Supplementary Information for
Explaining the evolution of gossip

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1 Supplementary Methods

1.1 Agents' Information About Each Other

For each pair of agents *X* and *Y*, *X*'s information about *Y*'s strategy is a probability distribution over the set of possible strategies, represented by a table as shown in Fig. S1. For each strategy S_i ($i \in \{1, 2, \ldots, n\}$, where *n* is the total number of cooperation strategies), the table gives the probability that *X* believes *Y*'s strategy is S_i. If *X* has no information about *Y* (i.e., if *X* has neither interacted with *Y* nor heard any gossip about *Y*), the probability distribution in the table is uniform, i.e., each probability is 1/*n*.

X's *hypothesized strategy* for *Y* is a strategy S_{XY} chosen at random from the probability distribution given in the table. *X* also has a *confidence level* for *Y*, C_{XY}, which is the maximum of the probabilities in the table. Here we are using the word "confidence" in the colloquial sense, not the statistical sense. Whenever *X* interacts with *Y*, *X* acts as if *Y*'s strategy is S_{XY}. Whenever *X* gossips about *Y*, *X* tells others that *Y*'s strategy is S_{XY} and that *X*'s confidence level for *Y* is C_{XY}.

1.2 Network Structures

1.2.1 Static Structures

In each simulation, there are *N* = 200 agents embedded in a social network. In the default model, a small-world network with an average degree of *swK* = 20 is used. Small world networks have been widely used to resemble connections in real-world (1, 2). The small-world network is generalized with the algorithm of Watts and Strogatz (3) using the "watts_strogatz_graph()" function in NetworkX with Python. This method first creates a ring over *N* = 200 nodes. Then each node in the ring is connected with its *swK* = 20 nearest neighbors. Then shortcuts are created by replacing some edges as follows: For each edge u-v in the network, with a probability *swP* = 0.5, replace it with a new edge u-w with uniformly random choice of existing node w (4). Other network structures, including small world networks with different levels of connection and random networks, were also explored in robustness tests.

1.2.2 Mobility

In the default model, the network structure is fixed. In other words, the mobility of the population *m* = 0 by default. However, we also explored the effects of network mobility in further analyses. If an agent moves, they randomly cut *cutP* = 90% of their connections and randomly select an agent in the population as a contact person. Next, they build a connection to the contact person. If the contact person has k neighbors at the moment, the relocated agent randomly selects k × *buildP* – 1 agents from these neighbors and build connections with them, where *buildP* = 90% by default. This process mimics the processes where when someone moves, they cut some old connections and build new connections in the destiny neighborhood.

1.3 Methods of Step 1

Beyond the main results, we ran two sets of simulations to test the causal pathways in the evolutionary cycle of gossip (Fig. 1). In Step 1, only the reputation dissemination function of gossip was examined. Specifically, only four cooperation strategies were used in this step: 1) unconditional cooperators (AC), 2) unconditional defectors (AD), 3) virtuous agents (CC), and 4) exploitive agents (CD). Similarly, in agents' probability tables, only these four strategies were listed. ACs and ADs do not utilize reputation information to guide their cooperation decisions. Thus, they will not directly benefit from the reputation dissemination function of gossip. CCs and CDs are reputation sensitive agents that directly benefit from the reputation dissemination function of gossip. Specifically, CCs utilize reputation information virtuously to protect themselves. Thus, if gossip boosts information accuracy, CCs will be able to better recognize defectors, avoid cooperating with defectors, and cooperate more effectively with cooperators. CDs, however, correspond to the exploitive side of the reputation dissemination function of gossip. They utilize reputation information not only to protect themselves, but also to exploit others, if possible. By implementing CDs, we extended previous literature on indirect reciprocity and avoided making the model biased toward cooperation (5). In other words, we did not assume that the reputation dissemination function of gossip necessarily brings more cooperation. Instead, it is possible that gossip brings individuals the information to exploit others and leads to the collapse of cooperation.

An experimental condition and a control condition were contrasted. In both conditions, agents are labeled as either gossipers (AG) or non-gossipers (AN). The only difference between the two conditions was the frequency of conversations, *talkF*. In the experimental condition, *talkF* = 10, representing a situation where agents talk frequently. In the control condition, *talkF* = 0, representing a situation where agents do not talk, even if they are labeled as gossipers. Thus, by comparing the two conditions, we were able to examine how the existence of gossip influences reputation accessibility, the evolution of reputation sensitive agents, and cooperation.

1.4 Methods of Step 2

In Step 2, two additional cooperation strategies, opportunistic (GC) and reverse-opportunistic agents (GD), were added. As mentioned in the main text, the evolution of GCs reflects the selfishness deterrence function of gossip. GDs are the opposite of GCs. We added GDs to avoid making the model biased toward gossipers.

A 2 (with vs. without gossip) × 2 (with vs. without reputation management) contrast was made. To manipulate the former variable, as in Step 1, we manipulated *talkF*. When *talkF* = 10, the reputation dissemination function was "on" whereas when *talkF* = 0, the reputation dissemination function was "off." The latter variable was manipulated as follows: In the with-rep-manage condition, gossiper sensitive agents were able to manage their reputation in front of gossipers, as described in the default model. However, in the no-rep-manage condition, everything was the same except that though GCs and GDs still behaved differently toward gossipers vs. non-gossipers, they could *not* manage their reputation in gossip. Both GCs and GDs presented their real strategies to both gossipers and non-gossipers in the no-rep-manage condition. This condition "blocked" the selfishness deterrence function of gossip.

2 Supplementary Results

2.1 Main Results

This section and its figures contain supplementary results for the main results (Fig. 3) in the main text.

Figure S5 shows that the evolution of gossipers is robust even when gossiping is costly, as long as this cost is not too high.

Figure S6 shows the cooperation rates among different strategies. Except for unconditional defectors and reverse-opportunists, all the other agents have high cooperation rates. Though exploitive agents exploit unconditional cooperators, they ended up cooperating most of the time because the majority of the population has become reputation sensitive and is not easy to exploit. For opportunistic agents, since the majority of the population has become gossipers, opportunists also cooperate most of the time.

Figure S7 shows the accuracy of agents' hypothesized strategies of their neighbors. As time passes by, agents gradually form relatively accurate hypotheses.

2.2 Step 1: When Gossip Only Has Reputation Dissemination Function

This section contains supplementary results for Step 1. In Step 1 (Fig. S10), only the reputation dissemination function of gossip was examined. Specifically, only four cooperation strategies were used in this step: 1) unconditional cooperators (AC), 2) unconditional defectors (AD), 3) virtuous agents (CC), and 4) exploitive agents (CD).

2.2.1 The Direct Effects of Reputation Accessibility

To support that the increased reputation accessibility caused by gossip is the *direct* reason for the evolution of reputation sensitive agents, we did a set of simulations that exogenously manipulate reputation accessibility and examine its effects. The setup is the same as in the default model, except that, throughout the simulation, agents' hypothesized strategies of each other are exogenously implemented with a certain level of accuracy, instead of endogenously got from interactions or gossip. By implementing different levels of information accuracy, we examined how information accuracy directly influences agents' cooperation strategies and behavior.

Figure S8 shows that in general, more agents become reputation sensitive and more cooperative as they have more accurate information. Interestingly, the effect follows a *piecewise* function. Fig. S8A shows that when information accuracy is below a certain threshold, almost none of the agents cooperate, while when information accuracy is high enough, the cooperation rate increases as information accuracy increases. Fig. S8B shows that when there is not enough information, unconditional defectors take over the major part of the population. However, after information accuracy has passed a threshold, more reputation sensitive agents evolve as information accuracy increases.

These results support that the increased reputation accessibility *causes* the evolution of reputation sensitive agents. The piecewise relationship is also consistent with previous research (6), which indicates that indirect reciprocity through reputation can only promote cooperation when the reputation information is prevalent enough. The piecewise relationship also suggests that gossip should have the strongest impact on cooperation when it can boost information accuracy up to above the threshold.

2.2.2 The Collapse of Gossipers When Gossiping is Costly in Step 1

Figure S9 shows the evolution of gossipers when gossiping is costly in Step 1 (i.e., when gossip only has its reputation dissemination function). Each condition includes 30 simulations. All these conditions are under the with-gossip condition in Step 1 in which agents talk frequently (*talkF* = 10). Results show that, even if a little cost is implemented to gossiping (e.g., *gCost* = 0.01, which is 1% of the cost of cooperation), it will cause the proportion of gossipers to drop dramatically. Along with Fig. 4 (Step 1) in the main text and Fig. S10, these results support the conclusion that the reputation dissemination function of gossip alone is *not* sufficient to explain the evolution of gossipers.

2.2.3 Robustness Tests Under Other Model Choices

In this section, we examine the robustness and boundary conditions of Step 1 by using different model choices. We varied the following parameters and model choices: 1) *bias*, bias toward more confident gossip when listeners process gossip, 2) *intF*, frequency of direct interactions, 3) *talkF*, frequency of conversations, 4) *dirW*, interaction depth—the amount of information gained from a single direct interaction, 5) *indirW*, general trust of gossip—the extent to which agents' beliefs of others are influenced by gossip, 6) network structures, 7) *updF*, frequency of strategy updating, and 8) *m*, network mobility.

We find that a high enough *bias* toward more confident gossip is essential for gossip to increase reputation accessibility. If there is no bias and individuals trust any gossip equally, the existence of gossip will decrease information accuracy and harm cooperation. Other than this critical parameter, our findings are supported across a broad range of model choices: Gossip increases reputation accessibility and leads to the evolution of more reputation sensitive agents. The utilization of reputation information boosts cooperation. However, in *none* of these simulations did gossipers evolve, a result indicating that the reputation dissemination function of gossip alone is *not* sufficient to explain the evolution of gossipers.

2.2.3.1 Effects of Bias

As discussed in Materials and Methods, we assume that agents are biased to learn from other agents that are more confident about their beliefs (7, 8). This bias is captured by the parameter *bias* (see Fig. S3). In the default model, we set *bias* = 5. In this section, we vary this parameter and examine the effects of bias on the results.

Figure S11A shows that gossip only increases information accuracy when agents are highly biased toward more confident gossip. Otherwise, if agents cannot give different weights to confident vs. unconfident gossip, the existence of gossip even compromises information accuracy compared with the no-gossip condition. Accordingly, Fig. S11B shows that gossip increases the proportion of reputation sensitive agents only when *bias* is high enough. Fig. S11C further shows that a high enough bias is essential for gossip to boost cooperation.

These results are important both methodologically and theoretically. Methodologically, previous modeling work on gossip directly assumed that gossip increases reputation accessibility (9). Some other modeling work did not make such an assumption directly but assumed that gossip always spreads accurate information (10). Our model shows that if agents learn about others' reputations gradually but are allowed to gossip with imperfect information, gossip does *not* necessarily increase reputation accessibility. In this case, gossip may *not* benefit cooperation. Theoretically, these results show that biased learning may be the key for individuals to figure out correct information from imperfect gossip and for the reputation dissemination function of gossip to take effect. Especially when people are allowed to gossip regardless of their knowledge about the target, it is crucial to differentiate more reliable gossip from random guesses and take the former more seriously. Otherwise, the truth and rumors will counteract each other, and gossip will decrease information accuracy and harm cooperation.

2.2.3.2 Effects of Direct Interaction Frequency

Next, we examine how the frequency of direct interactions influences the reputation dissemination function of gossip. Fig. S12A shows that gossip has stronger effects on boosting information accuracy when direct interactions are infrequent. This is because if individuals interact in cooperation games frequently, they can learn each other's reputation from these interactions directly and no longer need to rely on gossip. Fig. S12B shows that gossip increases the proportion of reputation sensitive agents particularly when the frequency of direct interactions is low. Fig. S12C shows that gossip boosts cooperation rates across all the conditions, but particularly when direct interactions are infrequent.

2.2.3.3 Effects of Conversation Frequency

Next, we examine how the frequency of conversations influences the reputation dissemination function of gossip. Frequency of conversations (*talkF*) controls how many agents are selected per iteration to speak. Holding the proportion of gossipers constant, this reflects the frequency of gossiping. Fig. S13A shows that even a small amount of gossip (e.g., *talkF* = 0.5) increases information accuracy substantially compared with the control condition (i.e., *talkF* = 0). Fig. S13B and Fig. S13C show that across all the conditions, gossip induces more reputation sensitive agents and boosts cooperation. Interestingly, conversation frequency shows a *curvilinear* effect. When there is too much gossip (e.g., *talkF* > 20), information accuracy and cooperation start to decrease as the frequency of conversation increases. This is probably because the surplus of inaccurate gossip pollutes the information pool. Nevertheless, in general, the existence of gossip increases reputation accessibility, the proportion of reputation sensitive agents, and cooperation, supporting the reputation dissemination function of gossip.

2.2.3.4 Effects of Interaction Depth

Next, we examine how the results are influenced by interaction depth—the amount of information gained from a single direct interaction (*dirW*). Fig. S14A shows that gossip increases reputation accessibility across all the conditions. Fig. S14B shows that gossip increases the proportion of reputation sensitive agents, especially when *dirW* is small. This is because when agents have deep interactions, the information from gossip becomes less necessary. Similarly, Fig. S14C shows that gossip is more effective for boosting cooperation when *dirW* is small. Nevertheless, the reputation dissemination function of gossip holds robust.

2.2.3.5 Effects of General Trust of Gossip

We also examine the effects of the general trust of gossip (*indirW*). This parameter can be interpreted as the extent to which agents' beliefs of others are influenced by gossip. Fig. S15 shows that across all the conditions, gossip benefits reputation accessibility, induces more reputation sensitive agents, and boosts cooperation. There is also a trend that the effects of *indirW* are curvilinear. For gossip to maximally benefit reputation accessibility, individuals need to rely on gossip *neither* too much *nor* too little. If they are not influenced enough by gossip, the information in gossip will not be as helpful. However, if they are influenced too much by gossip, it will compromise the knowledge learnt from direct interactions, which harms information accuracy and cooperation. Nevertheless, the main results are robust. Over a broad range of *indirW*, gossip increases reputation accessibility, the proportion of reputation sensitive agents, and cooperation.

2.2.3.6 Effects of Network Structures

We also examine the effects of network structures. To do that, we tested a small world network with a higher average degree (i.e., average number of neighbors, *swK* = 50). We also tested a random regular network with different levels of degree (*d* = [10, 20, 50]). Fig. S16 shows that, in general, gossip increases information accuracy, the proportion reputation sensitive agents, and cooperation across a variety of network structures, especially when the degree of a network is high. When agents have few neighbors, they can get sufficient information just from direct interactions. In this case, the reputation dissemination function of gossip is limited. Overall, these results support the robustness of the reputation dissemination function of gossip.

2.2.3.7 Effects of Strategy Updating Frequency

We also examine the effects of strategy updating frequency. From an evolutionary perspective, this represents the speed of cultural evolution. Fig. S17A shows that the existence of gossip increases information accuracy across all the conditions. Fig. S17B shows that gossip increases the proportion of reputation sensitive agents, especially when strategy updating is relatively frequent. Fig. S17C shows that the reputation dissemination function of gossip benefits cooperation across all the conditions, especially when strategy updating is frequent. Overall, these results support the robustness of our findings.

2.2.3.8 Effects of Network Mobility

Finally, we examine the effects of network mobility. Fig. S18 shows that across all the mobility levels, gossip increases reputation accessibility, the proportion of reputation sensitive agents, and cooperation. Notably, the reputation dissemination function of gossip is especially prominent when mobility is high. This is consistent with previous research that emphasizes the role of gossip in mobile organisms (9).

2.2.3.9 Summary

Overall, the robustness tests show that across a wide range of model choices, gossip increases reputation accessibility and benefits reputation sensitive agents who condition their behavior on others' reputations. As a result, gossip also facilitates cooperation, manifesting its reputation dissemination function.

However, in *none* of the simulations mentioned above does evolution favor either gossipers or non-gossipers (Figs. S10-18). This indicates that the reputation dissemination function of gossip alone is *not* sufficient to explain the evolution of gossipers. Instead, the selfishness deterrence function of gossip is the key to the evolution of gossipers, which will be elaborated in the next section.

