a smaller payoff than the cooperators two farms away, a cooperator immediately neighboring the *DDD*-cluster replicates the strategy of the neighboring cooperator and not that of

[6]Here we assume that the defector appears in the population because of a mutation. Alternatively, a defector could possibly enter the community of farmers via migration. In such a case, the size of the population will become $n + 1$. The qualitative results of the analysis will hold, however.

[7]Note that even though individuals are living along a road, we use the term 'cluster' to refer to a set of at least two neighboring individuals of the same type.

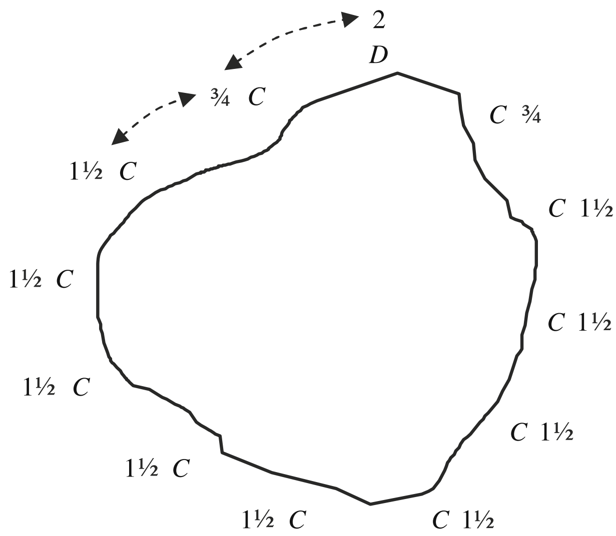

Fig. 2 A community of twelve farmers with a mutant defector (generation 1) for $r = 2$; the comparison of a descendent's payoff in generation 2 is indicated by dashed arrows

the neighboring defector. Therefore, the *DDD*-cluster does not expand in size. The defectors at the border of the *DDD*-cluster, on the other hand, cannot 'see' far enough to spot the successful cooperator (successful he is because he receives a payoff of $2R = 1^1\!/_2$) and thus they adhere to their *D*-strategy.

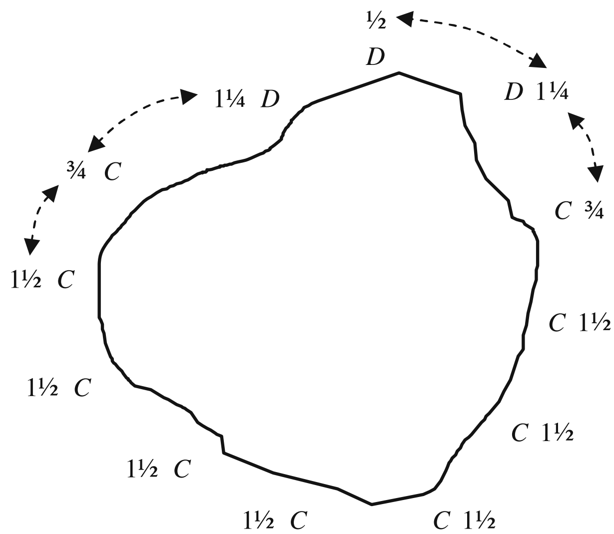

Fig. 3 A community of twelve farmers (generation 2) for $r = 2$; the comparison of the payoffs of two descendents in generation 3 is indicated by dashed arrows

Hence, the *DDD*-cluster does not shrink either; the fraction of cooperators is equal to $x_3 = {}^3\!/_4$ and likewise, generation after generation. Consequently, Fig. 3 depicts the equilibrium configuration in the wake of the mutation ($C \rightarrow D$) of a single individual. The long-run fraction of cooperators in the population will therefore be $\hat{x} = 1 - {}^3\!/_n$, which in the case of $n = 12$ yields $\hat{x} = {}^3\!/_4$.

