ABSTRACT

Title of Thesis:	THE ROLE OF GOSSIP IN THE EVOLUTION OF COOPERATION
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The prevalence of cooperation in human societies is astonishing. Scholars from many disciplines have been sought to understand why it evolves. Some studies have indicated that gossip may play an important role in the evolution of cooperation. However, there has yet to be a systematic attempt to test this hypothesis directly. In this thesis, I developed an evolutionary game theoretic model and examined the role of gossip in the evolution of cooperation as well as the mechanism of the evolution of gossipers. I found that gossip increases reputation accessibility and makes the utilization of reputation information effective and necessary. The utilization of reputation information not only leads to more cooperation but also motivates individuals to manage their reputation by cooperating more with gossipers. As a result, gossipers gain an advantage over non-gossipers, and this leads to the evolution of gossipers. I also examined the factors that moderate these results.

THE ROLE OF GOSSIP IN THE EVOLUTION OF COOPERATION

by

Xinyue Pan

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Chapter 1: Introduction

1.1 Overview

Cooperation occurs when an individual carries out an action that is costly to perform, but benefits other individuals (West et al., 2007). The prevalence of cooperation in human societies is astonishing (Fehr & Fischbacher, 2003; Sachs et al., 2004), and scholars from many disciplines have been sought to understand the puzzle of why it evolves (Axelrod & Hamilton, 1981; Hamilton, 1964; Nowak, 2006; Sachs et al., 2004; West et al., 2007). Some studies have indicated that gossip may play an important role in the evolution of cooperation (Dunbar, 1997; 2004; Enquist & Leimar, 1993; Foster, 2004; Piazza & Bering, 2007; Wu et al., 2016). However, there has yet to be a systematic attempt to test this hypothesis directly. In this thesis, I developed an agent-based model to explore the role of gossip in the evolution of cooperation as well as how gossiping behavior and cooperation co-evolve in the population.

In what follows, I first review previous work on the mechanisms for the evolution of cooperation. I focused on the indirect reciprocity mechanism, which depends greatly on the establishment and use of reputation (Nowak, 2006; Nowak & Sigmund, 1998b). Next, I discuss previous work on the role of gossip in cooperation. Particularly, I focus on two of the functions of gossip that are important for indirect reciprocity—1) the information function of gossip, in which gossip promotes the spread of reputation information, and 2) the influence function of gossip, in which people behave more altruistically under the threat of gossip (Foster, 2004). The limitations of previous empirical and modeling work on these two topics are also discussed. To fulfill the gaps, I then present an agent-based model with an evolutionary game theoretic framework. I examine how the existence of gossip promotes the evolution of cooperation through the two functions. Moreover, I show how gossipers co-evolve with cooperation as a result of the two functions. Finally, I discuss the contributions, limitations and future directions for this thesis.

1.2 The Evolution of Cooperation

From hunter-gatherers to modern societies, human societies are characterized with mass cooperation (Fehr & Fischbacher, 2003; Sachs et al., 2004). Cooperation occurs when an individual carries out a behavior that is costly to perform, but benefits other individuals (West et al., 2007). Since cooperation is not the "rational" behavior for interest pursuers (Amadae, 2015), researchers have long been interested in understanding why cooperation evolves in human societies (Axelrod & Hamilton, 1981; Hamilton, 1964; Nowak, 2006; Sachs et al., 2004; West et al., 2006).

Several mechanisms were identified for the evolution of cooperation (Nowak, 2006), among which a well-studied one is *indirect reciprocity* (Fu et al., 2008; Nowak & Sigmund, 1998b; Swakman et al., 2015). Indirect reciprocity is the mechanism in which one gains reputation from altruistic behaviors, which will get rewarded by receiving help from others in the future (Nowak & Sigmund, 1998b). As Nowak (2006) wrote, "helping someone establishes a good reputation, which will be rewarded by others; when deciding how to act, we take into account the possible consequences for our reputation" (p. 1561).

Much work, both empirically and theoretically, has been done on how reputation information influences cooperation. Behavioral studies have found that people actively seek reputation information and use the information to guide their cooperative decisions (Seinen & Schram, 2001; Swakman et al., 2015). Likewise, evolutionary models showed that with the help of reputation, individuals can initialize cooperation even in a society with many unconditional defectors. In the meantime, individuals also evolve to behave discriminatively toward others with good vs. bad reputations (Nowak & Sigmund, 1998a). Recent research has extended these findings by introducing more complex behaviors (e.g., enabling players to shift interaction partners; Fu et al., 2008), applying higher-order social norms (e.g., labeling people as good or bad according to different standards; Santos et al., 2018), and involving rewards and punishments (Hauert, 2010). Altogether, these studies showed that reputation is essential for the evolution of cooperation and individuals actively seek and utilize reputation information to guide their cooperation decisions.

1.3 The Functions of Gossip in Cooperation

Reputation information is managed in the population largely through a social behavior—gossip (Dunbar, 1997; 2004). Gossip has a variety of definitions across disciplines. In this thesis, I define it as the exchange of personal information given in an evaluative way about absent third parties (Foster, 2004). Gossip serves many social functions, such as entertaining, facilitating friendship and social networks, etc. (Foster, 2004; Shaw et al., 2011). However, the key roles that gossip plays in the reputation system is through two pathways: the information function and the influence function, as elaborated below (Foster, 2004; Paine, 1967).

The *information function* emphasizes the role of gossip as an efficient and, at times, exclusive means of gathering or disseminating social information. Through gossip, people share information about each other's cooperation reputation so that people can use this information to guide their decisions in social interactions. The content of gossip is admittedly not exclusively about reputation, but as an evaluative talk regarding a third party, especially when direct interaction and/or observation are not always viable, gossip increases the accessibility of each other's reputation. According to Nowak (2006), indirect reciprocity through reputation can only promote cooperation when the reputation information is prevalent enough. This indicates that gossip, by making reputation information more prevalent, can benefit the evolution of cooperation through indirect reciprocity.

The *influence function* describes the role that gossip plays in motivating people to alter their behavior in order to manage their reputation. When people feel that their behavior can be potentially gossiped with identifiable information, reputational concerns motivate them to behave in a more cooperative way (Piazza & Bering, 2008; Wu et al., 2019).

Numerous empirical studies have examined the two functions of gossip. With respect to the information function, in Sommerfeld et al. (2007), participants played a cooperation game and were allowed to send short sentences about others (i.e., gossip) to each other. Results showed that gossip transmitted reputation information successfully and people cooperated more with positively reputed others. With respect to the influence function, Piazza and Bering (2008) found that participants who were told that their behavior would be disclosed to a third party were more cooperative than participants who did not face the threat of gossip. Feinberg et al. (2012) did four behavioral studies and found that people were willing to gossip prosocially even at some personal cost. Moreover, those who were low on prosociality at ordinary times behaved more altruistically when their reputation mattered. For general effects of gossip, Wu et al. (2016) found that the option to gossip increased cooperation in the group. More importantly, the initial option to gossip made people more trusting and trustworthy in the subsequent game even when gossip was no longer possible.

1.4 Limitations of Previous Research

Though these experiments have important theoretical implications, they face some challenges and limitations. First, to understand the evolution of cooperation on the population level, it is difficult to recruit a large network of population and let them interact in real time. Experiments based on small groups, however, may fail to capture some important characteristics of the population, such as network structures and mobility.

Second, though these laboratory studies are usually successful in manipulating whether people gossip and how much they gossip, there are some variables that are difficult to directly manipulate on human participants, such as how much people trust a piece of gossip, how much they are influenced by gossip, etc. Thus, it is difficult to examine how the aforementioned factors moderate the role of gossip in cooperation.

Finally, and most importantly, though empirical studies can capture the current norms and values in human societies, they don't explain why gossiping behavior and reputation concerns evolved in the first place. Though gossip can bring information to and thus promote cooperation in the population, from an individual's perspective, gossiping is not entirely uncostly. It remains unknown, from an evolutionary perspective, why gossiping behavior is adaptive. Moreover, the evolution of reputation concerns under the threat of gossip is also a puzzle. Cooperating is costly and, at times, exposes oneself under the risk of being exploited by free-riders. Why are people motivated to leave a good reputation in gossip even at the risk of losing the present benefit? Furthermore, if gossip cannot transmit reputation information effectively, will people still behave cooperatively under the threat of gossip?