2.3 Step 2: When Gossip Has Both Reputation Dissemination and Selfishness Deterrence Functions

This section contains supplementary results for Step 2. In Step 2 (Fig. S19), we examine both the reputation dissemination and selfishness deterrence functions of gossip. All the six cooperation strategies are included in the models in Step 2.

2.3.1 Robustness Tests Under Other Model Parameters

In this section, we examine the robustness and boundary conditions of the results in Step 2. We varied the following model parameters: 1) *bias*, bias toward more confident gossip, 2) *intF*, frequency of direct interactions, 3) *talkF*, frequency of conversations, 4) *dirW*, interaction depth—the amount of information gained from a single direct interaction, 5) *indirW*, general trust of gossip—the extent to which agents' beliefs of others are influenced by gossip, 6) network structures, 7) *updF*, frequency of strategy updating, and 8) *m*, network mobility.

As in Step 1, Step 2 also shows that a high enough *bias* toward more confident gossip is essential for gossip to increase reputation accessibility. If people are not able to differentiate between confident vs. unconfident gossip, reputation accessibility will be compromised. That will reduce the evolution of reputation sensitive agents. As a result, not many opportunists and gossipers evolve, either.

Other than that, across a broad range of parameters, our conclusions are supported: The selfishness deterrence function of gossip is the key to the evolution of gossipers. When opportunists can manage their reputation by cooperating with gossipers, more individuals become opportunistic. This gives an advantage to gossipers and leads to their evolution.

2.3.1.1 Effects of Bias

First, we examine the effects of the bias toward more confident gossip. Fig. S20A shows that when opportunists can manage their reputation, a substantial amount of opportunists evolve, but only when *bias* is high enough. Fig. S20B shows that gossipers evolve as a result of reputation management when *bias* is high enough. Figs. S20C-F replicate the results in Step 1 that gossip only benefits reputation accessibility, the evolution of reputation sensitive agents, and cooperation when *bias* is high enough.

2.3.1.2 Effects of Direct Interaction Frequency

Next, we examine the effects of interaction frequency. Overall, Figs. S21A-B replicate the main findings that the reputation dissemination and selfishness deterrence functions of gossip lead to the evolution of opportunists and gossipers. More opportunists and gossipers evolve when direct interactions are frequent. Interestingly, Fig. S21C shows that gossip is more useful for boosting reputation accessibility when interactions are relatively infrequent. In fact, due to reputation management, gossip compromises information accuracy when interactions are frequent. These results indicate that interaction frequency has *opposite* effects on the reputation dissemination vs. selfishness deterrence functions of gossip.

Nevertheless, our main argument remains robust that both the reputation dissemination and selfishness deterrence functions of gossip contribute to the evolution of gossipers. If agents cannot manage their reputation by cooperating with gossipers, gossipers will not evolve. If gossipers do not disseminate reputation information, not many gossipers evolve, either.

2.3.1.3 Effects of Conversation Frequency

Next, we examine the effects of conversation frequency. Figs. S22A-B replicate the results that the reputation dissemination and selfishness deterrence functions of gossip lead to the evolution of opportunists and gossipers. More opportunists and gossipers evolve when agents have conversations frequently. Figs. S22C-E support the reputation dissemination function of gossip.

2.3.1.4 Effects of Interaction Depth

Next, we examine the effects of interaction depth. Figs. S23A-B show that the reputation dissemination and selfishness deterrence functions of gossip jointly lead to the evolution of opportunists and gossipers. More gossipers evolve when the interactions among individuals are deep. Figs. S23C-E illustrate the reputation dissemination function of gossip. Figs. S23C-D show that gossip increases reputation accessibility and the proportion of virtuous agents. However, the result of exploitive agents is a little complicated. Fig. S23E shows that gossip decreases the proportion of exploitive agents when interactions are deep, especially under the with-rep-manage condition. This is probably because the evolution of opportunistic agents crowds out some exploitive agents. Nevertheless, in general, across a wide range of interaction depth, the main finding remains robust—both the reputation dissemination and selfishness deterrence functions of gossip are necessary to explain the evolution of gossipers.

2.3.1.5 Effects of General Trust of Gossip

Next, we examine the effects of the general trust of gossip (*indirW*). This parameter can be interpreted as the extent to which agents' beliefs of others are influenced by gossip. Again, Figs. S24A-B show that the reputation dissemination and selfishness deterrence functions of gossip jointly lead to the evolution of opportunists and gossipers. Opportunists are most prevalent when agents rely neither too much nor too little on gossip. Gossipers are most prevalent when the trust of gossip is from medium to high.

2.3.1.6 Effects of Network Structures

Next, we examine the effects of network structures. We rerun the model on a random regular network with different levels of degree (*d* = [10, 20, 50]). Figs. S25A-B show that the reputation dissemination and selfishness deterrence functions of gossip jointly lead to the evolution of opportunists and gossipers. More gossipers evolve when the network degree is high, i.e., when individuals have many neighbors in their social network. In general, Figs. S25C-E support that gossip increases reputation accessibility and the evolution of reputation sensitive agents. The reputation dissemination function of gossip is particularly prominent when individuals have many neighbors. This is because when individuals have few neighbors, they can easily keep track of these neighbors' reputations through direct interactions and do not necessarily need to rely on gossip.

2.3.1.7 Effects of Strategy Updating Frequency

Next, we examine the effects of strategy updating frequency. Figs. S26A-B show that the reputation dissemination and selfishness deterrence functions of gossip jointly lead to the evolution of opportunists and gossipers. More gossipers evolve when agents update their strategies infrequently.

Figs. S26C-D support that gossip increases reputation accessibility and virtuous agents. Interestingly, Fig. S26E shows that when agents can manage their reputation, fewer exploitive agents evolve under the with-gossip condition when strategy updating frequency is 0.005. This is probably because the evolution of opportunistic agents under that condition crowds out some exploitive agents. In fact, the reputation dissemination function of gossip is the weakest when strategy updating frequency is low. Paradoxically, gossipers are more prevalent when the updating frequency is low. In this case, the conditions where gossipers are most prevalent are not the same conditions where gossip benefits reputation accessibility the most.

2.3.1.8 Effects of Network Mobility

Finally, we examine the effects of network mobility. Figs. S27A-B replicate the results that the reputation dissemination and selfishness deterrence functions of gossip jointly lead to the evolution of opportunists and gossipers. More gossipers evolve when mobility is low. Figs. S27C-E support the reputation dissemination function of gossip—the existence of gossip increases reputation accessibility and the evolution of reputation sensitive agents. Notably, the reputation dissemination function is more prominent when mobility is high, but more gossipers evolve when mobility is low. Once again, this indicates that the conditions where gossipers are most prevalent are not necessarily the same conditions where gossip benefits reputation accessibility the most.

2.3.1.9 Summary

Overall, across a broad range of parameters, our conclusions remain robust: the reputation dissemination and selfishness deterrence functions of gossip jointly lead to the evolution of gossip.

We examined the effects of a variety of factors on the evolution of gossipers. We show that gossipers are more prevalent when agents can differentiate between confident and unconfident gossip, when direct interactions are frequent, when agents have conversations frequently, when interactions are deep, when the trust of gossip is from medium to high, when agents have many connections in their social networks, when they update their strategies relatively infrequently, and when network mobility is low.

2.3.2 A Robustness Test With Another Reputation Management Option

In our default model, opportunistic agents present to gossipers that they are *virtuous agents* whereas reverse-opportunistic agents present to gossipers that they are *unconditional defectors*. Note that compared with unconditional defectors, virtuous agents are more likely to be treated cooperatively by reputation sensitive agents. This means that even under the no-gossip condition, in which gossipers do not disseminate reputation information, a reputation sensitive gossiper is still more likely to cooperate with an opportunistic agent than with a reverse-opportunistic agent. As a result, opportunistic agents will have an evolutionary advantage over reverse-opportunists as long as they can manage their reputations, regardless of whether we allow gossipers to disseminate reputation information. That being said, because 1) opportunists have an evolutionary advantage over reverse-opportunists and 2) opportunists cooperate with gossipers and defect with non-gossipers, this gives gossipers an evolutionary advantage over non-gossipers. This is particularly true if there are many reputation sensitive agents.

Indeed, we notice that in some cases, a few gossipers evolve under the no-gossip condition in Step 2. This raises the question whether the above mechanism is an alternative explanation for the evolution of gossip. We now describe another robustness test to rule out this alternative explanation.

In this robustness test, we make the following change: For reverse-opportunists, they still cooperate with non-gossipers and defect with gossipers. However, this time, they attempt to present to non-gossipers that they are virtuous while present their real strategy to gossipers. By making this change, we make the behaviors of opportunists and reverse-opportunists symmetric—what an opportunist does to a gossiper is exactly what a reverse-opportunist does to a non-gossiper.

With the above modification, in the no-gossip condition in Step 2 (i.e., the condition where agents are still labeled as "gossipers" and "non-gossipers" but neither of them gossip), "gossipers" and "non-gossipers" should be equivalent labels. Opportunists and reverse-opportunists should also perform equally well because they both manage their reputation in front of half of the population. However, in the with-gossip condition (i.e., if we allow gossipers to gossip), things will be different for opportunists and reverse-opportunists. This is because gossipers will tell other agents that the opportunists are virtuous while non-gossipers will not gossip about reverse-opportunists. This will give opportunists an evolutionary advantage compared to reverse-opportunists. In this case, we hypothesize that we will replicate the findings in the main text—more opportunists and gossipers will evolve when agents can manage their reputation *and* when gossipers do gossip.

Figure S28 supports our hypotheses. Fig. S28A shows that a substantial number of opportunists evolve when agents can manage their reputation and when gossipers do gossip. Fig. S28C, once again, replicates that most agents become gossipers under the joint effect of the reputation dissemination and selfishness deterrence functions of gossip. These results show that our conclusion is robust and is *not* due to this alternative explanation.

2.3.3 A Robustness Test Without Exploitive Agents

To show that our conclusion is not due to the inclusion of exploitive agents, we run another robustness test without exploitive agents. As in the main text, we run the tests through two steps. In Step 1, we include only the reputation dissemination function of gossip. We implement only three cooperation strategies this time—unconditional cooperators (AC), unconditional defectors (AD), and virtuous agents (CC). We contrast two conditions: In one condition, agents gossip whereas in the other condition, agents do not gossip (with-gossip vs. no-gossip).

Results are consistent with those in the main text. Fig. S29A shows that the information disseminated through gossip increases reputation accessibility. Fig. S29B shows that when agents gossip, more reputation sensitive (i.e., virtuous, CC) agents evolve. Fig. S29C shows that gossip increases overall cooperation rate. Most importantly, Fig. S29D shows that when gossip only has its reputation dissemination function, gossipers do *not* evolve. These results show that our findings in Step 1 are robust with or without exploitive agents.

In Step 2, we include both the reputation dissemination and selfishness deterrence functions of gossip. Five strategies are included this time—unconditional cooperators (AC), unconditional defectors (AD), virtuous agents (CC), opportunists (CC), and reverse-opportunists (CD). As in the main text, two variables are manipulated. The first variable is whether gossipers gossip (with-gossip vs. no-gossip). The second variable is whether gossiper sensitive agents can manage their reputations when interacting with gossipers (with-rep-manage vs. no-rep-manage).

Our main results remain robust. Fig. S30A shows that more opportunists evolve when both the reputation dissemination and selfishness deterrence functions of gossip exist. Fig. S30B shows that gossipers evolve under the joint effect of the reputation dissemination and selfishness deterrence functions. These findings support that our findings in Step 2 are robust with or without exploitive agents.

All in all, we show that our conclusions hold robust under various model choices. The reputation dissemination function of gossip increases reputation accessibility and induces the evolution of reputation sensitive agents. As more individuals condition their behavior on others' reputations, it becomes important to manage one's own reputation. This leads to the evolution of opportunists who cooperate with gossipers in order to leave a good reputation in gossip. The existence of opportunists benefits gossipers and thus leads to the evolution of gossip. The existence of gossip further facilitates the two functions of gossip and sustains the cycle. Ultimately, gossipers, reputation sensitive agents, and opportunists co-evolve and maintain cooperation in the population.

3 Supplementary Discussion

In this section, we provide some thought experiments to infer that adding or removing some strategies would not change the generalizability of our findings.

No matter how complicated a strategy is, two of its key features are 1) whether an agent's decision is influenced by the other's reputation and 2) whether an agent's decision is influenced by concerns about its own reputation.

First, for a candidate strategy whose decision is influenced by neither, its existence may influence the baseline cooperation rate and thus interact with the effects of gossip. However, because our results remain robust under various model choices that affect baseline cooperation (see Sections 2.2.3 and 2.3.1), we believe the results will remain robust after adding a candidate strategy that cares about neither others' nor its own reputation.

Second, for candidate strategies whose decisions are influenced by other's reputations, such strategies can be conceptually categorized into two types:

1) Those that use the reputation system to protect the self (e.g., CC). The previous literature on indirect reciprocity focuses largely on this type. In this literature, conditional cooperators cooperate with good-reputed others and defect with bad-reputed others, though the threshold of cooperation may vary across individuals (11–13). Our virtuous agents (CC) take the role of these conditional cooperators because they cooperate with potential cooperators and defect with potential defectors. Beyond that, with our strategy-based reputation system, CCs are even resistant to the "paradoxical nature of the discriminating strategy" (14) (p. 1293) because when a CC defects with potential defectors, they will be perceived as a conditional cooperator just as it is, without the cost of reducing reputation.
2) Those that use the reputation system to exploit others (e.g., CD). Going beyond the previous literature, we implemented the CD strategy to take this role. And in fact, CD agents turned out to be prevalent in our simulations. This result indicates that if individuals have the capability to differentiate between conditional and unconditional cooperators, a substantial population will exploit unconditional cooperators—those who are supposed to have perfect reputation in a binary reputation system. Nevertheless, our conclusions are not due to the inclusion of exploitive agents. In Section 2.3.3, we show that our findings remain robust even when CDs are excluded from the strategy set.

Finally, for a candidate strategy whose decision is influenced by concerns about its own reputation, as in previous experimental studies, we operationalize it as the behavioral difference under the threat of gossip (15, 16). Since we only have gossipers and non-gossipers, it's reasonable to have one strategy (i.e., opportunist, GC) cooperates only with gossipers and the other (i.e., reverse-opportunist, GD) cooperates only with non-gossipers. In addition, we also implemented different of ways of how cooperating vs. defecting with gossipers influence individuals' reputations (e.g., Section 2.3.2). Results robustly show that opportunists' successful management of reputation is critical for the evolution of gossipers.

4 Supplementary Figures

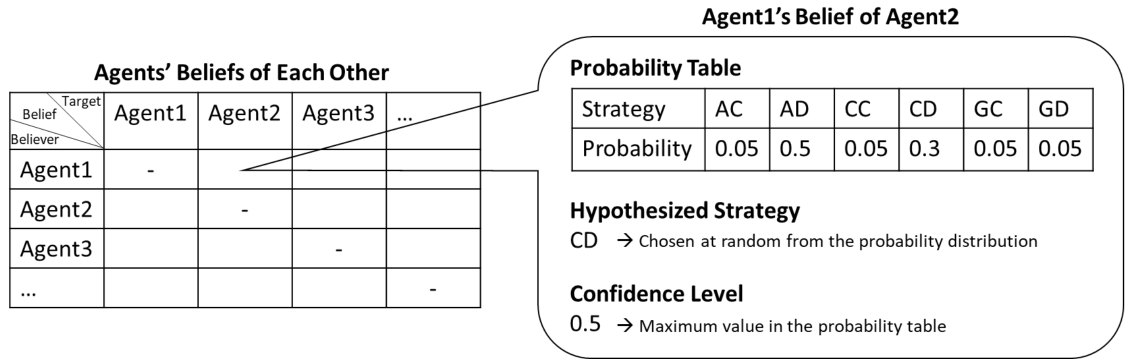


Fig. S1. Agents' beliefs about each other. Each agent has a belief about every other agent's cooperation strategy. These beliefs are represented by *probability tables*. This figure illustrates an example of Agent1's belief about Agent2. In this example, there is a probablility of 0.05 that Agent1 believes Agent2's strategy to be AC, a probablility of 0.5 that Agent1 believes Agents'2 strategy to be AD, etc. Agent1 also has a *hypothesized strategy* for Agent2, which is chosen at random using the probabilities in the table. In this example, it ends up that Agent1 believes Agent2 to be a CD. An agent's *confidence level* about their probability table is the maximum value in the probability table. In this example, Agent1's confidence level for Agent2 is 0.5. When Agent1 interacts with Agent2, Agent1 will treat Agent2 as if Agent2 is a CD. If Agent1 gossips about Agent2, Agent1 will also tell receivers that Agent2 is a CD with a confidence level of 0.5.