Investigating other initial configurations of defectors, we find that clusters of two mutant neighboring defectors expand to stable *DDDD*-clusters, while all clusters of at least three mutant defectors remain stable in size as long as they are separated from each other by at least three neighboring cooperators (or, for that matter, as long as they are separated from isolated defectors by at least four neighboring cooperators). Therefore, the 'fate' of the community depends not only on the number of mutant defectors, but also on their spread, that is, on the space between them. If there are only a few mutant defectors in a large community of cooperators then, by and large, the community remains a community of cooperators, the few spotted islands of defectors notwithstanding. Then, defectors never 'take over' the entire population. If, however, the number of the mutations is excessive, there will not be enough space left in-between the mutants to avert the spread of the defection strategy over the entire farming community: the requirement that for at least one isolated mutant defector there have to be at least five neighboring cooperators (to the left or to the right) separating the *D*-type individual from another isolated defector is the minimal requirement needed to guarantee the long-run survival of a positive fraction of *C*-type individuals.[8] Then defector clusters cannot expand and the long-run equilibrium composition of the population is a mixture of cooperators and defectors. If there are fewer than three cooperators, then there will be a pure defector community, entailing a per capita payoff smaller than that of any other steady-state composition of the community.

3.2 Imitating the behavior of the more successful of an individual's father and the father's four adjacent neighbors

Let there be twelve farmers, as in Fig. 1. Initially, all the farmers are cooperators. When the farmers' sons take over they imitate the most prosperous of their own father and their father's four neighbors ($r = 4$). Consequently, generation after generation, all farmers are cooperators. Suppose, alternatively, that one of the twelve farmers mutates to a defector. The opening

[8] When we have an isolated mutant defector, the requirement of five cooperators to the left and five cooperators to the right to separate the defector from another isolated mutant defector guarantees that two cooperator clusters which are large enough to 'recapture' the population survive. If there was one additional isolated defector, we would only need five cooperators on one side of the additional defector to ensure the existence of a third non-vanishing cooperator cluster, because on the other side we have already required presence of five neighboring cooperators. We can conclude that in this sense, the requirement of five neighboring cooperators *per* isolated mutant defector is a rather stringent condition to guarantee the long-run survival of the cooperating strategy, whereas the requirement of five neighboring cooperators *for at least one* isolated mutant defectors is the minimal requirement for guaranteeing the survival of at least one (small) cluster of cooperators.

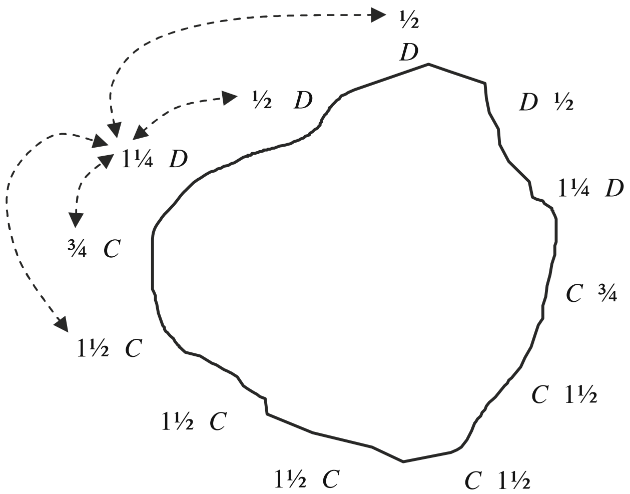

Fig. 4 A community of twelve farmers (generation 2) for $r = 4$; the comparison of a descendent’s payoff in generation 3 indicated by dashed arrows

configuration is depicted in Fig. 2. In the next generation, a cluster of five defectors is formed, as in Fig. 4. Therefore, the fraction of cooperators is $x_2 = {}^7\!/_{12}$.

