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Indirect reciprocity with negative assortment and limited information can promote cooperation

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ABSTRACT

Cooperation is ubiquitous in biological and social systems, even though cooperative behavior is often costly and at risk of exploitation by non-cooperators. Several studies have demonstrated that indirect reciprocity, whereby some members of a group observe the behaviors of their peers and use this information to discriminate against previously uncooperative agents in the future, can promote prosocial behavior. Some studies have shown that differential propensities of interacting among and between different types of agents (interaction assortment) can increase the effectiveness of indirect reciprocity. No previous studies have, however, considered differential propensities of observing the behaviors of different types of agents (information assortment). Furthermore, most previous studies have assumed that discriminators possess perfect information about others and incur no costs for gathering and storing this information. Here, we (1) consider both interaction assortment and information assortment, (2) assume discriminators have limited information about others, and (3) introduce a cost for information gathering and storage, in order to understand how the ability of discriminators to stabilize cooperation is affected by these steps toward increased realism. We report the following findings. First, cooperation can persist when agents preferentially interact with agents of other types or when discriminators preferentially observe other discriminators, even when they have limited information. Second, contrary to intuition, increasing the amount of information available to discriminators can exacerbate defection. Third, introducing costs of gathering and storing information makes it more difficult for discriminators to stabilize cooperation. Our study is one of only a few studies to date that show how negative interaction assortment can promote cooperation and broadens the set of circumstances in which it is know that cooperation can be maintained.

1. Introduction

The persistence of cooperation in biological and social systems is an evolutionary puzzle, because one would naively expect that, among cooperators who contribute their own resources to help other members of their group and defectors who do not, the defectors will do better and increase in numbers at the expense of the cooperators. This intuition is captured by simple models of evolutionary game theory predicting the demise of cooperation and the domination of defection. Nevertheless, cooperation is widespread across biological and social systems, and many mechanisms have been proposed to explain why. Several of these, including ostracism (Tavoni et al., 2012), punishment (Nowak, 2006), and reciprocity (Axelrod and Hamilton, 1981; Killingback and Doebeli, 2002; Nowak, 2006; Ohtsuki and Iwasa, 2006; Pacheco et al., 2006; Panchanathan and Boyd, 2003), rely on members of a group using information to discriminate in their behavior toward their peers. Such agents are called discriminators, as opposed to cooperators and defectors, who do not change their behaviors based on such information. But even among humans, individuals rarely—if ever—have perfect and complete information about all members of their social groups. Nor do they observe and interact with their peers entirely randomly. It is therefore important to understand how assortment within groups and constraints on the available information impacts the evolution of cooperation.

A commonly considered strategy for discriminators to use the information they have about their peers is to behave reciprocally, being more likely to cooperate with agents whom they expect to cooperate. Direct reciprocity is possible when pairs of agents en-

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gage in repeated interactions (Axelrod and Hamilton, 1981; Killingback and Doebeli, 2002; Nowak, 2006), so that paired agents can base their future behaviors on the past behaviors of their partners that they have experienced directly. In contrast, reciprocity is indirect when discriminators use information about the interactions between other pairs of agents, rather than memories of their own interactions, to decide how to behave. Indirect reciprocity can explain the persistence of cooperation even in groups whose members are unlikely to repeatedly interact with each other, and has thus frequently been used to model the evolution of cooperation (e.g., Brandt and Sigmund, 2004; Brandt and Sigmund, 2006; Nakamura and Masuda, 2011; Nowak and Sigmund, 1998a,b; Ohtsuki and Iwasa, 2006; Pacheco et al., 2006; Panchanathan and Boyd, 2003; Uchida, 2010; Uchida and Sigmund, 2010). (For discussions of direct reciprocity, see e.g., Killingback and Doebeli, 2002 and Nowak, 2006.)

Many existing models assume that there is no group structure, so that each agent is equally likely to encounter every other. However, few—if any—real biological groups are perfectly well-mixed. If members of a group inherit their behavioral strategies from their parents and do not move far from where they are born, the group will comprise patches of agents with similar behaviors. Structure can also arise if members of a group move away from agents who have defected against them (Hamilton and Taborsky, 2005) or away from parts of the environment that have been depleted by defectors (Pepper and Smuts, 2002). Each of these mechanisms could lead to different frequencies of interacting with cooperators, defectors, and discriminators, resulting in what we call interaction assortment. Positive interaction assortment has been shown to be effective for promoting cooperation (e.g., Ackermann et al., 2008; Axelrod and Hamilton, 1981; Doebeli and Hauert, 2005; Fletcher and Doebeli, 2006; Ghang and Nowak, 2015; Panchanathan and Boyd, 2004; Pepper and Smuts, 2002; Rankin and Taborsky, 2009; Roberts, 2015; for an exception see Hauert and Doebeli, 2004), while negative interaction assortment tends to inhibit cooperation (Fletcher and Doebeli, 2006; Forber and Smead, 2014; Smead and Forber, 2013; West and Gardner, 2010).