Original

Strategy	AC	AD	CC	CD	GC	GD
Probability	0.05	0.5	0.05	0.3	0.05	0.05

Increased Probability of AC

Strategy	AC	AD	CC	CD	GC	GD
Probability	0.05 + 0.5	0.5 – 0.263	0.05 – 0.026	0.3 – 0.158	0.05 – 0.026	0.05 – 0.026

New

Strategy	AC	AD	CC	CD	GC	GD
Probability	0.55	0.237	0.024	0.142	0.024	0.024

Fig. S2. Example of how an agent updates their probability table. The first table shows the original probability table. In the second table, the agent increases the probability of AC by 0.5. As a result, the probabilities of other strategies were decreased proportionally. The last table shows the new probability table.

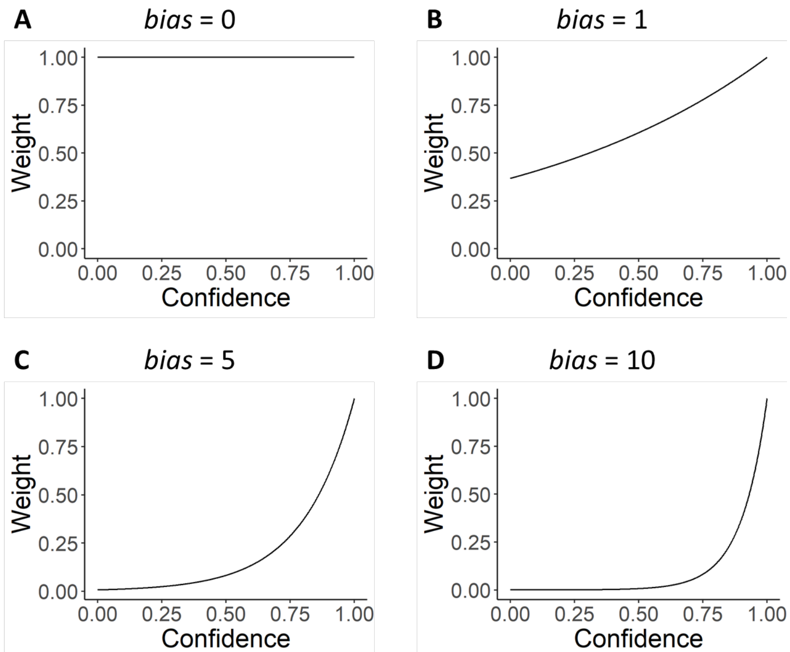


Fig. S3. Weight of a piece of gossip as a function of the gossiper's confidence under different levels of *bias*.

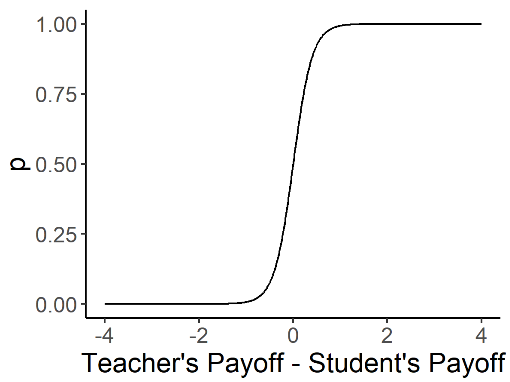


Fig. S4. Probability of strategy change in Fermi rule. The probability p that a student learns from a teacher is a function of the payoff difference between the teacher and the student. Selection strength *s* = 5 in this example.

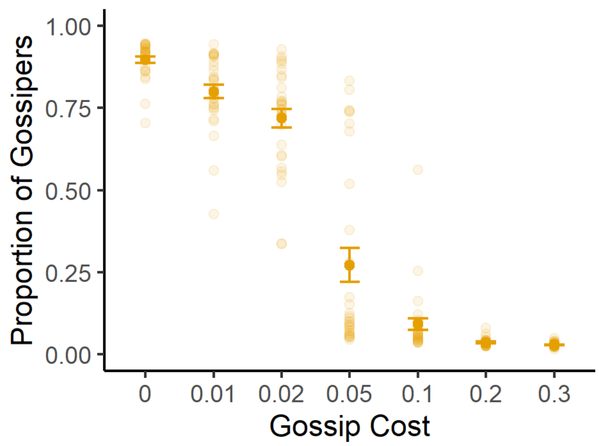


Fig. S5. Evolution of gossipers when gossiping is costly. Each condition is from 30 simulation runs. In all the conditions, agents are allowed to talk (*talkF* = 10) and gossiper sensitive agents (i.e., GCs and GDs) are allowed to manage their reputation in gossip (i.e., the with-rep-manage condition). Results show that a substantial proportion of gossipers evolve even when gossiping is relatively costly (e.g., *gCost* = 0.05, which is 5% of the cost of cooperation for a single piece of gossip). Note that each gossiper gossips about *targetN* = 2 targets per conversation and, on average, a gossiper has *talkF* = 10 conversations per iteration. Thus, a cost of *gCost* = 0.05 per piece of gossip is quite high. These results show that the evolution of gossipers is resistant to moderate cost if both the reputation dissemination and selfishness deterrence functions of gossip are enabled.

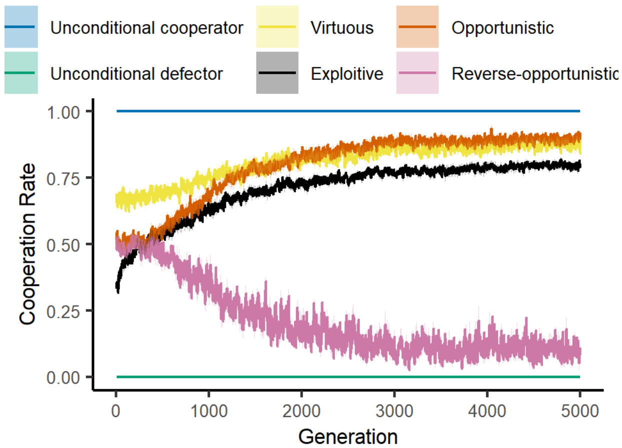


Fig. S6. Cooperation rates among different strategies.

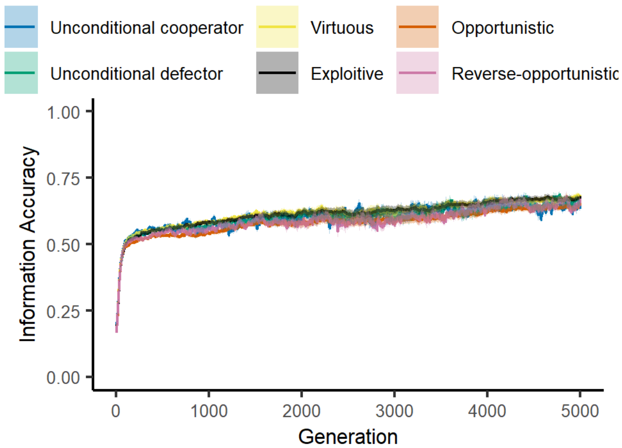
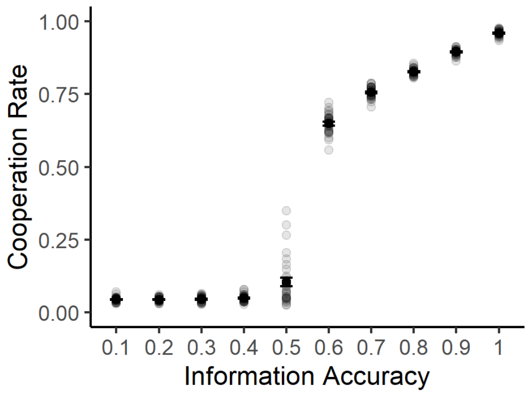


Fig. S7. Information accuracy among different strategies.

A



B

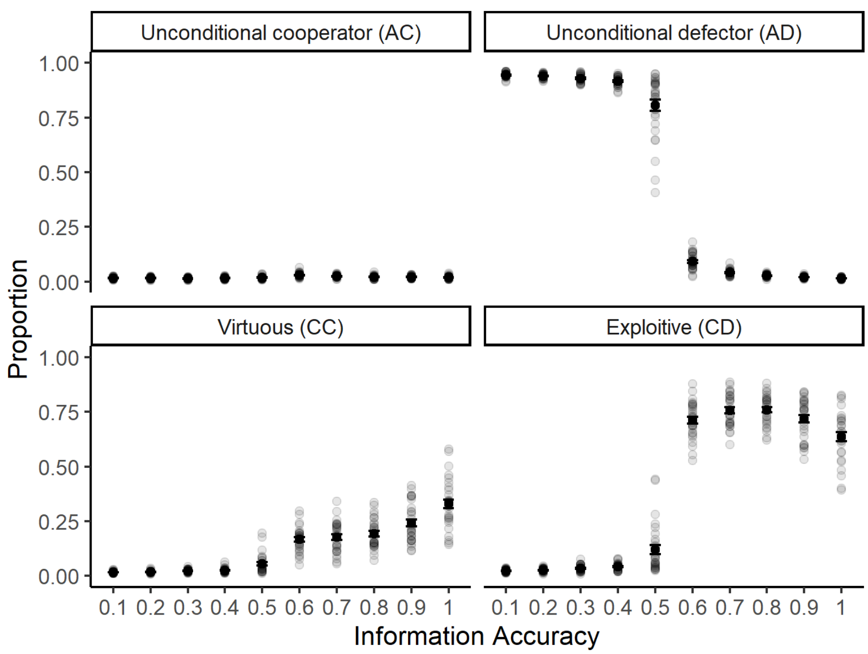


Fig. S8. The direct effects of reputation accessibility. 30 simulation runs in each condition. Agents do not talk in these conditions (*talkF* = 0). Instead, information accuracy is exogenously manipulated. Plot A shows when information accuracy is below a certain threshold (around 0.5), cooperation rate is very low. However, when information accuracy is high enough, cooperation rate increases as agents get more accurate information about their neighbors' strategies. Plot B shows that when there is not enough information, unconditional defectors take over a major part of the population. However, after information accuracy has passed a threshold, more reputation sensitive agents evolve as information accuracy increases.

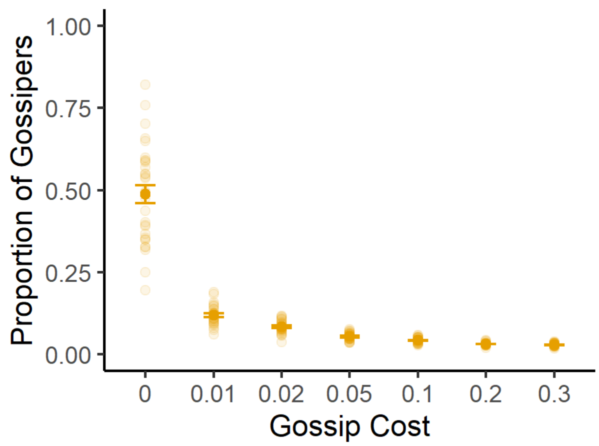


Fig. S9. Collapse of gossipers when gossiping is costly in Step 1.

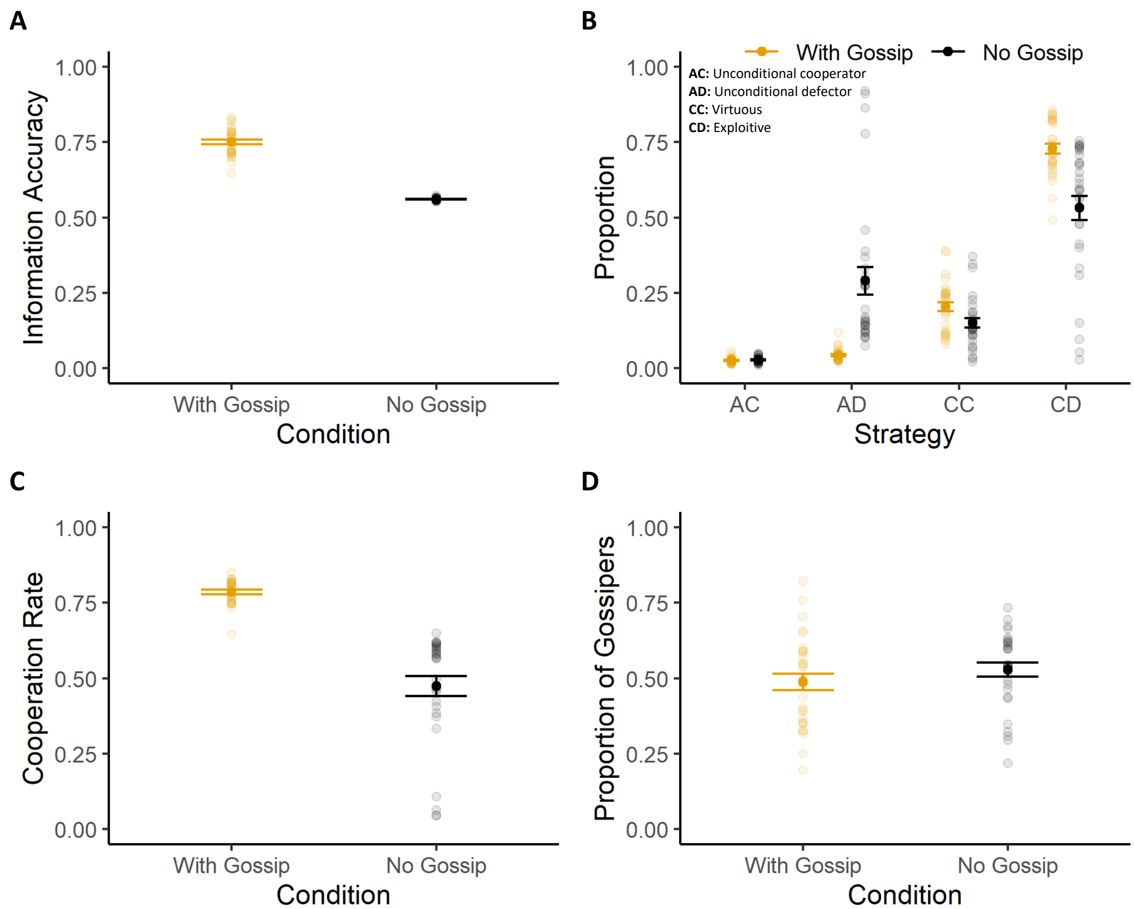


Fig. S10. Results of Step 1. The reputation dissemination function of gossip. The results are from 60 simulation runs. 30 of them are from a population where agents have frequent conversations (with-gossip) while the other 30 are from a population where there is no conversation (no-gossip). Each data point represents a single simulation run. The value is calculated as the average value from the 4000th to the 5000th iterations of that simulation run. The error bars show the standard errors. Plot A shows that gossip increases information accuracy. Plot B shows that the reputation dissemination function of gossip leads to the evolution of more reputation sensitive agents. Plot C shows that the reputation dissemination function increases cooperation in the population. Plot D shows that the reputation dissemination function of gossip alone is *not* sufficient to explain the evolution of gossipers.