The second generation, which includes a cluster of five defectors, will be followed by a third generation, with a cluster of three defectors (Fig. 3 above), because the sons of the defectors who are at the boundary of the *DDDDD* cluster follow the example of cooperators who are two farms away (as indicated by the dashed arrows in Fig. 4 for one defector at the boundary of the cluster); thus, the fraction of cooperators becomes $x_3 = {}^3\!/_4$. The subsequent, fourth, generation will revert to the original configuration as per Fig. 2. Hence, a stable 3-periodic fixed point is generated, with ‘blinkers’ that switch from a single defector surrounded by eleven cooperators to a cluster of five defectors, then to a cluster of three defectors and then back to a single defector surrounded by eleven cooperators. In the long run, each of the population’s splits of (defectors, cooperators): (1,11), (5,7), and (3,9) will exist one third of the time. Therefore, the long-run mean fraction of cooperators in the population is equal to $(x_1 + x_2 + x_3)/3$, which in turn is equal to $\hat{x} = 1 - {}^3\!/_n$, and which in the case of $n = 12$ yields $\hat{x} = {}^3\!/_4$, exactly as in the case of the more constrained imitation delineated in the preceding subsection.

3.3 Imitating the behavior of the more successful of an individual’s father and the father’s six or more adjacent neighbors

If individuals in our twelve-farmer community learn from neighbors up to three farms away ($r = 6$), the seemingly good news about the fortunes of a mutant defector in generation 1 spread to his descendent and across the

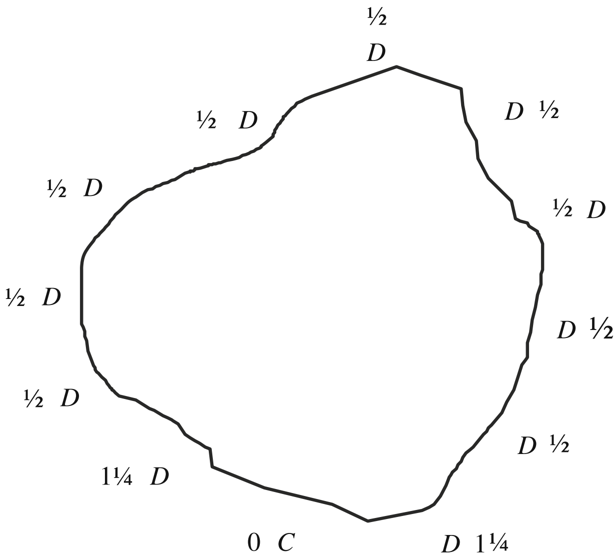

Fig. 5 A community of twelve farmers (generation 1) for $r = 10$

descendents of three neighbors to the left and three neighbors to the right. Their seven descendents become defectors in generation 2. The fraction of cooperators is then $x_2 = {}^5\!/_{12}$. The sons of the immediately neighboring cooperators decide, however, to maintain the C-type strategy of their fathers, because information about a cooperative farmer who is neighbored by another cooperator on each side is coming their way.[9] Thus, in generation 3, the defectors' cluster is as in Fig. 3, and the fraction of cooperators is $x_3 = {}^3\!/_4$. Since the descendents of the three defectors are aware of the success of cooperators who are trading with two neighboring cooperators, generation 4 consists only of cooperators; the fraction of cooperators is then $x_4 = 1$. Consequently, generation after generation, all farmers are cooperators, with a (maximal) per capita payoff of $2R = 1^1\!/_2$.

The preceding procedure can likewise be repeated for $r = 8$. But what happens for $r = 10$? In this case, the descendents of the five neighbors to the left of the mutant defector and of the five neighbors to the right of the mutant defector become 'infected' by the seemingly successful defecting behavior, as in Fig. 5. This leaves us with a single cooperator who collects a zero payoff. In generation 2, the descendent of this sole cooperator will defect as well. The descendents of the defectors cannot be induced to return to the cooperative mold, since no cooperator is left as 'an example' of the success of this mold.

[9]Nonetheless, since in generation 2 $\left(5 \times 2P + 2 \times (T + P) + 2 \times (S + R) + 5 \times 2R = 5 \times {}^1\!/_2 + 2 \times 1^1\!/_4 + 2 \times {}^3\!/_4 + 3 \times 1^1\!/_2 = 11\right)$, while in generation 1 $\left(2T + 2 \times (S + R) + 9 \times 2R = 2 + 2 \times {}^3\!/_4 + 9 \times 1^1\!/_2 = 17\right)$, the population is worse off.