Any mechanism that leads to interaction assortment could also lead to different frequencies of observing cooperators, defectors, and discriminators, resulting in what we call information assortment, which has not previously been studied. Furthermore, only a handful of studies have considered limited information, and these studies do not explicitly model the process of information gathering and storing (e.g. Brandt and Sigmund, 2006; Kreps et al., 1982; Nakamura and Masuda, 2011; Nowak and Sigmund, 1998a,b; Panchanathan and Boyd, 2003). With the exception of Kreps et al. (1982), who assumed that co-players do not always select the most rational strategy among those available to them, the few studies that considered indirect reciprocity under limited information assumed that each discriminator knows the last action of a fraction of its group at each point in time (e.g. Nakamura and Masuda, 2011; Nowak and Sigmund, 1998a,b; Panchanathan and Boyd, 2003). Limited information is thus described only phenomenologically, since the process by which discriminators collect such information is not considered. These earlier descriptions are also memory-less, since only behaviors at the last point in time is allowed to affect the discriminators' assessments and resultant behaviors. Finally, most models of indirect reciprocity ignore the costs incurred by discriminators for their information-related behaviors (but see Brandt and Sigmund, 2006). In reality, however, gathering and storing information can be costly, since it takes time and energy to engage in those activities, as has been studied in ecology, animal behavior, economics, and neuroscience (Laughlin, 2001; Laughlin et al., 1998; MacIver et al., 2010; Nelson, 1970; Waddington, 1985).

In this paper, we investigate how interaction assortment, information assortment, limited information, and costly information affect the ability of discriminators to stabilize cooperation. To study the dynamics of a group consisting of cooperators, defectors, and discriminators using indirect reciprocity, we extend the influential model of Nowak and Sigmund (1998b). In this model, three types of agents—cooperators, defectors, and discriminators—interact with each other for several rounds, during which discriminators cooperate with other agents that have recently cooperated and defect otherwise. We incorporate interaction assortment by allowing each type of agent to interact more or less frequently with other agents of the same type, and we incorporate information assortment by allowing discriminators to observe other discriminators more or less frequently than they observe the other types. Additionally, we incorporate limited information by restricting the number of observations that discriminators can make and by allowing discriminators to forget their observations of behaviors occurring more than one time step ago. Finally, we impose costs on the discriminators for their information-related behavior.

We find that cooperation can be stabilized by the presence of discriminators, provided that the discriminators preferentially interact with other types of agents or preferentially observe other discriminators, even when the discriminators have limited information. Surprisingly, making more information available to discriminators sometimes makes it harder for them to protect a cooperative group from invasion by defectors. Finally, we find that it becomes more difficult for discriminators to stabilize cooperation if they have to pay costs for gathering and storing information.

2. Model description

We model a group of agents who cooperate to differing extents: cooperators always cooperate, defectors never cooperate, and discriminators use information about their peers to decide whether to cooperate or to defect. All agents interact with each other and receive payoffs according to their own behavior and the behaviors of the agents they interact with. These payoffs then determine how the frequencies of the three types of agents change over time, with agents that receive higher payoffs becoming more frequent. In the following sections, we describe the agents and how they interact; how discriminators gather, store, and use information; how the expected payoff for each type of agent is calculated; and how these payoffs affect the frequencies of the types of agents.

2.1. Interaction dynamics

Following Nowak and Sigmund (1998b), we model cooperative interactions using the donation game. When two agents interact, each agent in the pair is given the opportunity to donate to its partner. If he chooses to donate, the recipient receives a benefit b and the donor incurs a cost c. If he chooses not to donate, neither agent's payoff changes. There are three types of agents. Cooperators always donate, defectors never donate, and discriminators decide whether or not to donate based on what they know about the recipient. We denote the frequency of cooperators in the group by x_1, that of defectors by x_2, and that of discriminators by x_3. We model a group that is sufficiently large (or in mathematical terms, infinitely large) that these quantities can take any value between 0 and 1. The set of combinations (x_1, x_2, x_3) with $x_1, x_2, x_3 \geq 0$ and $x_1 + x_2 + x_3 = 1$ is called the two-dimensional simplex.

The agents play the game for R rounds. Agents can be more or less likely to interact with other agents of the same type than with other types, or equally likely to interact with all types, depending on the assumed degree of what we call interaction assortment. Specifically, we assume that an agent is more likely by a factor a_{int} to interact with another agent of the same type than with either