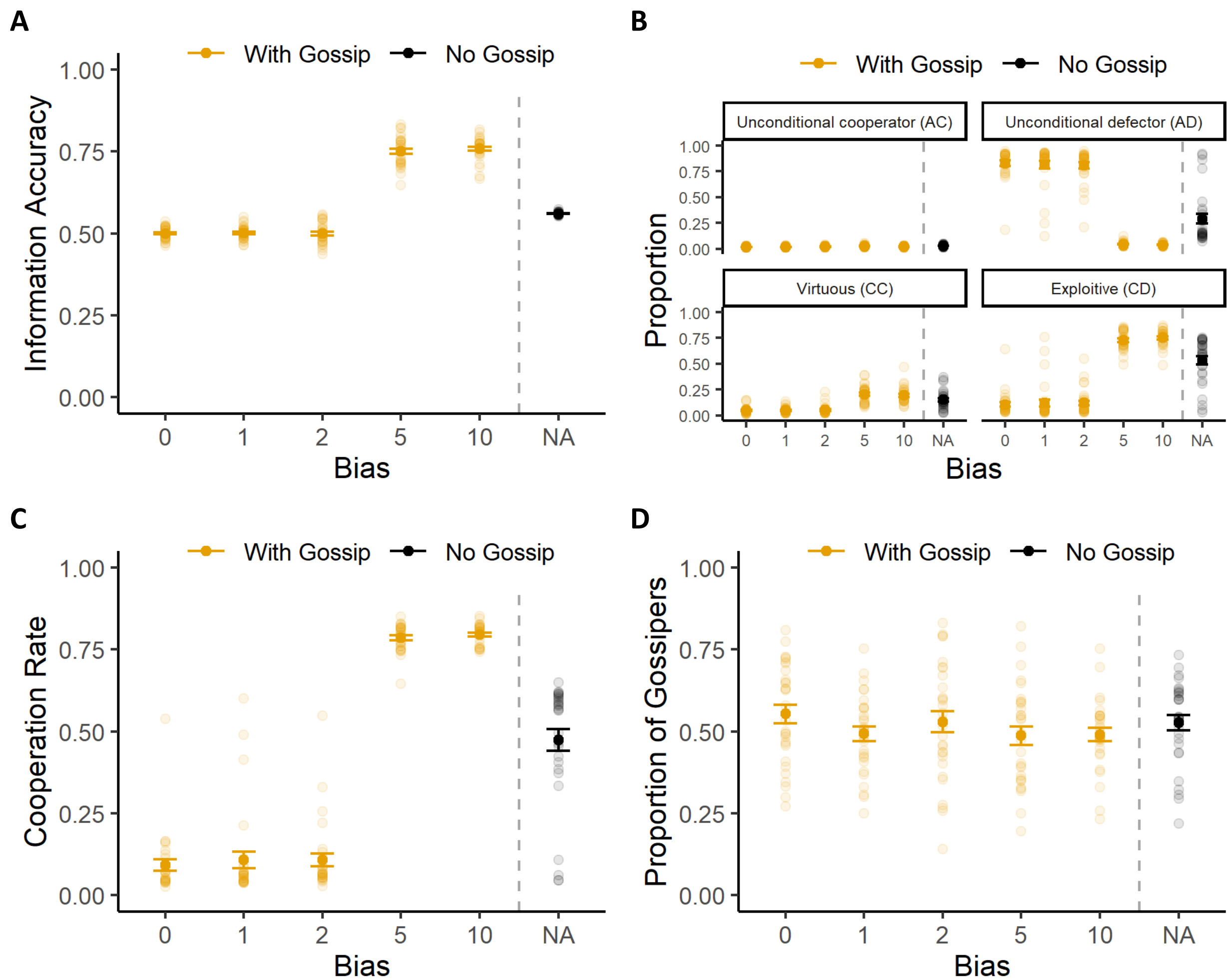


Fig. S11. Effects of *bias* in Step 1. On the left of each plot are conditions with gossip (yellow, *talkF* = 10) and with different levels of bias. On the right is the condition without gossip (black, *talkF* = 0) as the control condition. There are 30 simulations in each condition, except for the *bias* = 10 condition, where there are only 29 simulations due to a computer error. Plot A shows that when *bias* is low, gossip does not increase information accuracy compared with the control condition. Indeed, gossip makes information even less accurate if agents do not differentiate between confident and unconfident gossip. As a result, Plots B and C show that a low *bias* is harmful for the evolution of reputation sensitive agents and cooperation.

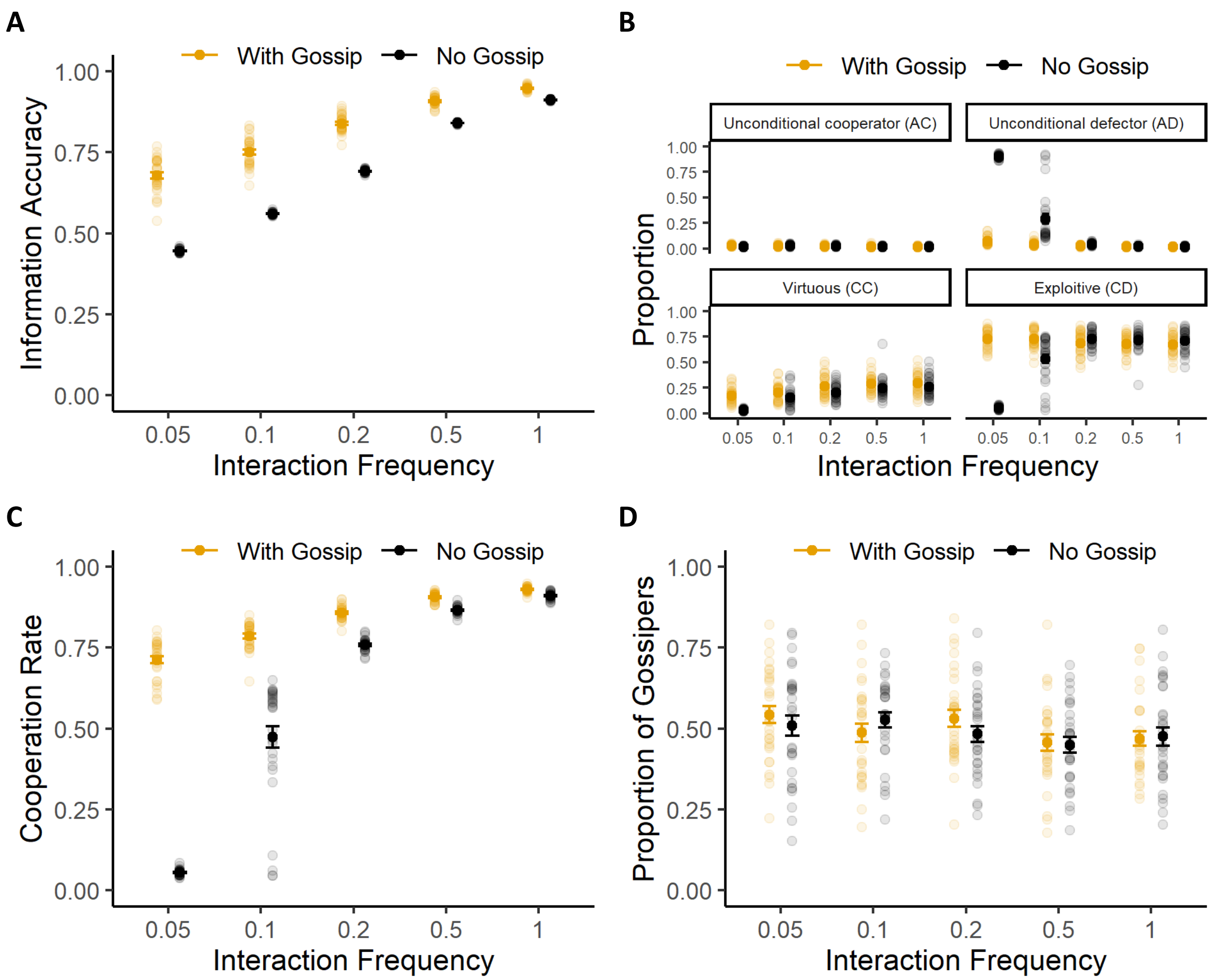


Fig. S12. Effects of interaction frequency in Step 1. For this figure and all the figures below, unless specified, there are 30 simulations in each condition.

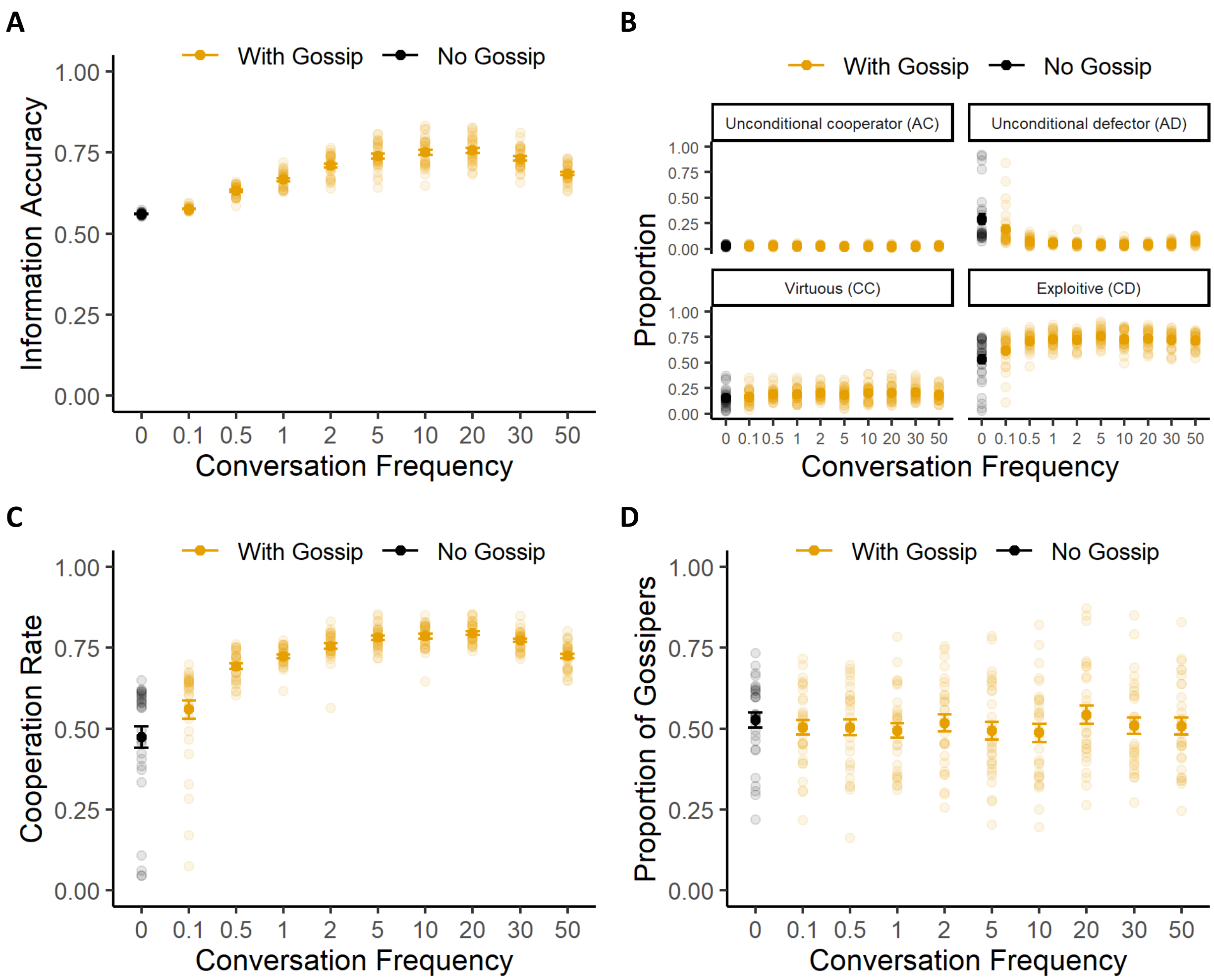


Fig. S13. Effects of conversation frequency in Step 1. Each condition represents a level of conversation frequency (*talkF*). When *talkF* = 0, it represents the control condition where there is no gossip. There are 30 simulations in each condition, except for the *talkF* = 2 condition, where there are only 29 simulations due to a computer error.

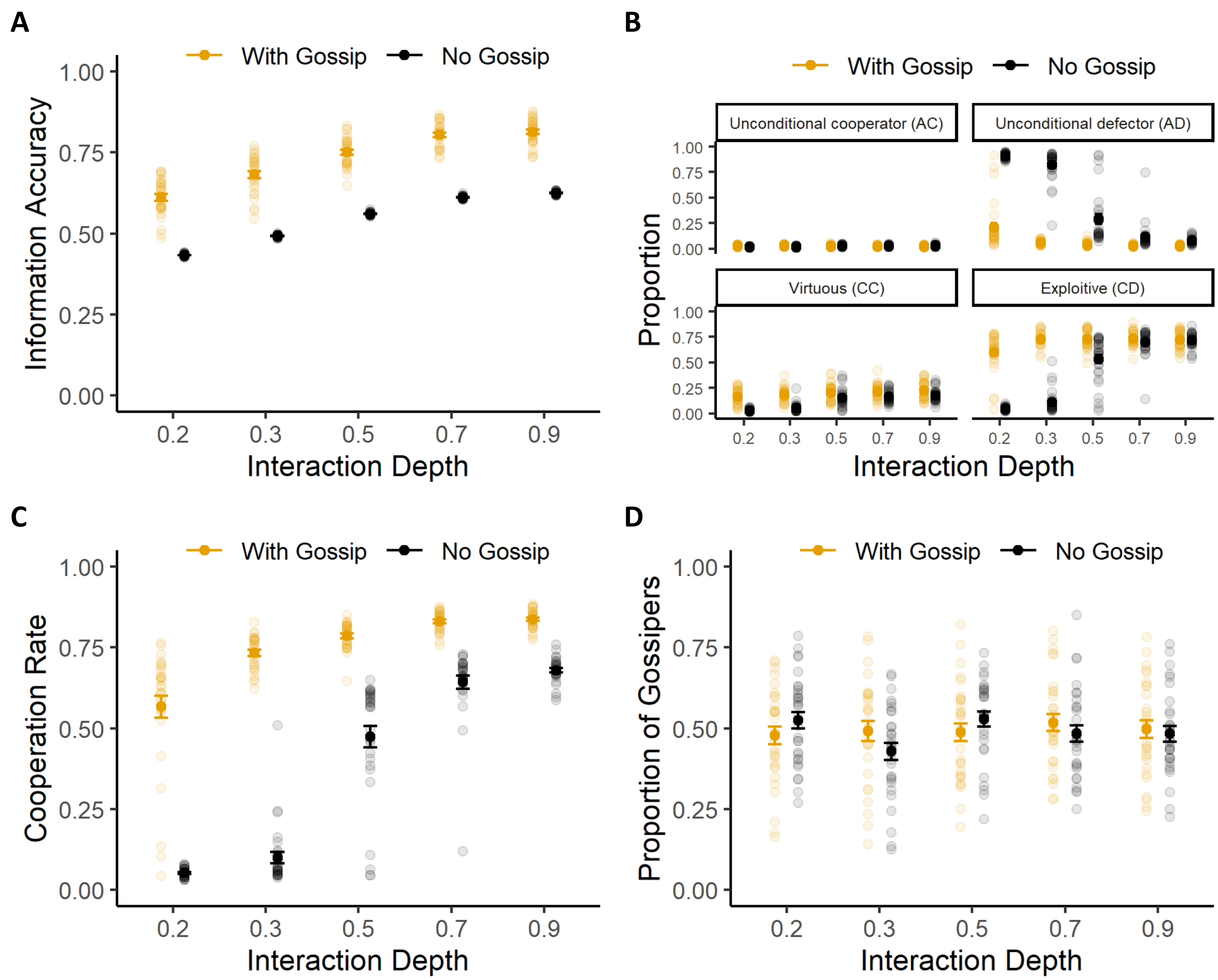


Fig. S14. Effects of interaction depth in Step 1. Each condition represents a level of interaction depth, which is manipulated as the amount of information that an individual gains about their partner from one direct interaction (*dirW*). There are 30 simulations in each condition, expect for the *dirW* = 0.3 in the with-gossip condition where there are only 29 simulations due to a computer error.