Given the limitations of empirical studies, a complementary method is computational modeling. Indeed, computational models have been widely used to study the mechanisms of the evolution of cooperation (Nowak, 2006; 2012), including the role of reputation in indirect reciprocity (e.g., Mohtashemi & Mui, 2003; Nowak & Sigmund, 1998a; Ohtsuki et al., 2015; see Giardini & Wittek, 2019, for a recent review). For example, in the seminal work of Nowak and Sigmund (1998a), a model was built in which individuals gained "image scores" (i.e., positivity of reputation) by cooperating with others. Individuals could choose from three strategies: 1) "unconditional cooperators" who always cooperate, 2) "unconditional defectors" who never cooperate, and 3) "discriminators" who cooperate only when the interaction partner's "image score" is high enough. They let virtual individuals with different strategies interact with each other and gain payoffs from the interactions. Individuals with higher payoffs reproduced more and individuals with lower payoffs were crowed out. Simulation results showed that a substantial proportion of individuals evolved to be "discriminators" and the existence of the reputation system could initialize cooperation even in a society with many defectors. Another model extended this model and examined the role of reputation in public vs.

private interactions (Ohtsuki et al., 2015). Specifically, they examined the evolution of "honest" individuals who cooperate both in public and in private and the evolution of "hypocritical" individuals who cooperate only in public, when many others are watching. By letting individuals with different strategies interact and compete through an evolutionary process, they found that cooperating in private interactions was suppressed if the observability was low *and* if private interactions were rare. The result indicated that the potential for one's reputation to be known to public influences people's cooperation decisions.

Though these models have showed the importance of reputation in the evolution of cooperation, they did not examine the role of gossip *directly*. In fact, fewer models have directly incorporated the process of gossiping. One of the exceptions is Enquist and Leimar (1993). They set up a model where individuals select partners based on reputation information. Reputation information is exchanged through gossip when individuals meet. Through a mathematical model with a term which represented the spread of gossip, they found that gossip promoted cooperation. There are also some agent-based models on the effects of gossip. One of the advantages of agent-based models is that they can implement the interactions between specific gossipers, listeners, and/or targets, instead of having to implement the global effects of gossip on the population level as in mathematical models. This is particularly helpful for simulating the spread of gossip in a social network and/or controlling the content of gossip. For example, Giardini and Vilone (2016) built an agent-based model where individuals play public goods games in groups. Groups selected new members based on the candidates' reputation. Reputation is updated based on both direct observation and gossip. They found that when the quantity of gossip was large enough, gossip supported cooperation (see Giardini et al., 2014, for a similar model).

All the models above showed how gossip increases the accessibility of reputation and thus promotes the evolution of cooperation—the information function of gossip. However, to my knowledge, there is not yet a computational model that has examined the influence function of gossip. One of the most relevant models is Ohtsuki et al. (2015), which indicated that people may evolve to cooperate only in public but not in private under certain circumstances, depending on how likely their reputation in private will be known by others. This suggests that the potential to gossip may motivate people to cooperate more in private. However, the model of Ohtsuki et al. (2015) did not incorporate the process of gossiping directly, leaving this inference untested.

Moreover, none of these models examined the evolution of gossipers. Even given the information and influence functions of gossip, it remains unclear why gossipers evolved in the first place. First of all, to gossip is to voluntarily share one's information resource with others. Though gossiping may be beneficial for the group, individuals still face the temptation to keep the information to themselves, so that they can maintain an "information advantage" over others. Moreover, gossiping is not necessarily uncostly. Like other prosocial behaviors, it is a puzzle why one is willing to share information with others even at a cost. Furthermore, it remains unclear whether the evolution of gossipers is a consequence of its information and/or influence functions in cooperation, i.e., how gossip and cooperation co-evolve.

1.5 Goals of This Thesis

To fulfill these gaps, this thesis implemented an agent-based model based on an evolutionary game theoretic (EGT) framework. Evolutionary game theory integrates theories from evolutionary biology and game theory (Hofbauer & Sigmund, 2003). As elaborated in the Method section, the logic of an EGT model is to put virtual individuals with different behavioral preferences in a certain context and let them interact. As in the natural selection in biology, individuals who perform well are more likely to survive and reproduce while individuals who do not perform well are likely to be wiped out. Overtime, an EGT model shows how adaptive the behaviors are in a certain context (Pan et al., in press). EGT models are particularly helpful for studying the emergence of behaviors from an evolutionary perspective and have been widely used to study the evolution of cooperation (Axelrod & Hamilton, 1981; Nowak, 2006), warfare (Choi and Bowles, 2007), cultural tightness (Roos et al., 2015), honor culture (Nowak et al., 2016), etc.

In this thesis, I simulated a population where individuals interact with each other and decide whether to cooperate. Individuals can also talk to each other and share their beliefs of others' reputation if they are gossipers. In the population, each individual's trait consists of two dimensions—a gossiping trait and a cooperation trait. For the gossiping part, they can either be a gossiper or a non-gossiper. For the cooperation part, there are three kinds of individuals: 1) individuals unaffected by gossip as their cooperation behaviors are insensitive to reputation information (i.e., unconditional individuals), 2) individuals susceptible to the information function of gossip as their cooperation behaviors are conditional on the interaction partner's reputation (i.e., reputation sensitive individuals), and 3) individuals susceptible to the influence function of gossip as their cooperation behaviors are conditional on whether there is a threat of gossip (i.e., gossiper sensitive individuals). By implementing all the possible combinations of these traits to the individuals, I observed the evolutionary trajectory of different behaviors and, thus, examined which behaviors are evolutionarily adaptive. Specifically, this thesis was aimed to achieve the following goals:

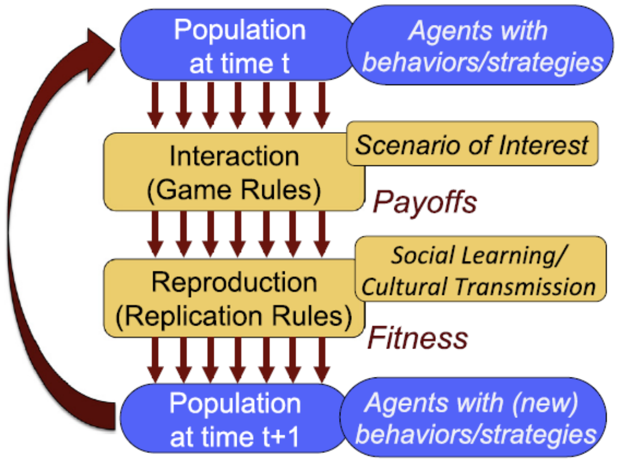
1. To build an integrated agent-based model which incorporates the processes of gossip spread, incorporates both the information and the influence functions of gossip, and is able to study the evolution of gossipers as well as the co-evolution of gossipers and cooperation;
2. To replicate the information function of gossip with this new model; specifically, to test whether a substantial proportion of individuals evolve to be reputation sensitive, whether increased accessibility of reputation information promotes cooperation, as well as whether gossiping boosts reputation accessibility, and thus benefits cooperation;
3. To test the influence function of gossip; specifically, to test whether a substantial proportion of individuals evolve to be gossiper sensitive and cooperate under the threat of gossip;
4. To study the mechanisms of the evolution of gossipers; specifically, to examine under what conditions gossipers evolve;
5. To build a new framework of how gossipers and cooperation co-evolve, through the information and influence functions of gossip.

Chapter 2: Methods

2.1 Introduction to EGT Framework

An agent-based EGT model was used for this thesis. In a typical agent-based EGT model, there is a population of virtual individuals embedded in a social network, each of which has a strategy. Based on their strategies, individuals interact with their neighbors in the network, gain the interaction consequences, and each gets a payoff, which represents their evolutionary fitness—the extent to which an individual and their strategy can successfully reproduce (Sigmund & Nowak, 1999). In the context of human behavior, reproduction may be interpreted as the processes of cultural transmission, either within or across generations (Cavalli-Sforza & Feldman, 1981; Harley, 1981). As with selection in biological evolution, strategies related to higher fitness are more likely to be reproduced. Accordingly, the proportions of the high-fitness strategies increase while the proportions of the low-fitness strategies decrease across time. Thus, by allowing agents to interact and update their strategies repeatedly, an EGT model can show the change of the proportions of different strategies overtime and examine the evolution of various behaviors (see Figure 1).

Figure 1 EGT Framework for Studying the Evolution of Behaviors



Note. From "Societal Threat and Cultural Variation in the Strength of Social Norms: An Evolutionary Basis," by P. Roos, M. Gelfand, D. Nau, and J. Lun, 2015, *Organizational Behavior and Human Decision*, *129*, p. 15. Copyright 2015 by Elsevier Inc.