Consequently, generation after generation all farmers are defectors, with a per capita payoff of $2P = \frac{1}{2}$. Thus, for a given population size, an expansion of the span of information, holding constant the span of interaction, is *detrimental* to the wellbeing of the lakeside community.[10]

Consequently, in order to guarantee that a single mutant defector does not take over the entire population, then in the second generation (where the maximum expansion of defectors occurs), there must be at least one cooperating farmer who is neighbored by another cooperator on each side, given the payoff structure of Eq. 1. In other words, for the long-run survival of cooperating behavior in a population it is necessary that some islands of cooperators exist, which are blind or deaf to the success of the mutant defector.

3.4 The evolving composition of the farmer community for an arbitrary population size n, and an arbitrary span of information r

For a trade to take place, we obviously assumed that the community consists of at least two farmers. To allow for trades with neighbors on each side, we obviously need to assume a community of at least three farmers (that is, that $n \geq 3$). Let the generation 0 fraction of farmers who are cooperators be $x_0 = 1$. If one of the cooperator farmers 'mutates' to a defector, the fraction of cooperators in generation 1 becomes

$$x_1 = 1 - \frac{1}{n}. \tag{2}$$

The information about the payoff garnered by the mutant defector ($2T$) in generation 1 spreads in generation 2 to the descendents of $r/2$ neighbors to the left and to the descendents of $r/2$ neighbors to the right, where r is equal to 2, 4, 6, ... This spread decreases the fraction of cooperators in generation 2 (for an arbitrary n) to

$$x_2 = \begin{cases} x_1 - r/n \;=\; 1 - \frac{1}{n}(r+1) & n > r+1 \\ 0 & n \leq r+1. \end{cases} \tag{3}$$

According to Eq. 3, a fraction of cooperators $x_2 \in (0, 1]$ survives in generation 2 if $r = 2, 4, 6,..., n-2$ (if n is an even number) or if $r = 2, 4, 6,..., n-3$ (if n is an odd number). According to Eq. 3, only if $r = n-1$ and n is an odd number then no cooperator remains in the community, and the second generation consists entirely of defectors; and likewise generation after generation. The fraction of cooperators then remains zero, that is, $x_2 = x_3 = x_4 = \ldots = \hat{x} = 0$.

We proceed by distinguishing between two cases, according to a further refinement of the relationship between the population size n and the span of information $r < n-1$. Without loss of generality, we emphasize in what follows the case of an even population size yet for the sake of completeness, we provide results also for an odd population size.

[10]This result complements the results of Jun and Sethi (2007) who do not study the intersection of 'global information' with 'local interaction.'

Case 1 The size of the population is given by $n < r + 4$ (if n is an even number), or by $n < r + 5$ (if n is an odd number)

When $n < r + 4$ and n is an even number, we know from Eq. 3 that it is impossible that in generation 2 a 'successful' cooperator exists who is neighbored by a cooperator to the left and by a cooperator to the right. (A cooperator is termed 'successful' as and when because he is neighbored by a cooperator to the left and by a cooperator to the right, he receives a payoff of $2R$.) Therefore, the most successful individuals are defectors neighbored by one cooperator (receiving each a payoff of $T + P$, which, according to the ranking of the payoffs ($T > R > P > S$), maintains that $T + P > R + P > R + S > 2S$). Information about the success of these individuals now spreads, converting the community into a pure defector community:

$$x_3 = 0. \tag{4}$$

Thus, according to Eq. 4, if $r = n - 2$ (if n is an even number) or if $r = n - 3$ (if n is an odd number), in generation 3 there is no cooperator left in the community from whom to learn about the benefits of the C-strategy in a neighborhood of cooperators. Thus, it must be that the fraction of cooperators in the community remains zero, that is, $x_3 = x_4 = \ldots = \hat{x} = 0$.