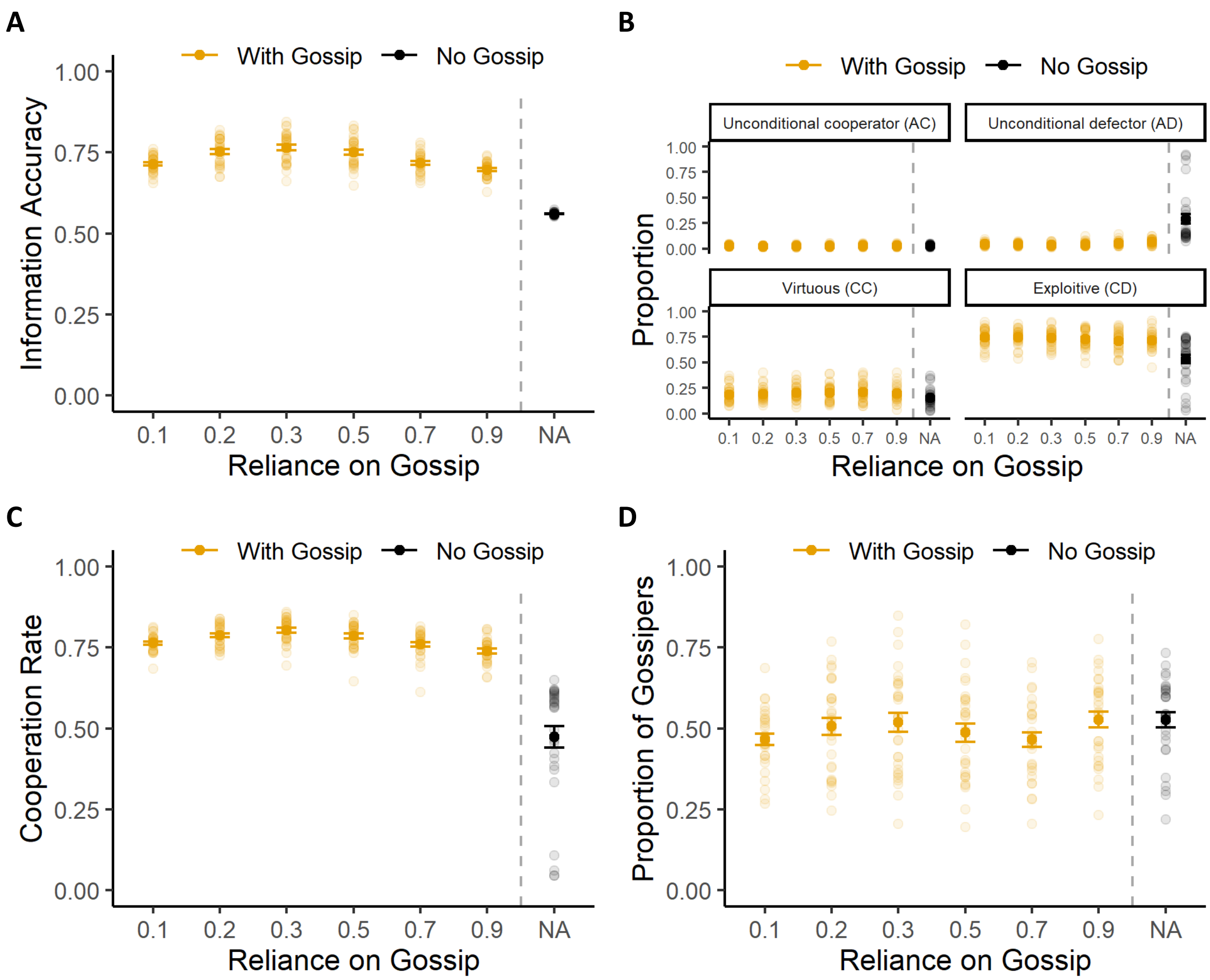


Fig. S15. Effects of general trust of gossip in Step 1. On the left of each plot are conditions with gossip (yellow, *talkF* = 10) and with different levels of reliance on gossip (*indirW*). On the right is the condition without gossip (black, *talkF* = 0) as the control condition.

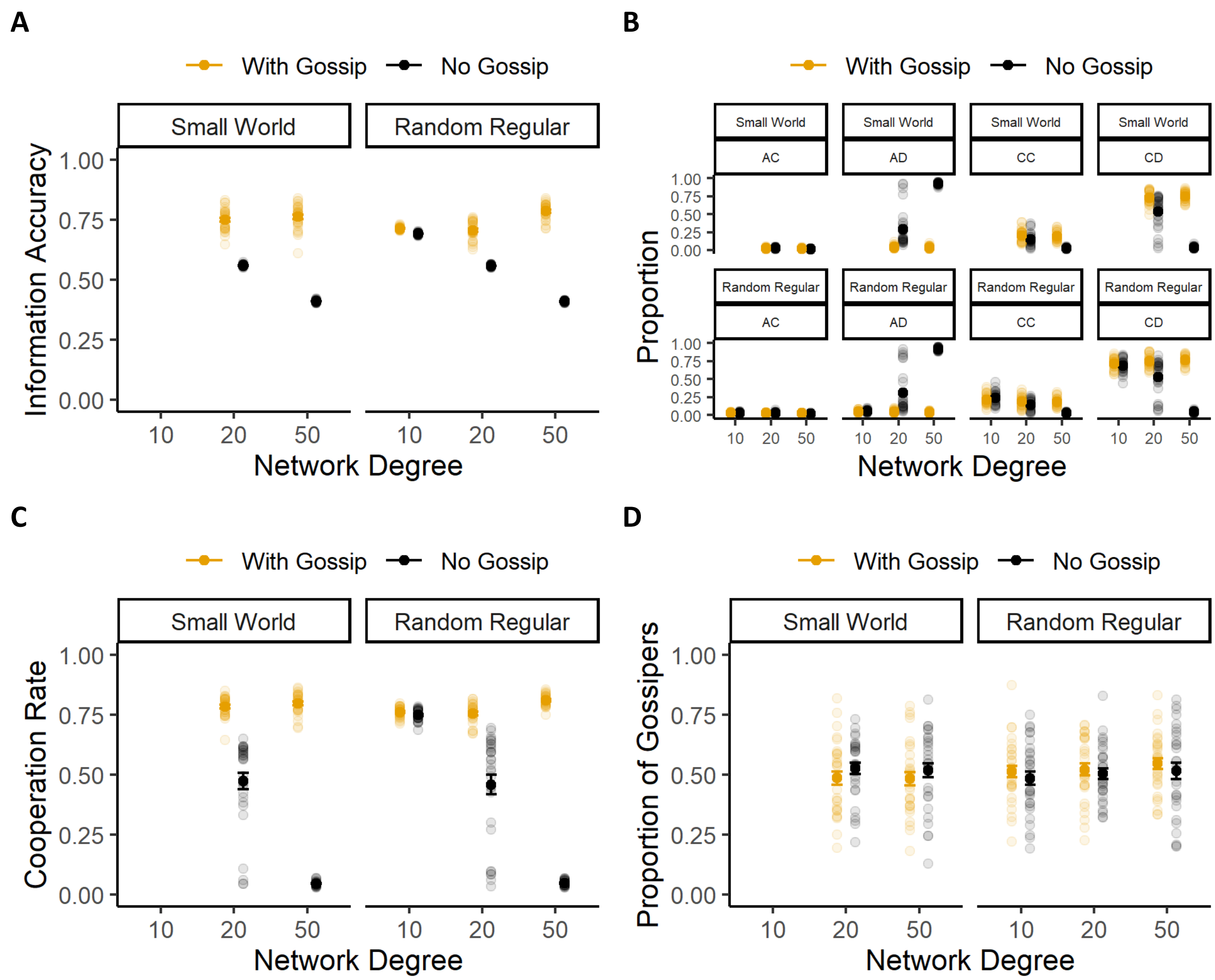


Fig. S16. Effects of network structures in Step 1.

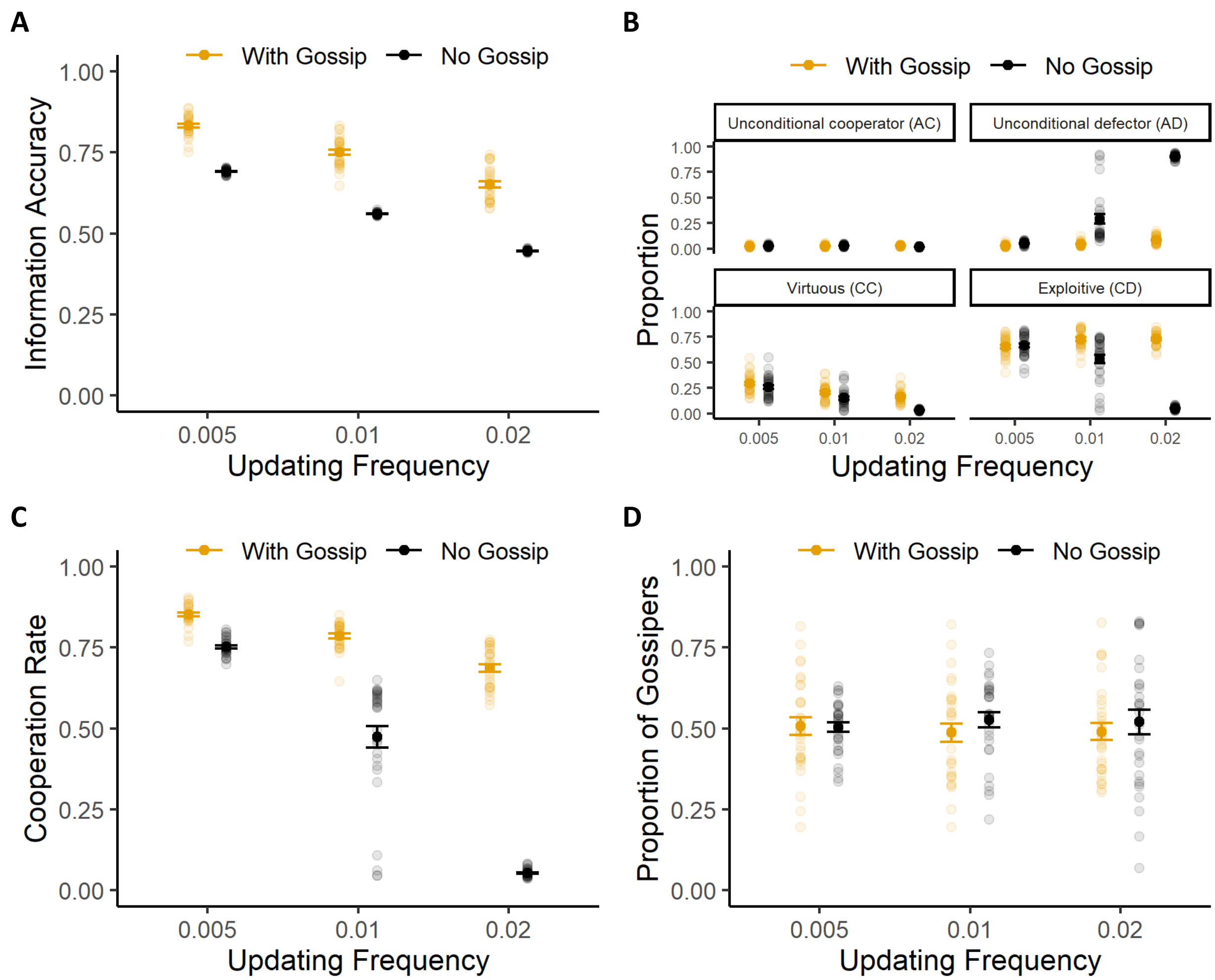


Fig. S17. Effects of strategy updating frequency in Step 1.

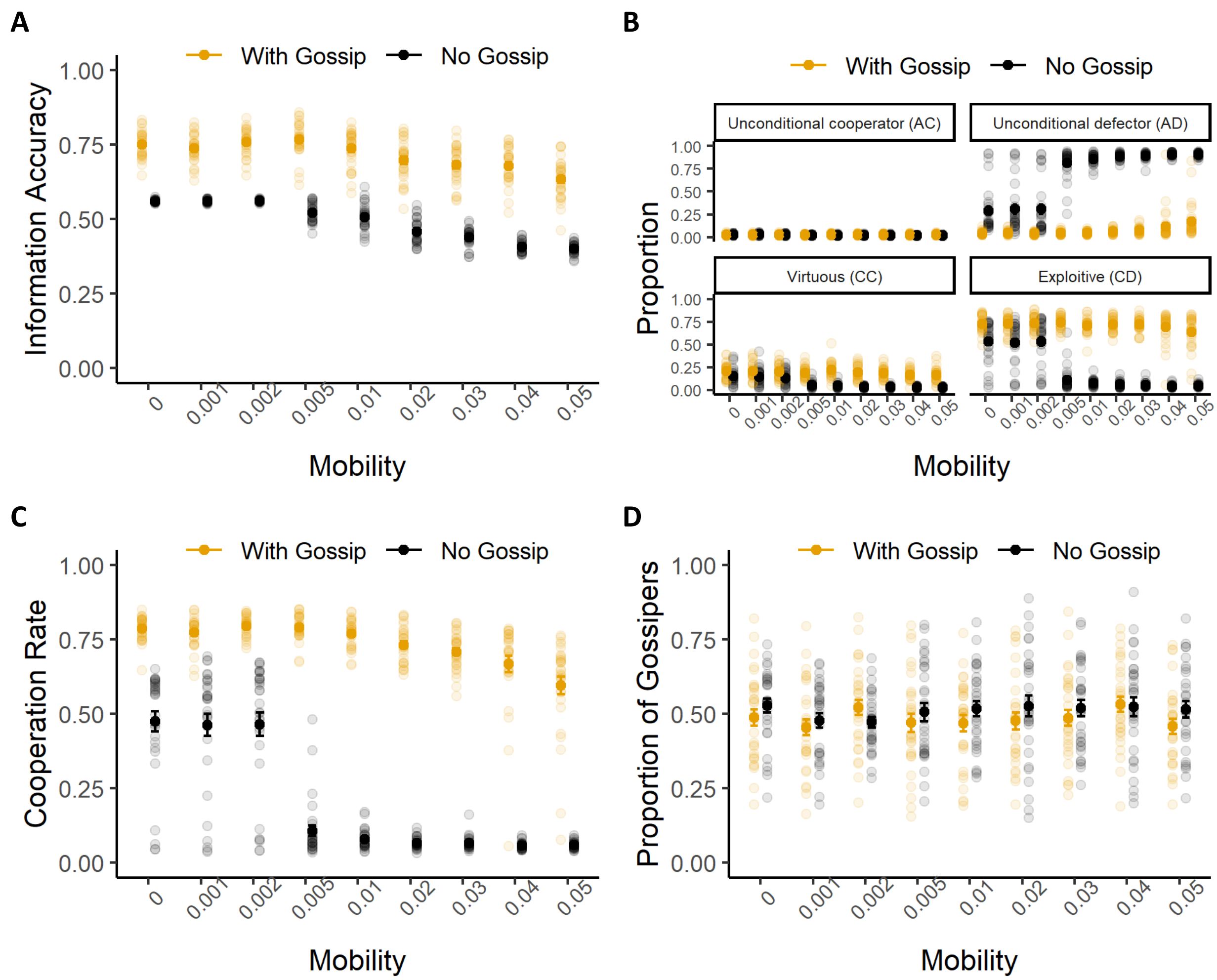


Fig. S18. Effects of network mobility in Step 1.