2.2 Agents' Strategies

In my model, each agent's strategy consists of two parts—a gossiping strategy and a cooperation strategy. There are two possible *gossiping strategies*: *gossipers* (AG) who always gossip in a conversation and *non-gossipers* (AN) who never gossip. Agents' gossiping strategies are transparent—every agent knows whether everyone else is a gossiper or non-gossiper.

An agent's *cooperation strategy* decides under what circumstances they cooperate in the interactions. There are six possible cooperation strategies, which can be defined into three categories. The first category is *unconditional* strategies. Agents with unconditional strategies conduct the same behavior to everyone. There are two strategies in this category: *unconditional cooperators* (AC) who always cooperate and *unconditional defectors* (AD) who always defect. AC and AD are the most basic strategies that have been widely used in models of cooperation (e.g., Axelrod & Hamilton, 1981). The second category is *reputation sensitive* strategies. Agents of this category take their interaction partners' cooperation reputation into consideration and make cooperation decisions accordingly. There are two strategies in this category: *Virtuous* agents (CC) use the reputation information to protect themselves from defectors. They only defect when they believe that their interaction partner will defect with them. *Exploitive* agents (CD), however, use the reputation information to exploit others. They only cooperate when they believe that their interaction partner is a reputation sensitive agent. Otherwise, they will defect and exploit their interaction partner. The implementation of these two strategies was inspired by the reputation sensitive strategies in previous models (e.g., Nowak & Sigmund, 1998a). The last category is *gossiper sensitive* strategies. Agents with these strategies are concerned about their reputation in gossip. Thus, they will behave differently when interacting with gossipers vs. non-gossipers. There are also two strategies in this category: *Hypocritical* agents (GC) defect with non-gossipers but cooperate with gossipers and thus will leave a good reputation in gossip. *Reverse-hypocritical* agents (GD), however, cooperate with non-gossipers but defect with gossipers and thus intentionally ruin their own reputations in gossip. The two gossiper sensitive strategies were implemented to enable the influence function of gossip. Note that GD should be unusual in real life, but I added it to make the model "neutral." That way, the model was not set-up to benefit gossipers. Agents' cooperation strategies are not transparent to everyone. An agent may learn about another agent's cooperation strategy through direct interactions or gossip, as elaborate below. A summary of the strategies can be found in Table 1. An agent may have any combinations of a gossiping and a cooperation strategy. Thus, there are 2 * 6 = 12 possible combinations in total.

Table 1 Summary of Gossiping and Cooperation Strategies

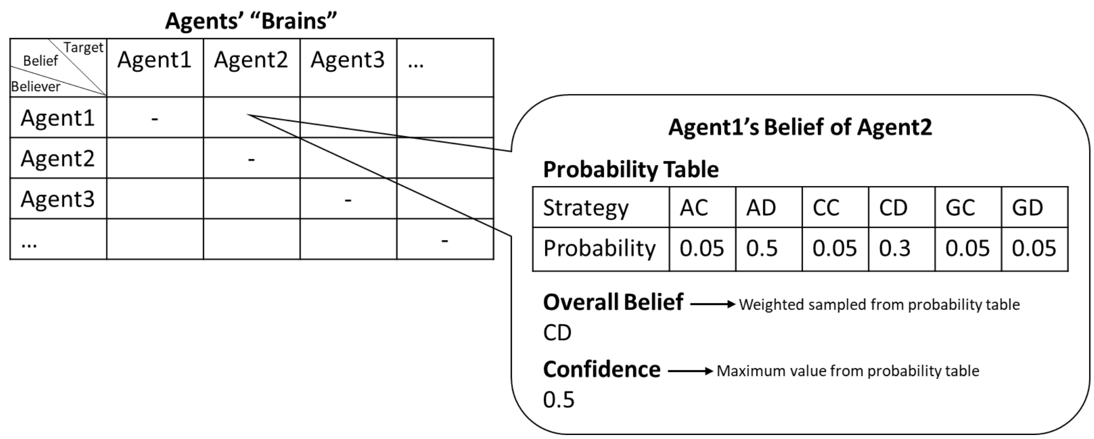
Strategy	Description
Gossip strategy	
Gossiper (AG)	Always gossip
Non-gossiper (AN)	Never gossip
Cooperation strategy	
Unconditional	
Unconditional cooperator (AC)	Always cooperate
Unconditional defector (AD)	Always defect
Reputation sensitive	
Virtuous (CC)	Only defect when believing the partner will defect, otherwise cooperate
Exploitive (CD)	Only cooperate when believing the partner is reputation sensitive, otherwise defect
Gossiper sensitive	
Hypocritical (GC)	Cooperate only to gossipers
Reverse-hypocritical (GD)	Defect only to gossipers

2.3 Agents' "Brains"

In addition to strategies, each agent also has a "brain" that stores their belief about every other agent's strategy. This set-up differs from previous studies that treated reputation as a "rating" which is pubic for everyone (Nowak & Sigmund, 1998a; Santos et al., 2018). Instead, this model assumes that reputation is stored in individuals' minds. Everyone has a unique belief of everyone else's strategy based on their previous interactions with the target and/or what they have heard about the target. An agent's belief of each other agent's strategy can be represented by a *probability table* as shown in Figure 2. The probability table shows the probability of the target being of each cooperation strategy, in the believer's mind. This is consistent with the theory of naive probability in psychology in which people construct mental models of what is true in the various possibilities (Johnson-Laird et al., 1999).

The believer also has an *overall belief* of the target, which is weighted sampled from the probability table. In addition, the believer has a *confidence level* of their belief, which is the maximum value in the probability table. The awareness of one's confidence is consistent with the psychological theory of metacognition (Dunlosky & Metcalfe, 2008). When the believer interacts with the target, the believer treats the target as if the target is of the believed strategy. If the believer gossips, the believer tells others that the target is of their believed type as well as the confidence level related to that belief. When an agent has no information about another agent (i.e., when an agent has not interacted with or heard of another agent yet), the probability table is a flat distribution where the probability of being any type is equal to chance (i.e., 1 divided by the total number of possible strategies) and the overall belief is randomly selected from all the possible types. However, the distribution will become uneven as agents directly interact and/or hear about each other through gossip, which will be elaborated below.

Figure 2 Agents' "Brains"



Notes. Each agent has a belief of every other agent's strategy. The belief is represented by a probability table. In this example, Agent1 believes that Agent2 has a probability of 0.05 to be an unconditional cooperator (AC), a probability of 0.5 to be an unconditional defector (AD), etc. Agent1 also has an overall belief of Agent2, which is weighted sampled from the probability table. An agent's confidence about their overall belief is the maximum value in the probability table. In this example, a virtuous (CD) is sampled as the overall belief. The confidence of this belief is 0.5. Agent1 will treat Agent2 as an CD when they interact in a cooperation game. If Agent1 gossips, Agent1 will tell others that Agent2 is an CD with a confidence of 0.5.

2.4 Cooperation Phase

2.4.1 Gain Payoffs

In the cooperation phase, agents play pairwise cooperation games. An agent decides whether to cooperate based on their own cooperation strategy and their overall belief of their partner's strategy, as shown in Table 2. As in Nowak (2006), if an agent chooses to cooperate, they pay a cost, c, for the partner to receive a larger benefit, b. If an agent chooses to defect, they pay no cost and the partner receives nothing. Same as Roos et al. (2015), $b = 3$ and $c = 1$. The payoff matrix for a pairwise cooperation game can be found in Table 3.

Table 2 Cooperation Behavior When Different Strategies Encounter

Decision-maker \ 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

Note. In the four-letter strategy codes, the first two digits represent one's cooperation strategy and the last two digits represent one's gossip strategy. Rows represent decision-makers' strategies; columns represent the partners' strategies in the decision-makers' overall belief. In the behavior 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-hypocritical agents (GD) because GDs defect with gossipers. However, if the CC is a non-gossiper (AN), they will defect with hypocritical agents (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.

Table 3 Payoff Matrix for a Pairwise Cooperation Game

	The action of AgentY	
	Cooperate	Defect
The action of AgentX		
Cooperate	(X: 2, Y: 2)	(X: -1, Y: 3)
Defect	(X: 3, Y: -1)	(X: 0, Y: 0)

Note. The cost of cooperation, $c = 1$, and the benefit of cooperation, $b = 3$.

2.4.2 Manifest Strategies

During the interactions, agents also manifest their cooperation strategies to their interaction partners. For unconditional cooperators (AC), unconditional defectors (AD), virtuous agents (CC), and exploitive agents (CD), they manifest their real strategies. For hypocritical agents (GC) and reverse-hypocritical agents (GD), they will behave differently in front of gossipers vs. non-gossipers and manipulate a different strategy in front of gossipers. Specifically, when they interact with a gossiper, a GC will manifest to be a CC while a GD will manifest to be an AD. GCs and GDs will manifest their real strategies in front of non-gossipers, because there is no motivation to fake without the threat of gossip. Alternative choices of what a GC manifests to be were explored in robustness tests.