Case 2 The size of the population is given by $n \geq r + 4$ (if n is an even number), or by $n \geq r + 5$ (if n is an odd number)

When $n \geq r + 4$ and n is an even number, we know from Eq. 3 that in generation 2 at least one 'successful' cooperator must exist who is neighbored by a cooperator to the left and by a cooperator to the right (receiving thereby the payoff of $2R$). Consider then the neighborhood of a cooperator who is separated from the cluster of the $r + 1$ defectors by exactly one 'non-successful' cooperator (non-successful he is since he receives a payoff of $R + S < 2R$). On this side, the information about the payoff of the successful cooperator spreads then to the descendent of the immediately neighboring non-successful cooperator and to the descendents of the $r/2 - 1$ defectors immediately neighboring the non-successful cooperator. Since the payoff of a defector neighbored by two defectors is $2P < 2R$, and the payoff of a defector neighbored by a cooperator on one side and a defector on the other side is $T + P$, and since (according to Eq. 1) $T + P < 2R$, the fraction of cooperators in generation 3 becomes

$$x_3 = x_2 + 1/n\ \left[\left(r/2 - 1\right) + \left(r/2 - 1\right) \right] = 1 - 3/n. \tag{5}$$

Equation 5 tells us that irrespective of the span of information (that is, $r = 2, 4, 6, \ldots, n - 4$ (if n is an even number) or $r = 2, 4, 6, \ldots, n - 5$ (if n is an odd number)), in generation 3 a cluster of three neighboring defectors inhabits the community of the farmers. Generation 4 evolves, however, differently for different values of r. The success of the cooperator (receiving a payoff of $2R$) who is separated from the three neighboring defectors by an immediately neighboring non-successful cooperator is replicated by the non-successful cooperator's descendent and the $r/2 - 1$ descendents of the defectors who form the cluster of the defectors in generation 3. This yields the following fraction of cooperators in generation 4:

$$x_4 = \begin{cases} x_3 + 1/n \left[(r/2 - 1) + (r/2 - 1)\right] = 1 + 1/n\,(r - 5) & r - 5 < 0 \\ 1 & r - 5 \geq 0. \end{cases} \quad (6)$$

According to Eq. 6 we find that for $r = 2$, the fraction of cooperators remains constant at $x_4 = \ldots = \hat{x} = 1 - 3/n$, the fraction already given by Eqs. 3 and 5, while for $r = 4$, $x_4 = x_1$. Therefore, for $r = 4$, $x_{i+3} = x_i$ for all $i \in \mathbb{N}$ and, consequently, $\hat{x}_{i+3} = \hat{x}_i$. If $r = 6, 8, ..., n - 4$ (when n is an even number) or if $r = 6, 8, ..., n - 5$ (when n is an odd number), defection is eliminated from the population in generation 4, and $x_4 = \ldots = \hat{x} = 1$. These results allow us to calculate in a fairly straightforward way the steady-state per capita payoff (or per capita income), a measure of the social welfare of the community of n farmers, as a function of the span of information r. This we display in Subsection 3.5.

3.5 Does assessing more information increase social welfare?

From the preceding discussion we infer that in spite of the appearance of a mutant defector, a community of initially cooperating, locally learning optimizing individuals can eventually exhibit either heterogeneity or perfect homogeneity (consisting entirely of cooperators or entirely of defectors), depending on the span of information, with heterogeneity being possible only if farmers learn from a few ('close') individuals ($r = 2, 4$). Put differently, heterogeneity is only possible if the span of information is small, while more information ($r \geq 6$) yields conformism.

Furthermore, we have learned that a single defector in a community of cooperators can only be 'successful' in the sense of 'spreading the D-strategy' if the community size, n, is small relative to the span of information, r. That is, after the information about the $2T$-payoff of the mutant defector has spread across the farmer community (converting r descendents into additional defectors), there must be at least three neighboring cooperators left, guaranteeing that the one in the middle receives a payoff of $2R$, in order for cooperative behavior to subsequently take over. Thus, we can conclude that if individuals learn from more than $n - 4$ individuals,[11] defection will eventually spread over the entire community whereas otherwise it will not; cooperating behavior will still prevail. What conclusions can we draw from this review of alternative configurations about the wellbeing of the community?