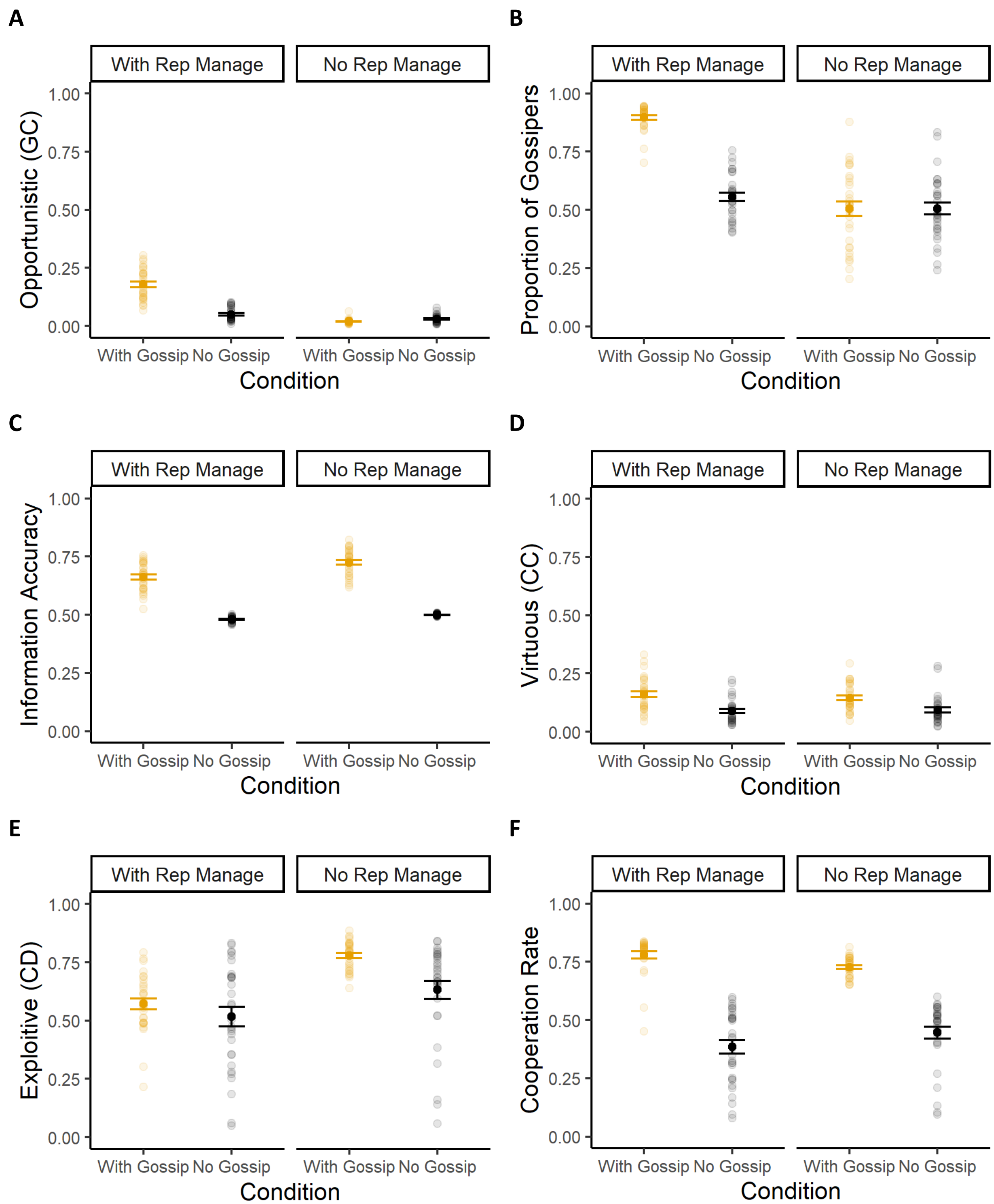


Fig. S19. Results of Step 2. The effects of the reputation dissemination and selfishness deterrence functions. There are 30 simulation runs in each condition. Plot A shows that opportunists evolve under the joint effect of the two functions of gossip. Plot B shows that gossipers evolve under the joint effect of the two functions of gossip.

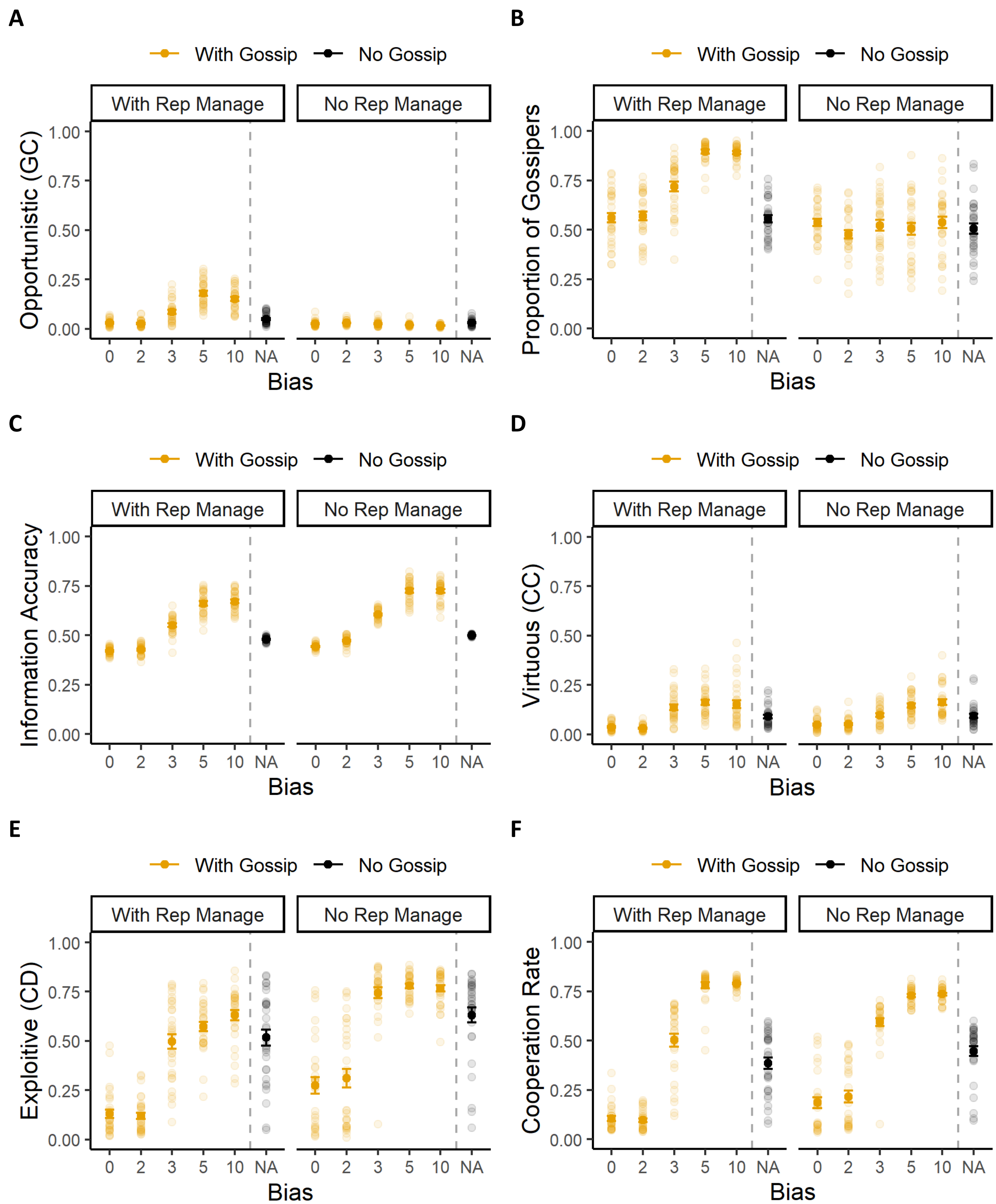


Fig. S20. Effects of *bias* in Step 2.

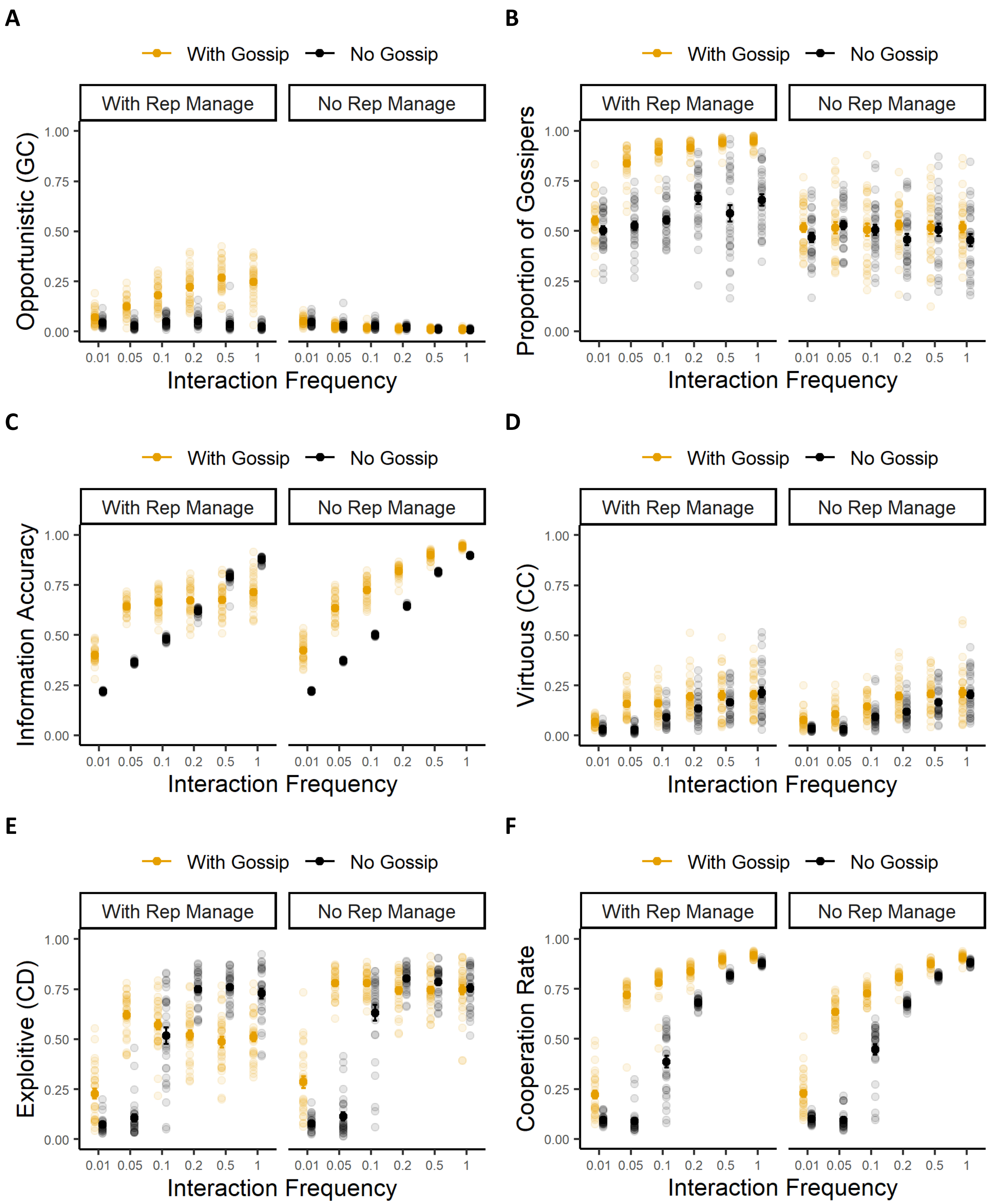


Fig. S21. Effects of direct interaction frequency in Step 2.

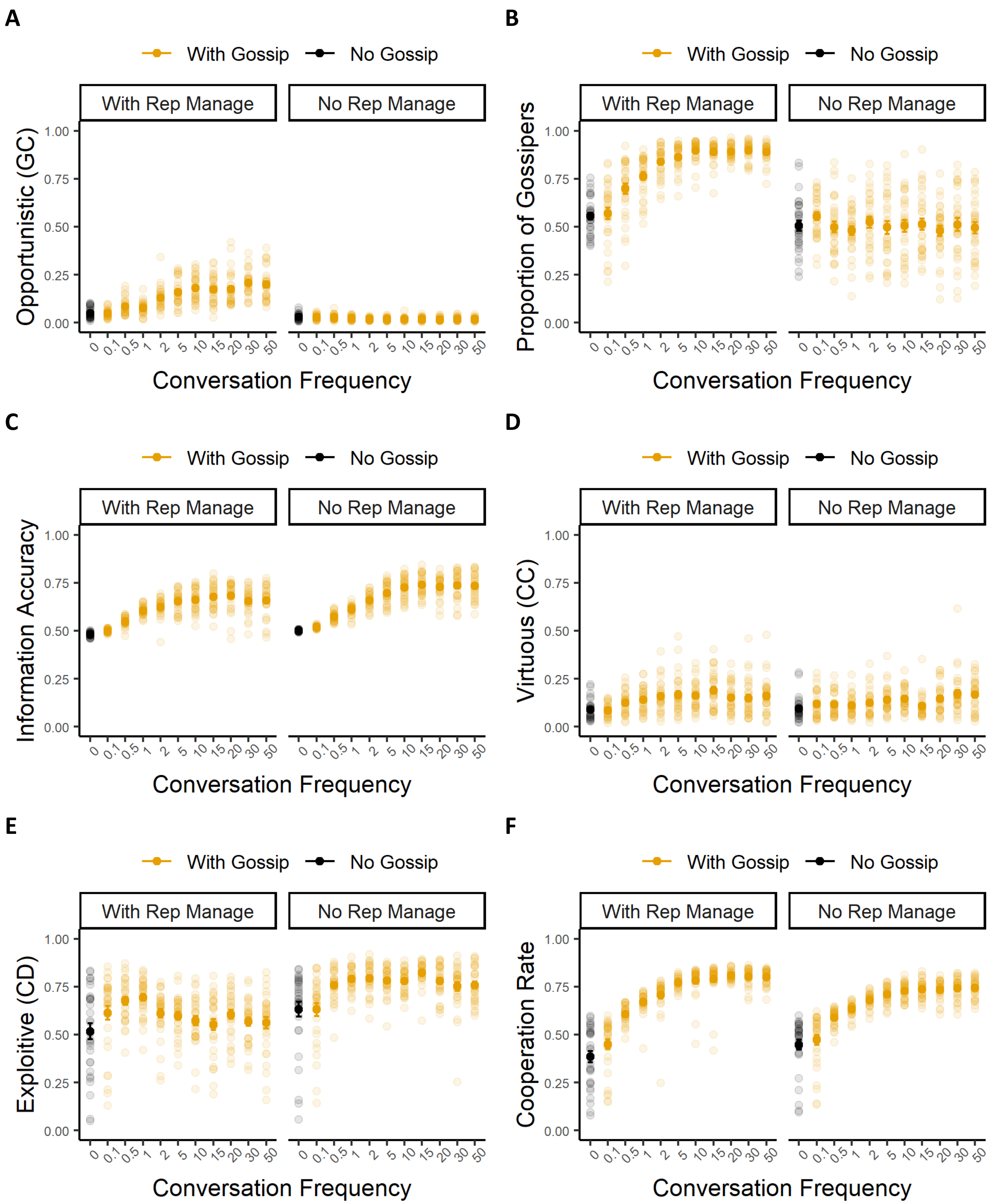


Fig. S22. Effects of conversation frequency in Step 2.