If an agent X manifests a certain strategy, in their interaction partner Y's mind, the probability of X being of that strategy will be increased by *dirW* ($0 < dirW < 1$), with a maximum of 1. *dirW* indicates the amount of information that an individual gains about their partner from one direct interaction. As a consequence, the probability of other strategies will be decreased proportionally for the table to sum to 1 (see Figure 3). After changing the probability table, Y will also update their overall belief and confidence, based on the rules in Figure 2. In the default model, *dirW* was set as 0.5. Other values of *dirW* were explored in robustness tests.

Figure 3 Change of Probability Table

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

Note. The first table shows the original probability table. In the second table, the probability of AC was increased by 0.5. As a result, the probability of other strategies was decreased proportionally. The last table shows the new probability table after change.

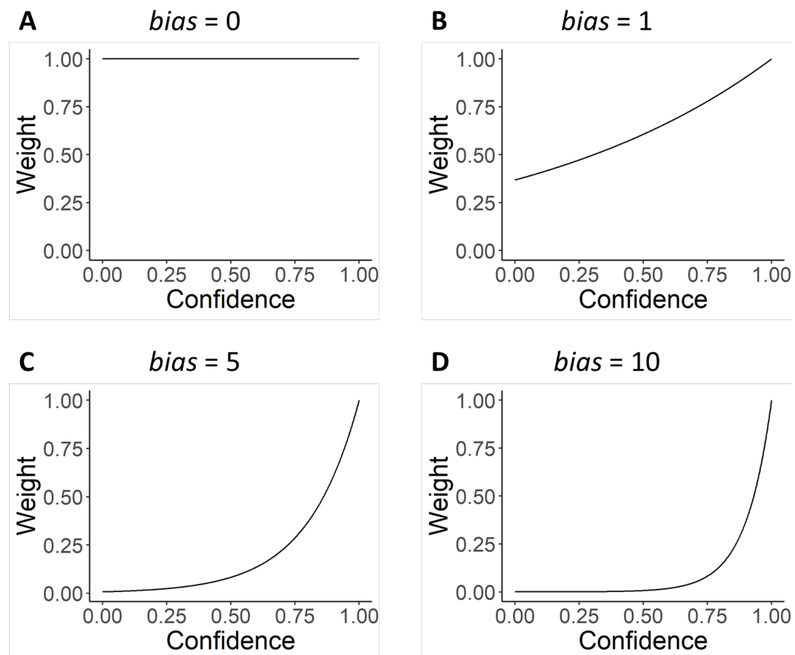
2.5 Conversation Phase

In the conversation phase, agents have pairwise conversations. In each conversation, there is a speaker and a listener. If the speaker is a gossiper (AG), the speaker will gossip to the listener regarding *targetN* = 2 targets. The targets are randomly selected from the common neighbors of the speaker and the listener. If there are 2 or less common neighbors, all the common neighbors will be selected as targets, if any. In the default model, we did not consider the cost of gossip based on the assumption that the effort spent on gossiping is neglectable compared with the effort needed for a cooperative behavior. However, in robustness tests, we explored the situations when gossip is costly. If gossip is costly, each time when an agent gossips about a target, they pay a gossip cost, *gCost*.

When X gossips to Y about Z, X tells Y about X's overall belief of Z as well as the confidence of it. Research has shown that people are biased to learn from others perceived as more confident (Birch et al., 2010; Jaswal & Malone, 2007). Thus, when Y hears about X's belief of Z, a *weight* will be given to that piece of gossip based on the confidence of X, as shown in Equation (1). The parameter *bias* ≥ 0 controls the extent to which people are biased toward more confident gossip. When *bias* = 0, the weight is always 1, in which case people value any gossip equally. As *bias* becomes larger, people give much higher weight to more confident gossip while lower weight to unconfident gossip, as shown in Figure 4. The default value of *bias* was set as 5. A sufficiently high *bias* is essential for agents to form accurate belief of each other through gossip, as elaborated in the Results section.

$$\text{weight} = e^{bias \times \text{confidence}} / e^{bias} \tag{1}$$

Figure 4 Weight of Gossip as a Function of Confidence



Next, Y updates the probability table of Z based on the gossip from X. Specifically, if X tells Y that Z has a certain strategy (i.e., X's overall belief of Z), in Y's probability table of Z, the probability of that strategy will be increased by *indirW* × weight, following the same rule as in Figure 3. The parameter $0 < indirW < 1$ controls the maximum influence of gossip. The larger *indirW* is, the more that people tend to change their belief based on what they hear from gossip. By default, *indirW* = 0.5, though other values were also explored. After changing the probability table, Y also updates their overall belief and confidence of Z as explained above.

2.6 Network Structures

2.6.1 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 (Milgram, 1967; Weeden & Cornwell, 2020). The small-world network is generalized with the algorithm in Watts and Strogatz (1998) using the "watts_strogatz_grah()" function in NetworkX in 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 (Hagberg et al., 2008). An illustration of the network structure can be found in Figure S1. Other network structures, including small world networks with different levels of connection and random networks, were also explored in robustness tests.

2.6.2 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 selected 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 will randomly select 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 builds new connections with the destiny neighborhood.

2.7 Simulation Phases

To initialize each simulation, $N = 200$ agents with random cooperation and gossiping strategies are embedded in a social network. Each agent has an evenly distributed probability table and a randomly selected overall belief for every other agent. Then the simulation repeats iterations consisting of the following three steps: 1) cooperation phase, 2) conversation phase, and 3) strategy updating phase.

2.7.1 Cooperation Phase

At the beginning of each iteration, $N \times intF$ agents are randomly selected[1] to play a cooperation game with a randomly selected neighbor. $intF$ indicates the frequency of direct interactions. The default value of $intF$ was 0.1, though other values were also explored in robustness tests. In the pairwise cooperation game, an

[1] Random sampling with replacement.

agent makes the decision based on their own strategy and their belief of the partner's strategy, as elaborated in Table 2. Within a pair, the two players make decisions simultaneously. Across pairs, the pairs engage in the games one by one. Through direct interactions, agents get payoffs as well as update their "brains" for interaction partners.

2.7.2 Conversation Phase

Next, $N \times talkF$ agents are randomly selected as speakers. *talkF* indicates the frequency of conversations. The default value of *talkF* was 10, assuming that conversations are much more frequent than direct interactions. Other values of *talkF* were also explored in robustness tests. For each selected speaker, a listener is randomly selected from their neighbors, if any. If the speaker is a gossiper (AG), the speaker gossips to the listener about $targetN = 2$ targets. As a result, the listener updates their "brain" for the two targets, as elaborated above. If the speaker is a non-gossiper (AN), no action will be conducted. The speakers are randomly selected with replacement, so it is possible that an agent speaks for more than one time in an iteration. The conversations are conducted one by one.

2.7.3 Strategy Updating Phase

$N \times updF$ agents are selected[2] as "students" who will update their strategies based on Fermi rule (Roca et al., 2009). *updF* indicates the frequency of strategy updating or the speed of evolution. $updF = 0.01$ was used by default, though other values were also explored in robustness tests. When updating their strategies, each "student" randomly selects a neighbor as their "teacher." With a probability of p, the

[2] Random sampling without replacement.

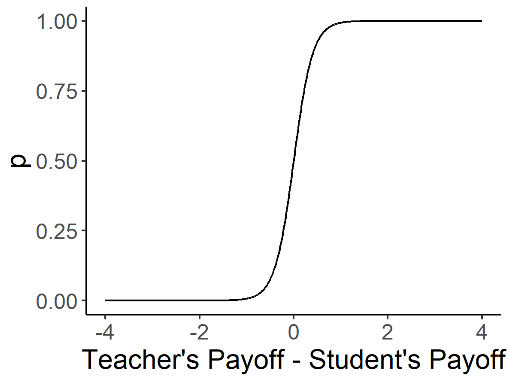
"student" will adopt both the cooperation and gossiping strategies of the "teacher." The magnitude of p is decided by the payoff of the "student," π_s, and the payoff of the "teacher," π_t, as shown in Equation (2) and Figure 5. In general, the higher payoff the "teacher" has compared to the "student," the more likely the "student" will adopt the "teacher's" strategies. The parameter *s* = 5 represents the strength of selection. One's payoff is calculated as the average payoff from all the interactions in the current iteration subtracted by the gossip cost, if any. If someone did not interact with anyone in the current iteration, the payoff from the latest iteration where there was an interaction will be used. If the "teacher" or the "student" has not been involved in any interaction throughout the simulation yet, the "student" will not update their strategy. The strategy updating process resembles how individuals with low fitness are replaced by individuals with higher fitness in the evolution.

$$p = \frac{1}{1+e^{-s\times(\pi_t-\pi_s)}} \tag{2}$$

In addition to the payoff-based strategy updating, with a probability of μ = 0.05, a "student" will randomly select a cooperation strategy and a gossiping strategy from all the possible strategies, regardless of their payoff. This resembles the random mutation in evolution.