From Subsection 3.4 we know that for $r = 2$ (and a population of at least six farmers), the steady-state community after the community's reaction to

[11] If n were an odd number, the condition would be $n - 5$. Unless otherwise noted, all the other conditions (and results) are valid for both even and odd numbers of farmers.

a mutation of one cooperator farmer into a defector farmer consists of a three-defector cluster and a 'cluster' of $n-3$ cooperators. Thus we know that we have one defector neighbored by a defector on each side, two defectors and two cooperators neighbored by a cooperator on one side and a defector on the other side, and $n-5$ cooperators neighbored by cooperators on both sides. This yields the following aggregate steady-state payoff for the n-farmer community

$$\underbrace{2P}_{<2R} + 2\underbrace{(T+P)}_{<2R} + 2\underbrace{(R+S)}_{<2R} + (n-5)\,2R$$
$$= 2T + (n-4)\,2R + 4P + 2S < n2R\,. \tag{7}$$

For $n \geq 6$, the per capita payoff for $r = 2$ can be directly derived from Eq. 7, and is depicted in Fig. 6 for $S = 0$, $P = 1/4$, $R = 3/4$, and $T = 1$. The 3-periodic steady-state population that emerges for $r = 4$ (and a population of at least eight farmers) has a steady-state payoff that is already given by Eq. 7. (The corresponding per capita payoff is depicted in Fig. 6 for $S = 0$, $P = 1/4$, $R = 3/4$, and $T = 1$.) This means that as long as the span of information is smaller than six, then even when more cooperators can witness the success of a defector, no more cooperators switch to defection, on average. For $n \geq r + 4 \geq 10$ (if n is an even number) or $n \geq r + 5 \geq 11$ (if n is an odd number), the long-run fraction of cooperators increases, however, to one. This yields the highest payoff steady-state configuration ($n2R$) for the community. The corresponding per capita payoff ($2R$) is depicted in Fig. 6 for $R = 3/4$. If individuals' optimization were to be based on the assessment of more information than the critical level,

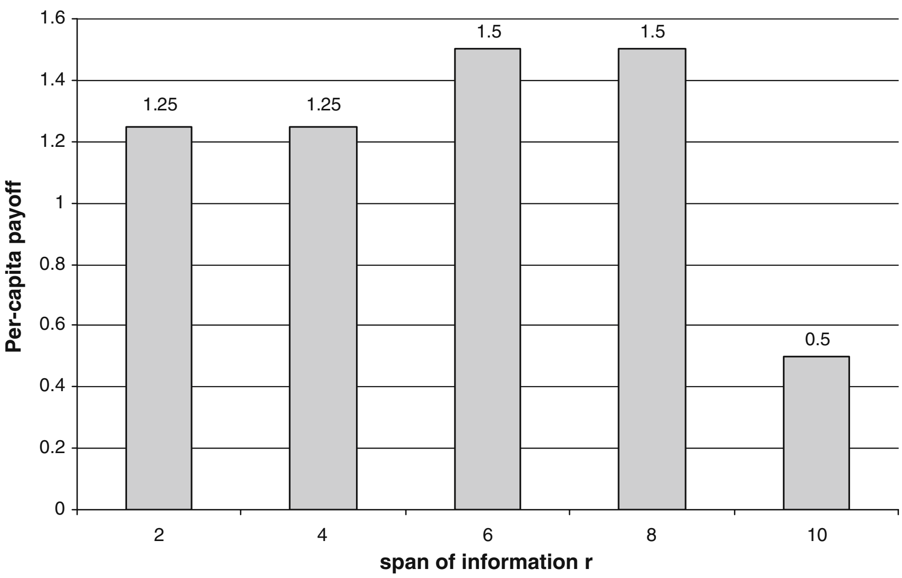

Fig. 6 Per capita payoff as a function of the span of information, r, for $n = 12$ farmers, and when the payoffs are $S = 0$, $P = 1/4$, $R = 3/4$, and $T = 1$

that is $r > n-4$ (if n is an even number; $r > n-5$ if n is an odd number), then the corresponding outcome would be a per capita payoff of $2P$, as in Fig. 6 for $P = {}^1\!/_4$.

We might well expect that the community's per capita payoff will correlate positively with the information available to the members of the community. However, at least in the present setting, this is not the case, as illustrated by Fig. 6. We see that when n is a natural number and $n \geq 3$, r is an even number, and $2 \leq r \leq n-1$, then

$$Y(n,r) = \begin{cases} {}^1\!/_n\,(2T + (n-4)\,2R + 4P + 2S) & r \leq n-k,\ r = 2,4 \\ 2R & 6 \leq r \leq n-k \\ 2P & r > n-k \end{cases} \tag{8}$$

for $k = 4$ if n is an even number, or for $k = 5$ if n is an odd number.