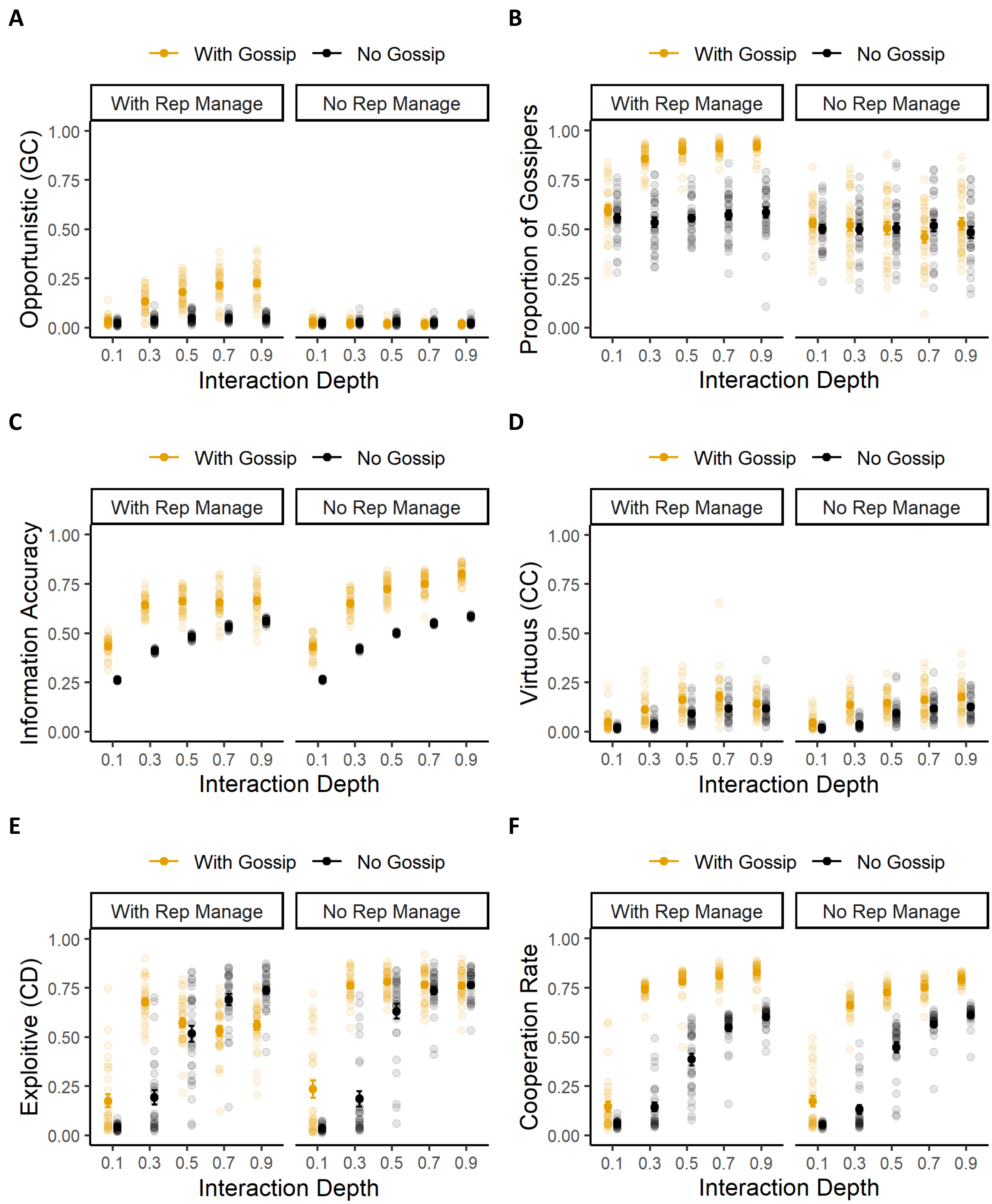


Fig. S23. Effects of interaction depth in Step 2.

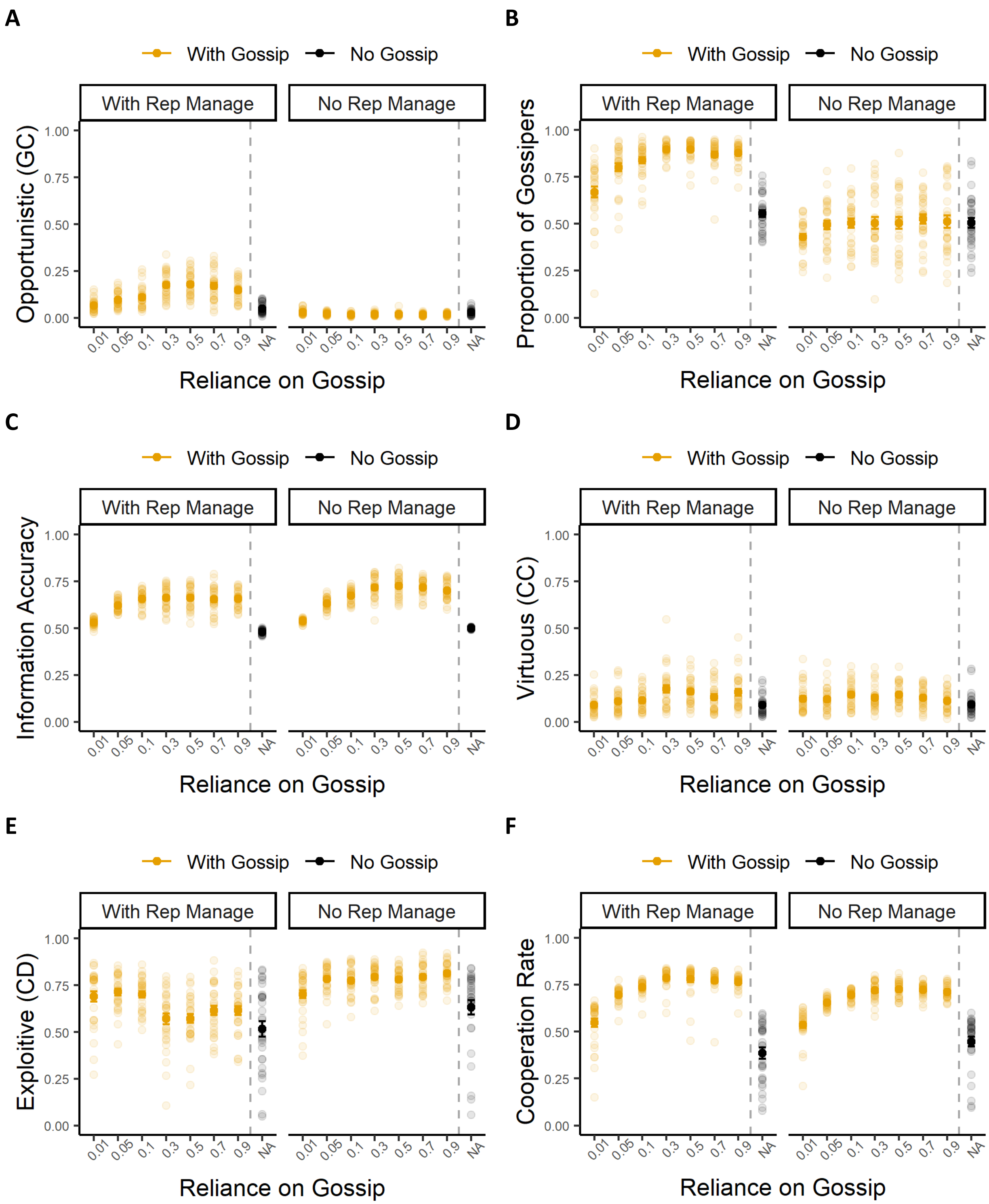


Fig. S24. Effects of general trust of gossip in Step 2. There are 30 simulations in each condition, except for the *indirW* = 0.1 in the with-rep-manage condition, in which there are only 29 simulations due to a computer error.

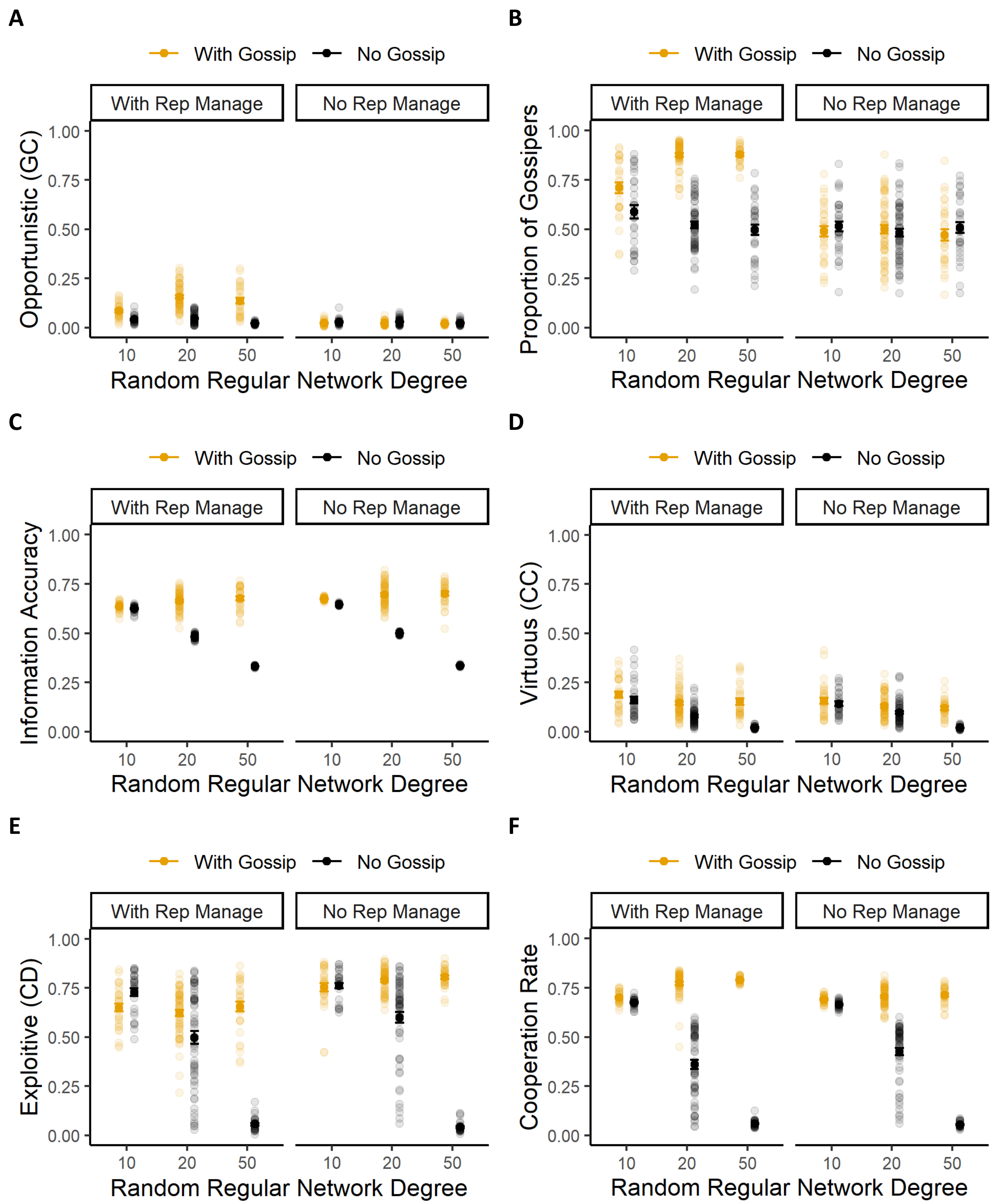


Fig. S25. Effects of network structures in Step 2. All the results in this figure are drawn from populations embedded in random regular networks with different levels of average degree (*d*). There are 30 simulations in each condition, except for the *d* = 50 in the with-rep-manage and with-gossip condition, where there are only 29 simulations due to a computer error.

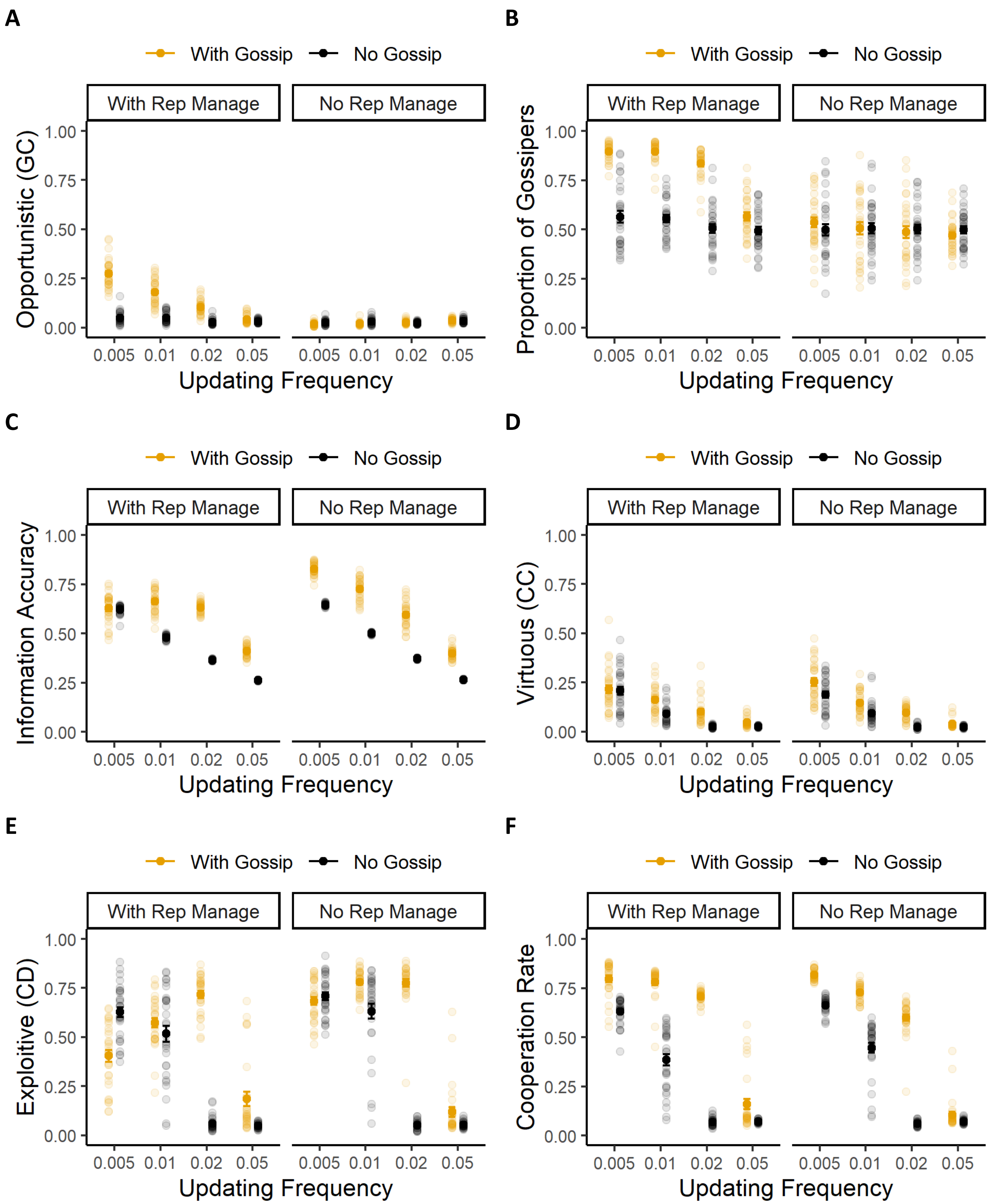


Fig. S26. Effects of strategy updating frequency in Step 2.