If a "student" changes their strategy in the payoff-based updating or they are selected for random mutation, their payoff, behavior history, and "brain" will be reset to default. In addition, everyone else's probability table, overall belief, and confidence for this "student" will also be reset to default. The strategy updating happens parallelly for all the "students."

Figure 5 Probability of Strategy Change in Fermi Rule



Note. The probability of a "student" changing strategy as a function of the payoff difference between the "teacher" and the "student." Selection strength $s = 5$ in the Fermi rule.

A summary of default model parameters can be found in Table 4. The population repeatedly perform the three steps for *iterN* = 5000 iterations in each simulation. This is long enough for the proportion of different strategies to fluctuate around a stabilized value. For each simulation, the following four characteristics were extracted: 1) cooperation rate, calculated by the proportion of "to cooperate" actions in all agents' latest interactions, 2) the proportion of gossipers (AG), 3) information accuracy, calculated by the average of the proportion that an agent's overall belief of a neighbor is the same as that neighbor's true strategy, and 4) proportion of different cooperation strategies in the population.

Table 4 Model Parameters

Parameter	Description	Default value
c	Cost of cooperation	1
b	Benefit of cooperation	3
dirW	Information gained from direct interaction, the probability increased for the manifested type after direct interaction	0.5
targetN	Number of targets in a gossip conversation	2
gCost	Cost of a piece of gossip	0
bias	Bias toward more confident gossip	5
indirW	Maximum influence of a piece of gossip	0.5
N	Number of agents	200
swK	Average degree in small world network	20
swP	Probability of rewiring each edge when generating 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

2.8 A Two-Step Approach

To achieve the research goals of this thesis, I built this project by two-steps. In Step 1, I focused only on the information function of gossip. I tuned the model and tested whether the new model framework could replicate results from previous models on cooperation, reputation, and the information function of gossip. In Step 2, I incorporated the influence function of gossip and examined the interaction between the information and influence functions, as elaborated below.

2.8.1 Step 1: Information Function

In Step 1, only the information function of gossip was examined. Only four cooperation strategies were used in this step: 1) always cooperators (AC), 2) always defectors (AD), 3) virtuous agents (CC), and 4) exploitive agents (CD). Similarly, in agents' "brains", only these four strategies were listed in probability tables. ACs and ADs do not utilize reputation information to guide their cooperation decisions. Thus, they will not directly benefit from the information function of gossip. CCs and CDs are the reputation sensitive agents that directly benefit from the information function of gossip. Specifically, CCs utilize reputation information virtuously to protect themselves from being exploited by defectors. Thus, if gossip boosts information accuracy in the population, CCs will be able to better recognize defectors, stop cooperating with defectors, and cooperate more effectively with cooperators. CDs, however, correspond to the exploitive side of the information function of gossip. They utilize reputation information not only to protect themselves, but also to exploit others, if possible. By implementing CDs, I extended previous models of indirect reciprocity and avoided making the model biased toward cooperation. In other words, I did not assume that the information 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 model and a control model were contrasted. In both models, there were both gossipers (AG) and non-gossipers (AN). The only difference between the two models was the frequency of conversations, *talkF*. In the experimental model, *talkF* = 10, representing a situation where individuals talk frequently. In the control model, *talkF* = 0, representing a situation where individuals do not talk, even they are gossipers (AG). Thus, by comparing the two models, I was able to examine how the existence of gossip influence information accuracy and cooperation rate in the population. Specifically, I compared the following outcomes in the two models: 1) information accuracy, which is the precondition of the information function of gossip, measured as the average of the proportion that an agent's overall belief of a neighbor is the same as that neighbor's true strategy, 2) proportions of reputation sensitive agents, which reflects the utilization of reputation information, 3) cooperation rates, which reflects the function of gossip in the evolution of cooperation, and 4) proportions of gossipers, which reflects the evolution of gossipers.

In addition to the models with default parameters as shown in Table 4, robustness tests were also conducted, examining the moderating effects of a variety of parameters and model choices. These parameters and model choices included: 1) *bias*, bias toward more confident gossip when listeners receive gossip, 2) *intF*, frequency of direct interactions, 3) *talkF*, frequency of conversations, 4) *dirW*, information from one direct interaction, 5) *indirW*, maximum influence of a piece of gossip, 6) network structures, and 7) *updF*, frequency of strategy updating.

2.8.2 Step 2: Information Function and Influence Function

In Step 2, the model was expanded to examine the influence function of gossip. Two gossiper sensitive strategies were added beyond Step 1: 1) hypocritical agents (GC) and 2) reverse-hypocritical agents (GD). Hypocritical agents cooperate only with gossipers because they want to leave a virtuous reputation in gossip. Thus, the evolution of GCs reflects the influence function of gossip. GDs are the opposite of GCs. They want to leave a defective reputation. I added GDs to make the model "neutral." That way, the model was not set-up to benefit gossipers.

A 2 (with vs. without information function) × 2 (with vs. without influence function) contrast was made to examine the information function of gossip, the influence function of gossip, and their interaction. To manipulate the information function of gossip, as in Step 1, we manipulated *talkF*. When *talkF* = 10, the information function was "on" while when *talkF* = 0, the information function was "off." The influence function was manipulated as follows: In the "with reputation management" condition, gossiper sensitive agents were able to manipulate their reputation in front of gossipers, as described in the default model. However, in the "without reputation management" condition, everything was the same expect that though GCs and GDs still behaved differently toward gossipers vs. non-gossipers, they could *not* manipulate their reputation in the gossip. GCs would be perceived as GCs for both gossipers and non-gossipers and GDs would be perceived as GDs. This condition "blocked" the influence function of gossip because these gossiper sensitive agents could not manipulate their reputation even by cooperating/defecting with gossipers. In all the 2 × 2 conditions, there were both gossipers (AG) and non-gossipers (AN).

With this contrast, I examined the following outcomes: 1) information accuracy and proportions of reputation sensitive agents, which reflects the information function of gossip, 2) the proportions of gossiper sensitive agents, which reflects the influence function of gossip, 3) cooperation rates, and 4) the evolution of gossipers.

A variety of robustness tests were also conducted in Step 2 to examine the moderating effects of different parameters and model choices. These parameters and model choices include: 1) *bias*, 2) *intF*, 3) *talkF*, 4) *dirW*, 5) *indirW*, 6) network structures, 7) *updF*, and 8) *m*, mobility.

Chapter 3: Results

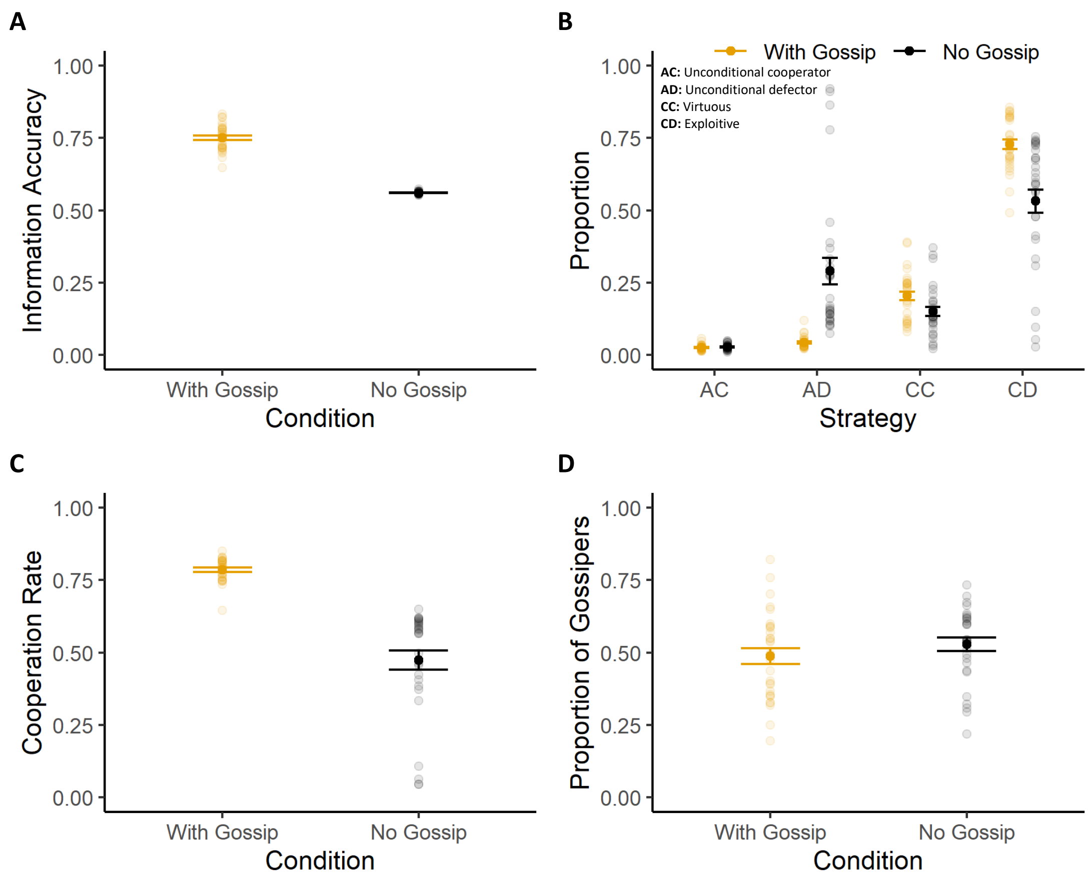
3.1 Step 1: The Information Function of Gossip