Thus, for $n \geq 10$ when n is an even number, and for $n \geq 11$ when n is an odd number,we can reformulate Eq. 8 as follows: as the span of information r increases (starting from $r = 2$), the steady-state per capita payoff rises to its maximal level of $2R$, and thereafter (for $r > n-4$ if n is an even number, or for $r > n-5$ if n is an odd number) it sharply falls to its minimal level of $2P$.[12] Since $\partial\big({}^1\!/_n\,(2T + (n-4)\,2R + 4P + 2S)\big)/\partial n = \left({}^1\!/_n\right)^2(-2\,(T+P) + 8R - 2\,(P+S)) > 0$, that is, the derivative of the per capita payoff with respect to population size n for $r = 2{,}4$ and $n \geq r+4$ (if n is an even number; $n \geq r+5$ otherwise) is positive, then, other things being equal, a large community fairs better than a small community. We thus conclude that when individuals' optimization is based on the assessment of *less* information (corresponding to what could be described as information being spanned locally), the social outcome can be superior to that which would have been obtained had individuals' optimization been based on the assessment of, and the corresponding response to, more information (corresponding to what could be described as information being spanned globally), and that for a given span of interaction, size confers an edge.[13]

[12]This finding is in nice congruence with the finding of Haag and Lagunoff (2006, p. 266) that 'some [spatially less connected] designs are more conductive than others to socially desirable outcomes.' Note, however, that a Haag-and-Luganoff-type individual is forward-looking and 'only interacts with, and observes behavior of, those with whom he is linked' (p. 266). Nonetheless, the analogy of the results is revealing, since Haag and Luganoff study forward-looking agents (with heterogeneous discount factors), whereas we study agents who 'simply' imitate past (seemingly successful) strategies.

[13]If we were to relax the assumption that the farmers trade only with their adjacent neighbors and assume instead that they trade also with the adjacent neighbors of their adjacent neighbors, then we could show that the qualitative results reported in the paper carry over to this more general case, provided that an additional, although quite natural set of assumptions on the payoff structure is introduced. The reason for the need to make these additional assumptions is that increasing the number of interactions from two to four increases the number of the possible payoff configurations that have to be compared. An appendix displaying the case of a span of interaction of four, variable spans of information, and the associated per capita payoffs, and illustrating the conditional generalizability of the case analyzed in the paper, is available on request.

We may now revisit the question posed at the outset: Why did natural selection not eradicate cooperating behavior a long time ago? Why has our global and interconnected society not been taken over by non-cooperators learning from reports about the 'prosperity' of defectors? One reason could be that the spread of information is still far from universal (with some 'isolated' populations being unaware of the success of the defectors). Another reason could be that the pace of population growth is ahead of the pace at which information networks widen. This would allow maintenance of a high level of per capita income.[14] Since we associate income with wellbeing and with a community's social welfare, our results indicate that an increase in the span of information, r, from local to global, that is, of r becoming greater than $n-4$ (if n is an even number) or $n-5$ (if n is an odd number) leaves the community worse off.

4 Summary and complementary reflections

We studied a community of farmers who interact (exchange) and optimize. We placed a wedge between the farmers' span of interaction and the farmers' span of information, varying the latter to become larger than the former. We have seen that limited knowledge about other farmers' successes and failures can lead to stable coexistence of cooperators and defectors in the farming community. This happens when farmers never learn what goes on outside their near neighborhood, and that the strategy of the grandfathers and the grand-grandfathers is replicated by their descendents: when the farmers' optimization is based on the assessment of less information, the social outcome can be better than when optimization is based on the assessment of, and the corresponding response to, more information. If farmers also learn from distant neighbors of their fathers' neighbors, that is, if information links increase for a given population size, it is indeed possible, as eloquently noted by Bala and Goyal (1998), that 'a society gets locked into a sub-optimal action' (p. 609).