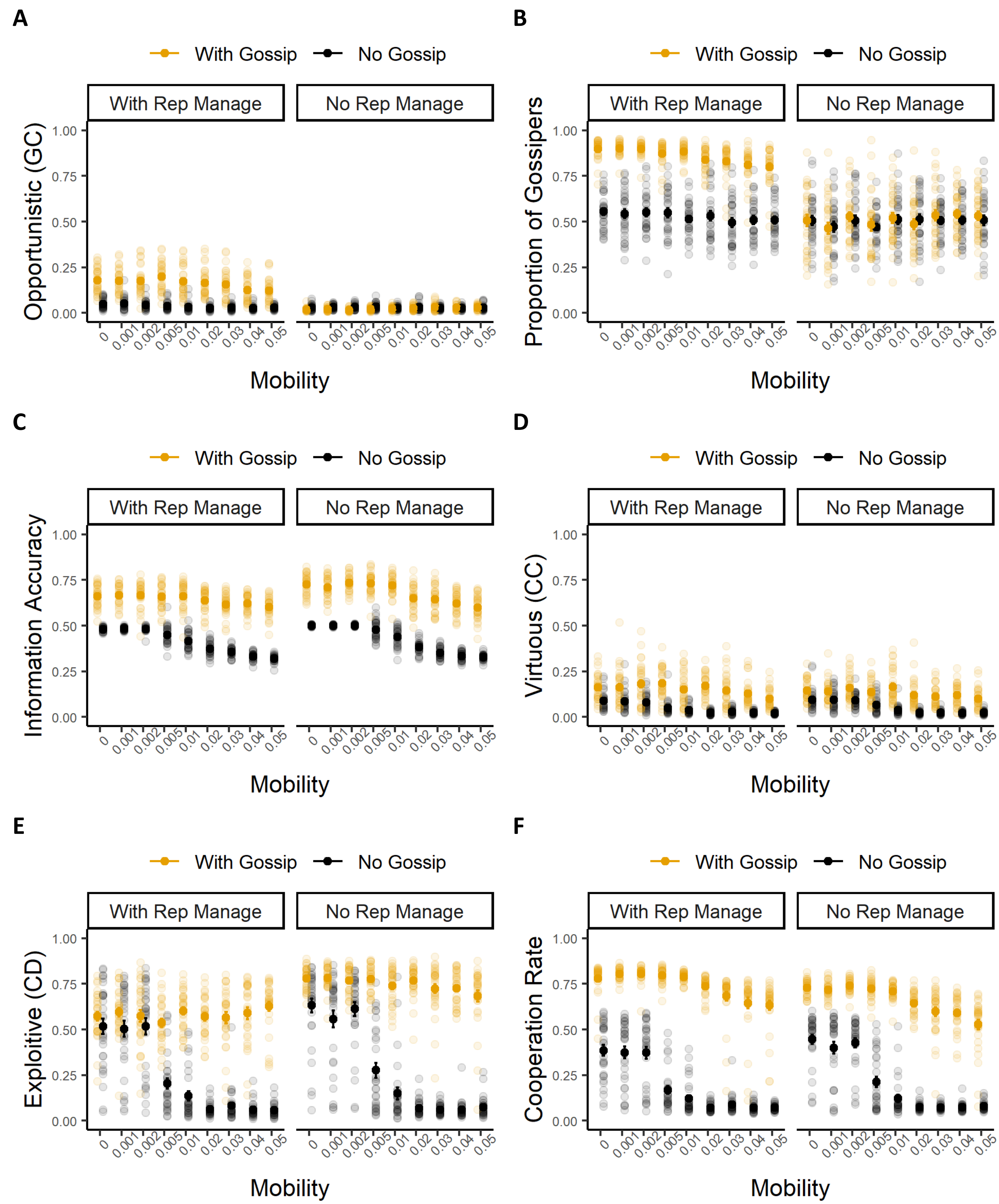


Fig. S27. Effects of network mobility in Step 2.

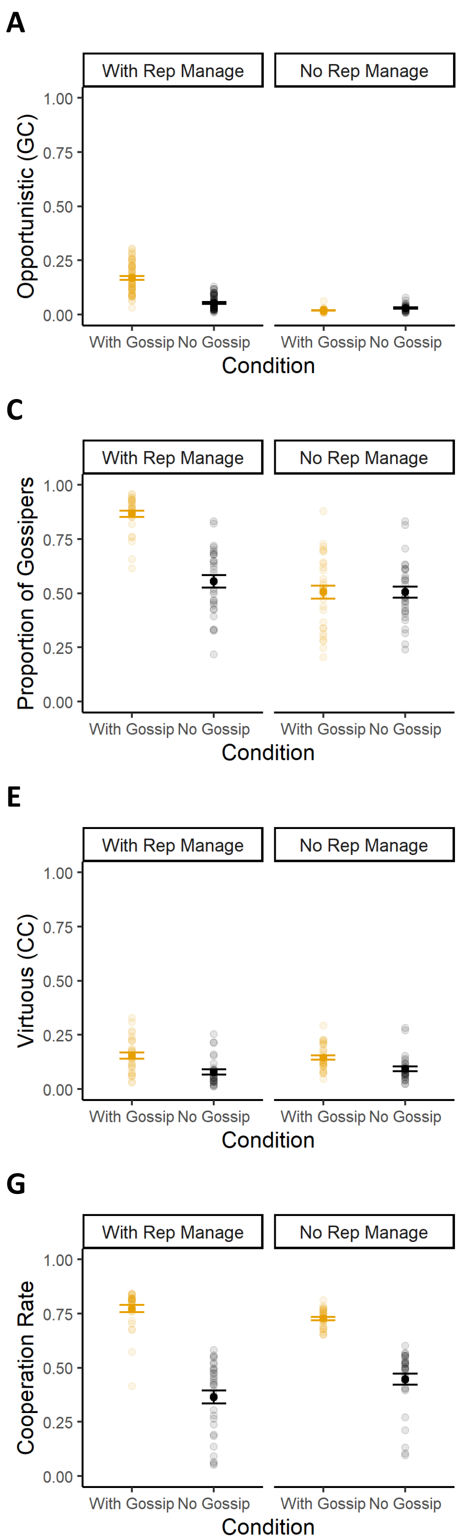


Fig. S28. Results when reverse-opportunists present to non-gossipers that they are virtuous but present their real strategy to gossipers.

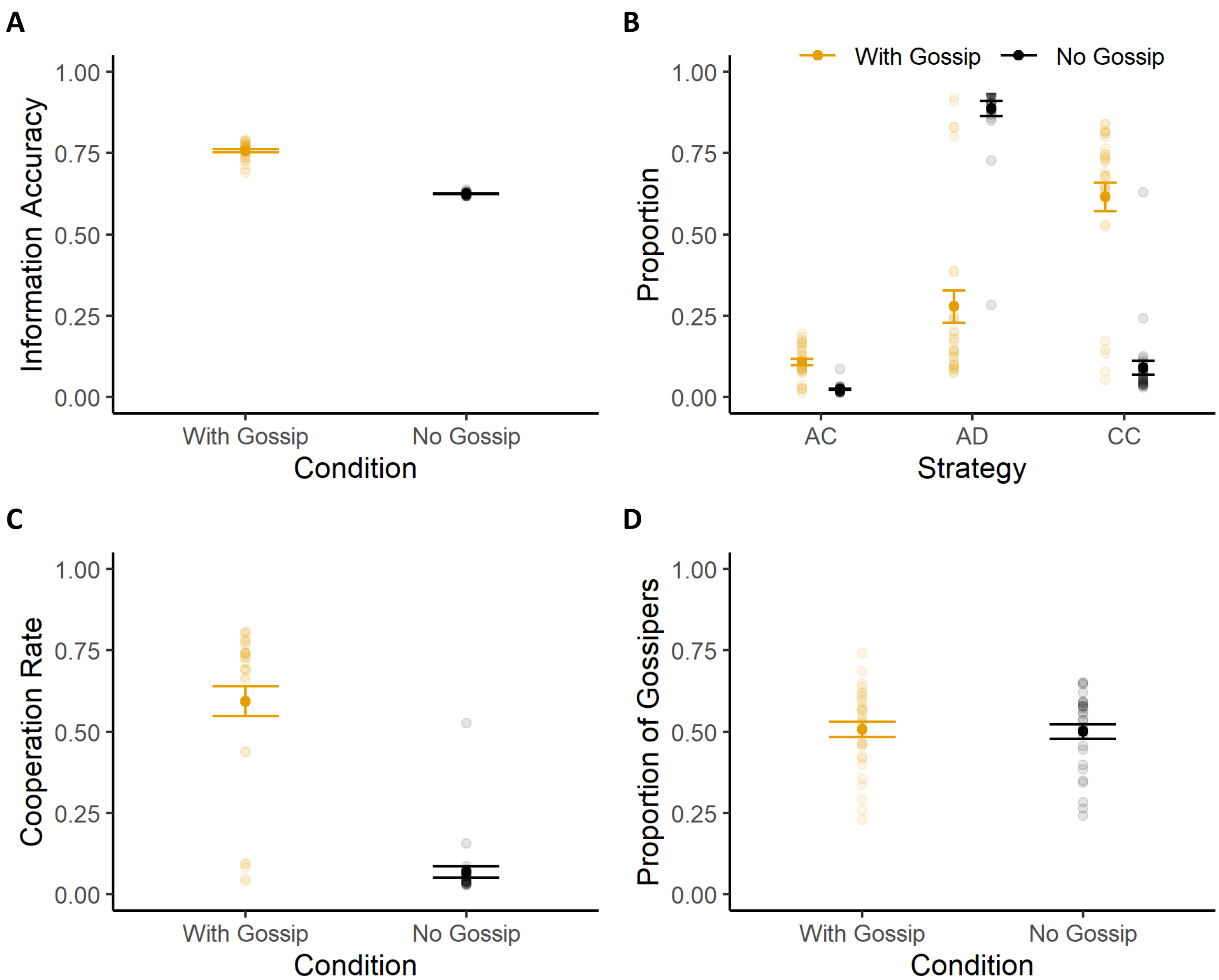


Fig. S29. Results without exploitive agents in Step 1.

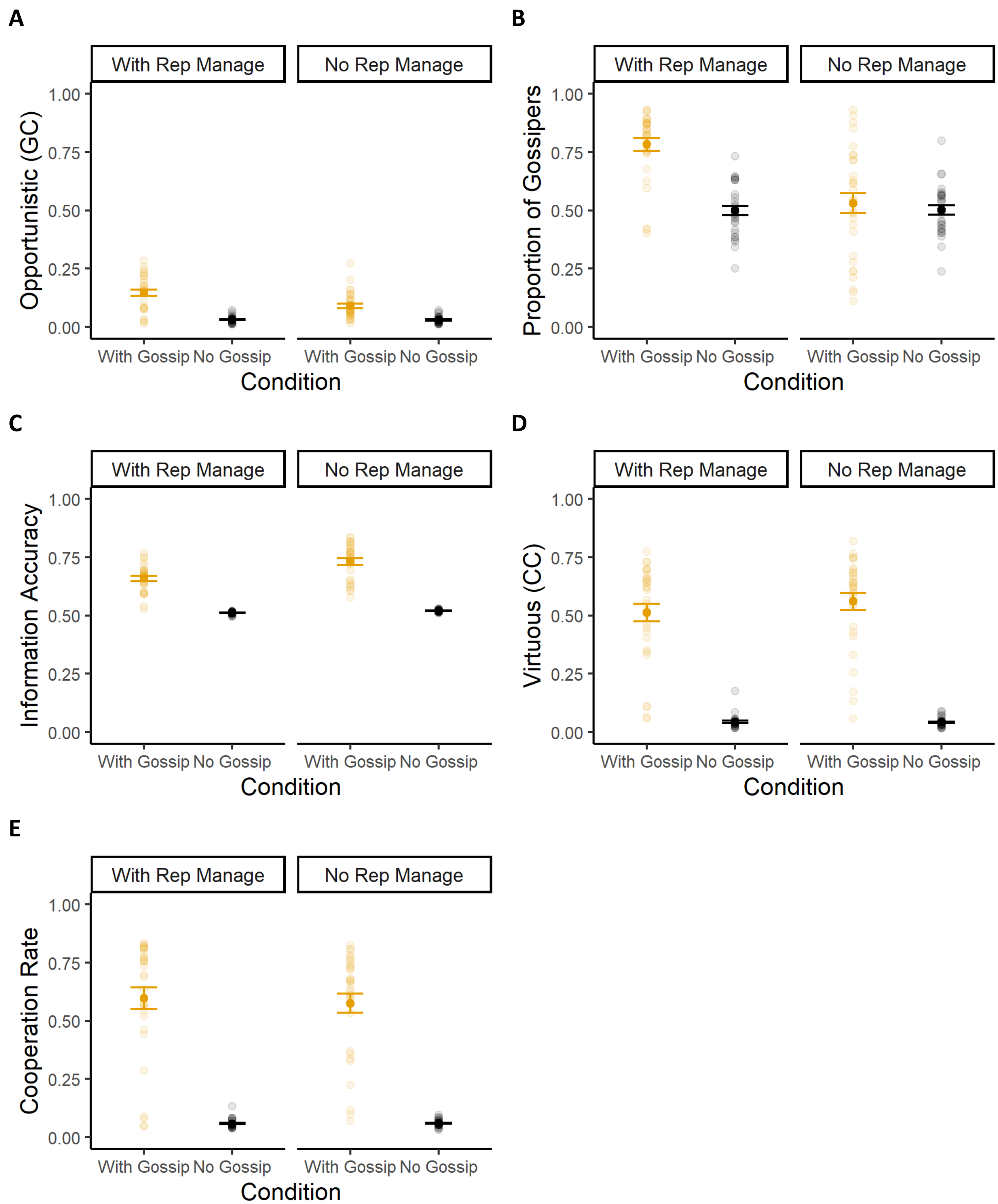


Fig. S30. Results without exploitive agents in Step 2.

5 Supplementary Tables

Table S1. Cooperation behavior when different strategies encounter each other. In the four-letter strategy codes, the first two digits represent one's cooperation strategy and the last two digits represent one's gossiping strategy. Rows represent the decision-maker's strategy; columns represent the decision-maker's hypothesized strategy of the partner. In the matrix, "C" represents "to cooperate" and "D" represents "to defect." Unconditional cooperators (AC) always cooperate. Unconditional defectors (AD) always defect. Virtuous agents (CC) only defect when they believe that their partner will defect. Thus, CC will defect with AD. If the CC is a gossiper (AG), they will also defect with reverse-opportunists (GD) because GDs defect with gossipers. However, if the CC is a non-gossiper (AN), they will defect with opportunists (GC) because GCs defect with non-gossipers. Exploitive agents (CD) only cooperate with reputation sensitive agents. Thus, a CD will only cooperate with CCs or CDs. A GC cooperates only with AGs and a GD cooperates only with ANs.

Decision-maker \ Hypothesized strategy of the partner	ACAG	ADAG	CCAG	CDAG	GCAG	GDAG	ACAN	ADAN	CCAN	CDAN	GCAN	GDAN
ACAG	C	C	C	C	C	C	C	C	C	C	C	C
ADAG	D	D	D	D	D	D	D	D	D	D	D	D
CCAG	C	D	C	C	C	D	C	D	C	C	C	D
CDAG	D	D	C	C	D	D	D	D	C	C	D	D
GCAG	C	C	C	C	C	C	D	D	D	D	D	D
GDAG	D	D	D	D	D	D	C	C	C	C	C	C
ACAN	C	C	C	C	C	C	C	C	C	C	C	C
ADAN	D	D	D	D	D	D	D	D	D	D	D	D
CCAN	C	D	C	C	D	C	C	D	C	C	D	C
CDAN	D	D	C	C	D	D	D	D	C	C	D	D
GCAN	C	C	C	C	C	C	D	D	D	D	D	D
GDAN	D	D	D	D	D	D	C	C	C	C	C	C

Table S2. The payoff matrix of a pairwise cooperation game. If an agent chooses to cooperate, the agent pays a cost, *c*, for their interaction partner to receive a larger benefit, *b*. If the agent chooses to defect, they pay no cost and their partner receives nothing from this decision. Thus, if both players make such decisions simultaneously, the pairwise payoff matrix will be as below.

		Player *Y*'s decision	
		Cooperate	Defect
Player *X*'s decision	Cooperate	*X*: *b* - *c*, *Y*: *b* - *c*	*X*: -*c*, *Y*: *b*
	Defect	*X*: *b*, *Y*: -*c*	*X*: 0, *Y*: 0

Table S3. Model parameters.

Parameter	Description	Default value
c	Cost of cooperation	1
b	Benefit of cooperation	3
dirW	Interaction depth, amount of information gained from a single direct interaction	0.5
targetN	Number of targets in a gossip conversation	2
gCost	Cost of a single piece of gossip	0
bias	Bias toward more confident gossip	5
indirW	General trust of gossip, the extent to which agents' beliefs of others are influenced by gossip	0.5
N	Number of agents	200
swK	Average degree of the small world network	20
swP	Probability of rewiring each edge when generating the small world network	0.5
m	Mobility	0
cutP	Percentage of connections that one cuts when moving	90%
buildP	Percentage of connections of the contact person that one builds when relocating	90%
intF	Frequency of direct interactions	0.1
talkF	Frequency of conversations	10
updF	Frequency of strategy updating	0.01
s	Selection strength in Fermi rule	5
μ	Mutation rate in strategy updating	0.05
iterN	Number of iterations	5000

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