Figure 6 shows the effects of gossip on information accuracy and the proportions of reputation sensitive agents, cooperation, and gossipers. The results were got by contrasting 30 simulation runs in a population where agents are allowed to "talk" (*talkF* = 10) vs. 30 simulation runs where the conversations are "blocked" (*talkF* = 0). Plot A shows that when agents are allowed to talk and gossip, agents have more accurate beliefs about their neighbors' strategies ($t(30) = 23.29$, $p < 0.001$) compared with the control condition. Plot B shows that when agents are allowed to gossip, more agents evolve to be reputation sensitive and utilize reputation information to guide their cooperation decisions (CC: $t(58) = 2.45$, $p = 0.017$; CD: $t(39) = 4.55$, $p < 0.001$). Moreover, there are fewer unconditional defectors (AD) when there is gossip ($t(29) = -5.39$, $p < 0.001$). Plot 3 shows that the existence of gossip increases overall cooperation rate ($t(32) = 9.03$, $p < 0.001$). Altogether, these results support and have replicated the information function of gossip: The existence of gossip increases reputation accessibility and the proportion of agents who utilize reputation information to guide their decisions. As a result, more cooperation evolves across the population. The causal relationship between reputation accessibility and cooperation is further elaborated in the "Reputation Accessibility and Cooperation" section below.

Despite the effects of gossip on cooperation, Plot 4 shows that evolution favors *neither* gossipers *nor* non-gossipers in this setting. The proportions of gossipers do not differ in the "with gossip" vs. "no gossip" conditions ($t(56) = -1.11$,

$p = 0.270$). In the “with gossip” condition, the proportion of gossipers do not differ from chance (one sample t-test from 0.5, $t(29) = -0.47$, $p = 0.643$). In fact, further analyses show that even if a little cost is implemented to gossiping, it will cause the proportion of gossipers to drop dramatically (see Figure S2). This indicates that the information function of gossip alone is *not* sufficient to explain the prevalence of gossipers in human evolution.

Figure 6 The Information Function of Gossip



Note. Results from 60 simulations. 30 of them are from a population where agents have frequent conversations ("with gossip", *talkF* = 10) while the other 30 are from a population where there is no conversation ("no gossip", *talkF* = 0). For this figure and all the figures below, unless specified, each data point in the scatter plot represents a single simulation. The value is calculated as the average value from the 4000th to the 5000th iteration in that simulation. The middle dots in the error bars show the mean values across the 30 simulations in that condition. The error bars show the standard errors.

3.2 Step 1: Robustness Tests

In this section, I provide evidence from additional experiments that supports the information function of gossip. I also examine the robustness and boundary conditions of the model by using different model choices. These model choices included: 1) *bias*, bias toward more confident gossip when listeners receive gossip, 2) *intF*, frequency of direct interactions, 3) *talkF*, frequency of conversations, 4) *dirW*, information from one direct interaction, 5) *indirW*, maximum influence of a piece of gossip, 6) network structures, and 7) *updF*, frequency of strategy updating. In general, the information function of gossip is robustly supported across various model choices.

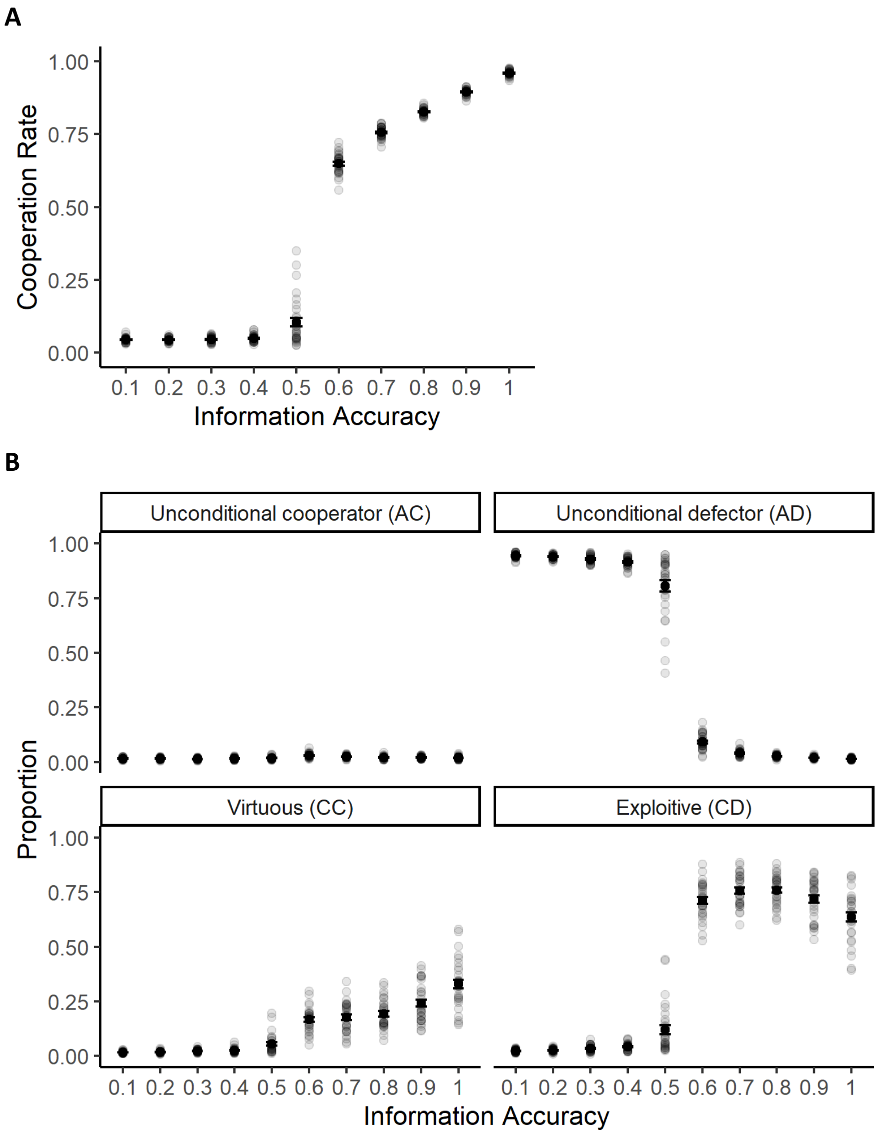
3.2.1 Reputation Accessibility and Cooperation

To support that reputation accessibility is the key factor that *mediates* the effects of gossip on cooperation, I did an experiment that exogenously manipulates reputation accessibility and directly examines its effects on the evolution of cooperation. In this experiment, the set-up is the same as the default model in Step 1, except that agents' beliefs are exogenously implemented with a certain level of accuracy, instead of endogenously got from interactions or gossip. By implementing different levels of information accuracy, I examined how information accuracy influences agents' cooperation strategies and behavior.