In subsequent work, we will seek to extend the analysis in several challenging directions. Four ideas come to mind. First, increasing the span of interaction such that farmers do not trade only with their adjacent neighbors but also with their neighbors' neighbors will enable us to further study the prerequisites that yield coexistence of cooperators and defectors.

[14] Yet another reason could be that the information that individuals marshal depreciates in distance. For example, let more distant information be considered less credible, that is, let the weight attached to information from an individual be inversely proportional to the distance that the information travels (that is, to the distance between farms). Then, information about a mutant defector will spread less aggressively. In such a case, even for large spans of information, a single defector will hardly be able to 'take over' the entire community.

Second, holding the span of interaction at two, suppose that a mutation of a C to a D occurs not only once, or solely in a particular generation. Imagine that the first mutation is as per the preceding discussion (afflicting, say, farmer number 12, where a number–name accorded to a farmer in the twelve-farmer community is as per the hours of the clock; see Figs. 1–5), and that the second mutation occurs to a second-generation cooperator who is separated from the cluster of defectors that emerges as a consequence of the initial mutation by two cooperators, viz. to cooperator 5 (or, for that matter, to cooperator 7). When the span of information, r, is equal to four, it is easy to show that convergence to an all-defector steady state will take four periods, whereas when the span of information is 6, the said convergence will take three periods. Here again, a higher r is detrimental to social-welfare, as the all-defectors equilibrium is reached sooner.

Third, while in our setting a son imitates the most successful of his father and a set of neighbors of his father, it might be interesting to ponder how would our results change if, instead, a son were to imitate the most successful of his father, a set of neighbors of his father, his grandfather, and a corresponding set of neighbors of his grandfather. In such a case, the transition of the community to its long-run steady state may change, but neither will the equilibrium fraction of cooperators nor the steady-state per capita payoff. The only exceptions are communities converging towards period-n fixed points ($n \geq 2$). To see this, consider a case in which a son learns from the experience of his father and that of his father's four adjacent neighbors and, additionally, also from the fathers of those neighbors. In such a setting, the second generation (recall Fig. 4), which includes a cluster of five defectors, will be followed by a third generation of an identical composition since, by construction, the information about the mutant defector from the grandfather's generation lingers twice as long as in the case originally studied by us. The fourth generation 'hosts' a cluster of three defectors (recall Fig. 3), because the sons of the defectors who are at the boundary of the *DDDDD* cluster follow the example of the cooperators who are two farms away in their father's or in their grandfather's generation. The subsequent, fifth, generation will then revert to the configuration of a single defector as per Fig. 2. Thus, in this case, a stable 4-periodic fixed point is generated (rather than a 3-periodic fixed point). In the long run, each of the population's splits of (defectors, cooperators): (1,11), (5,7), (5,7), and (3,9) will exist one fourth of the time. Calculating the associated per capita income, we find that it is smaller than in the case presented in Section 3.2. This discussion reinforces then the tenor of our main argument: not only more information, but also a 'longer memory' can be deleterious to the long-run survival of cooperation.

Fourth, while the individuals in our setting are rational, they are not sophisticated. If they were, then the strategy to adopt could differ from the one that we have outlined. For example, suppose that in the case exhibited in Fig. 3, the son of the cooperator farmer (farmer 2) has a cluster of defectors as neighbors on one side and on the other a cooperator (farmer 3) who is in turn surrounded by cooperators. In this case we anticipate that the son of the cooperator neighbor farmer 3 will be a cooperator. Then, it would be better for him to select defection because he will end up with a payoff of $T + P = 1\frac{1}{4}$ rather than with a payoff of $R + S = \frac{3}{4}$. But if he were to select D, then the son of farmer 3, realizing that he will have as neighbors a defector and a cooperator, will choose defection (since $1\frac{1}{4} > \frac{3}{4}$), and so on, such that in generation 4, the community will become an all-defector community (rather than a mixed community of nine cooperators, and three defectors). This example may prompt us to re-think our approach, perhaps suggesting to us that not only more information, but also more sophistication, is detrimental to the long-run survival of cooperation.

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