Figure 7 shows that in general, the population indeed cooperate more as they have more accurate information. However, the effect follows a piecewise function where information accuracy only increases cooperation when it is sufficiently high. Specifically, Plot A shows that when information accuracy is below a certain threshold, almost no one cooperates, while when information accuracy is high enough, cooperation rate increases as information accuracy increases. Plot B shows that when there is not enough information, unconditional cooperators (AD) take 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 not only support the importance of reputation accessibility in the evolution of cooperation but are also consistent with Nowak (2006), which indicated that indirect reciprocity through reputation can only promote cooperation when the reputation information is prevalent enough. Moreover, the piecewise relationship between information accuracy and cooperation suggests that gossip should have the strongest impact on cooperation when it can boost information accuracy up to above the threshold. Overall, these results support that as long as gossip can increase reputation accessibility to a sufficiently high level, it will benefit cooperation through its information function.

Figure 7 Effects of Information Accuracy on Cooperation



Note. 30 simulations in each condition. Agents did not talk in these conditions (*talkF* = 0). Instead, information accuracy is exogenously manipulated. Plot A shows when information accuracy is below a certain threshold, cooperation rate is very low. However, when information accuracy is high enough, cooperation rate increases as agents get more accurate beliefs about their neighbors' strategies. Plot B shows that when there is not enough information, unconditional defectors (AD) take the major part of the population. However, after information accuracy has passed a threshold, more reputation sensitive agents evolve as information accuracy increases.

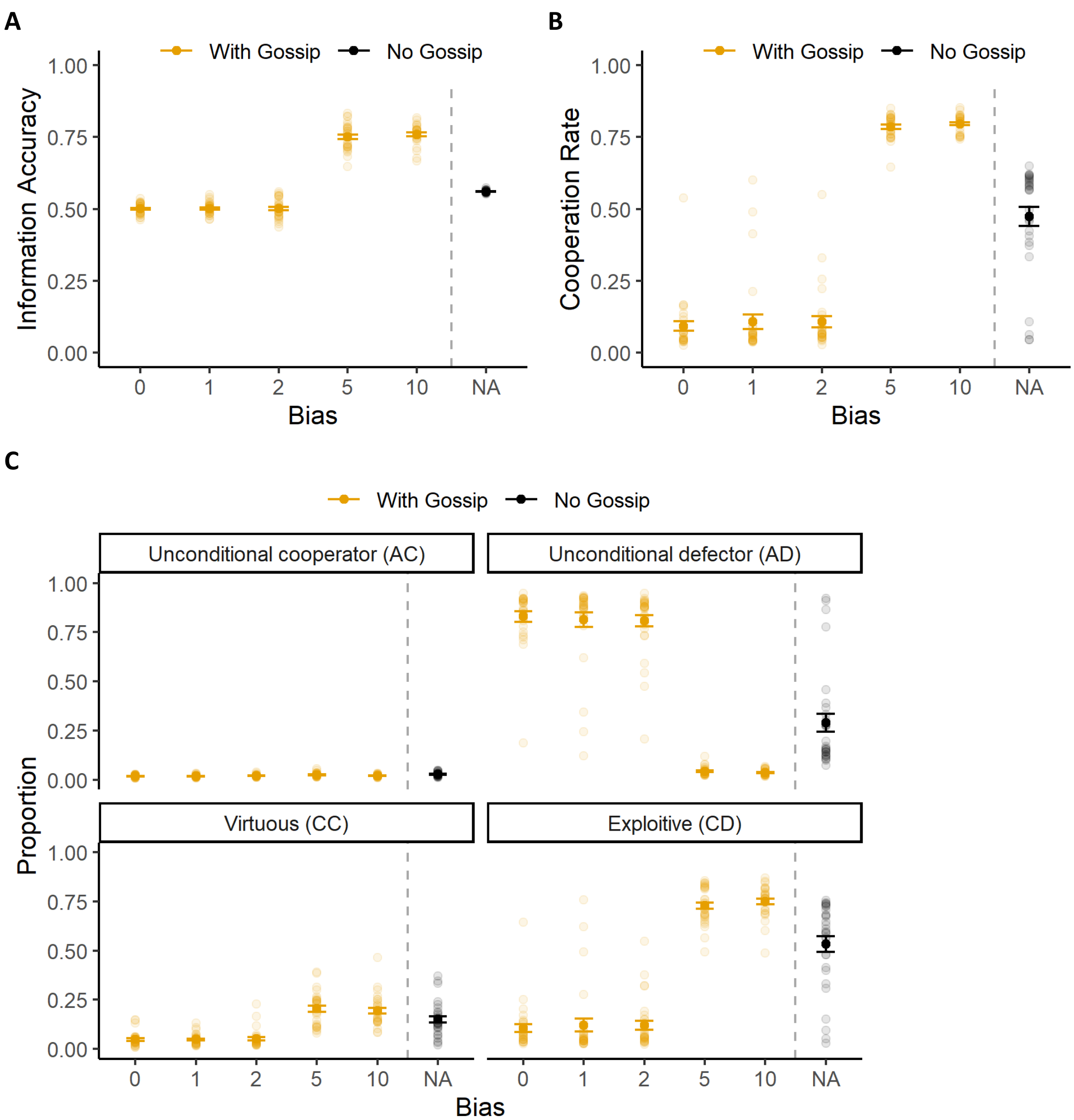
3.2.2 Effects of Bias (*bias*)

In the default model, we assume that agents are biased to learn from others who are more confident about their beliefs (Birch et al., 2010; Jaswal & Malone, 2007) and the differentiation between confident vs. unconfident gossip is captured by the parameter *bias* (see Figure 4). In the default model, we set *bias* = 5. Through further exploration, we found that this value is essential for whether gossip can successfully boost information accuracy. Specifically, Plot A in Figure 8 shows that gossip only increases information accuracy when agents are highly biased toward more confident gossip. Otherwise, if agents cannot weigh confident vs. unconfident gossip discriminatively, the existence of gossip even compromises information accuracy compared with the control group. As a result, Plots B and C show that gossip only benefits cooperation when bias is sufficiently high. Otherwise, gossip will harm cooperation because of the compromised information accuracy.

These results have important implications both methodologically and theoretically. For its methodological implication, much previous modeling work on gossip directly assumed that gossip increases reputation accessibility (e.g., Enquist & Leimar, 1993). Some other modeling work did not make such assumption, but because the agents in those models always get either fully correct information or no information about a target, gossip always brings accurate information (e.g., Giardini et al., 2014). My model relaxes this restriction and shows that if agents learn about others' reputation gradually but are allowed to gossip with imperfect information, gossip does *not* necessarily increase reputation accessibility. In this case, gossip may not benefit cooperation.

For its theoretical implication, these results show that biased learning may be the key for individuals to figure out correct information from imperfect gossip and for the information 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.

Figure 8 Effects of Bias

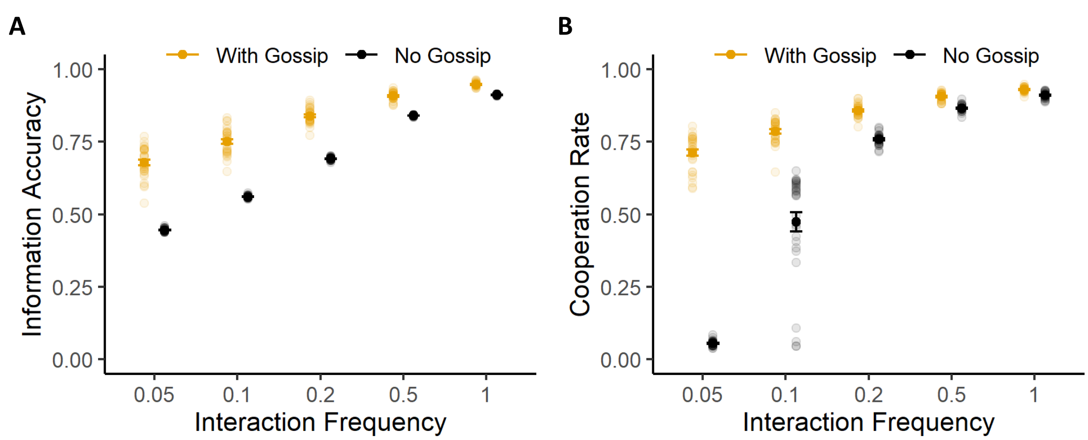


Note. On the left of each plot are conditions with gossip (yellow, *talkF* = 10) and with different levels of bias. On the right is the condition without gossip (black, *talkF* = 0) as the control condition. There are 30 simulations in each condition, except for the *bias* = 10 condition, where there are only 29 simulations due to computer error. Plot A shows when bias is low, gossip does not increase information accuracy compared with the control condition. Actually, 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 low bias is harmful for the evolution of cooperation.

3.2.3 Effects of the Frequency of Direct Interactions (*intF*)

Next, I examined how the frequency of direct interactions moderates the information function of gossip. Figure 9 shows that gossip has stronger effects on boosting information accuracy and cooperation when direct interactions are infrequent. This is because if individuals frequently interact in cooperation games, they can learn each other's reputation from these interactions directly and no longer need to rely on gossip. Nevertheless, in any situation, gossip increases information accuracy and cooperation rate, supporting the robustness of the results.

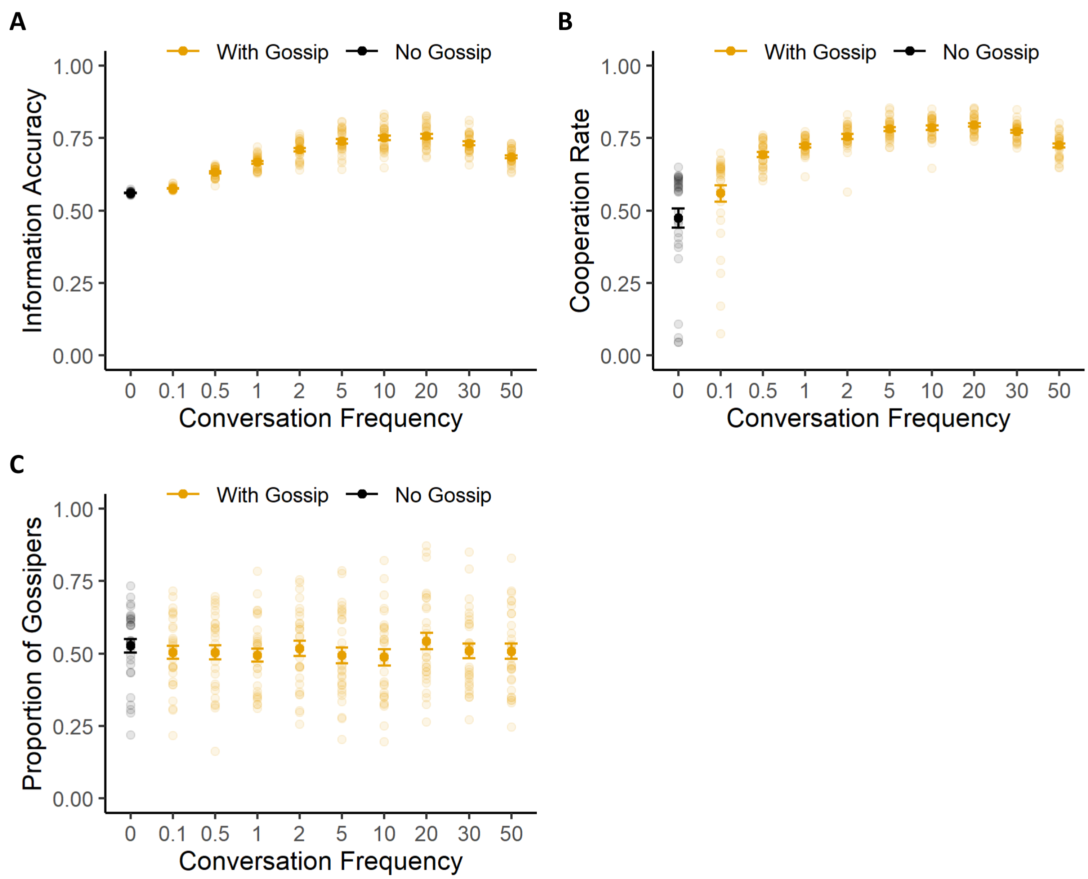
Figure 9 Effects of Interaction Frequency



3.2.4 Effects of the Frequency of Conversations (*talkF*)

Next, I examined how the frequency of conversations moderates the information function of gossip. Frequency of conversations (*talkF*) controls how many agents are selected per iteration to speak. Holding the proportion of gossipers constant, this also reflects the frequency of gossiping. Figure 10 shows that even a small amount of gossip (e.g., *talkF* = 0.5) increases information accuracy and cooperation substantially compared with the control condition (i.e., *talkF* = 0). However, the amount of gossip shows a slightly *curvilinear* effect. When there is too much gossip (e.g. *talkF* > 20), information accuracy and cooperation start to decrease as the frequency of gossip increases. This is probably because the surplus of inaccurate gossip pollutes the information pool. Nevertheless, in general, the existence of gossip increases reputation accessibility and cooperation, showing the robustness of the model.

Figure 10 Effects of Conversation Frequency

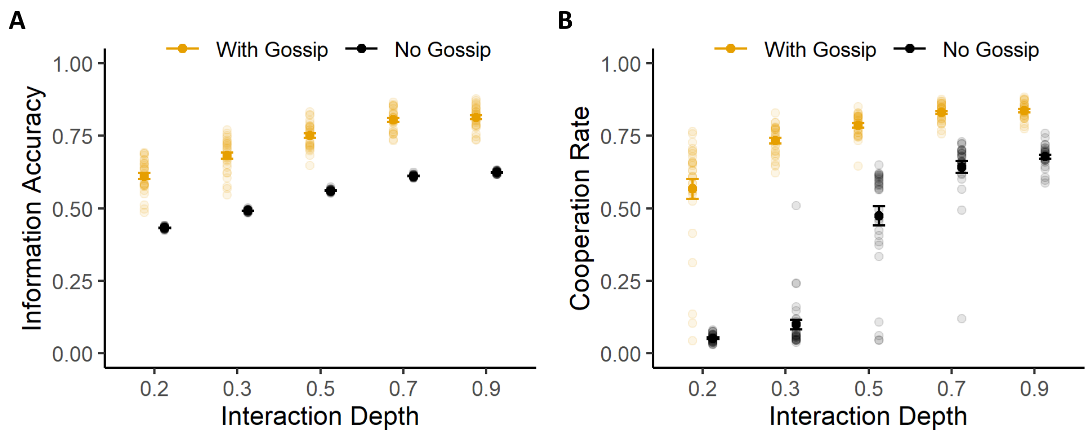


Note. Each condition represents a level of conversation frequency (*talkF*). When *talkF* = 0, it represents the control condition where there is no gossip. There are 30 simulations in each condition, except for the *talkF* = 2 condition, where there are only 29 simulations due to computer error.

3.2.5 Effects of the Amount of Information From Direct Interaction (*dirW*)

Next, I examined how the results are moderated by the amount of information that an individual gains from one direct interaction (*dirW*). This can be interpreted as the depth of interaction. The higher the *dirW* is, the more knowledge an individual gains about their partner from an interaction. Plot A in Figure 11 shows that gossip increases information accuracy effectively across a broad range of interaction depth, though Plot B shows that gossip is more effective for increasing cooperation when interaction depth is low. This is because when interaction depth is low, information accuracy is low without gossip. Thus, gossip can boost the reputation accessibility up to above the threshold for cooperation (see Figure 7).

Figure 11 Effects of Interaction Depth

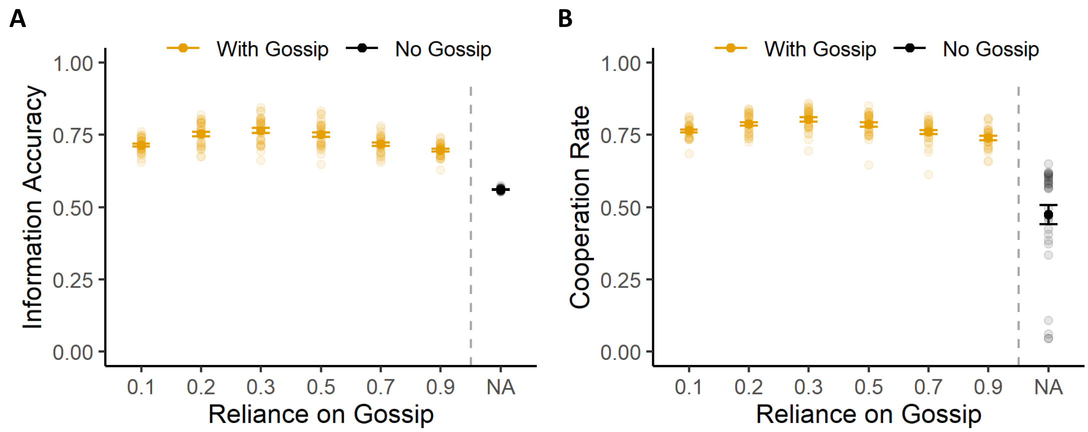


Note. Each condition represents a level of interaction depth, which is manipulated as the amount of information that an individual gains about their partner from one direct interaction (*dirW*). There are 30 simulations in each condition, expect for the *dirW* = 0.3 in the "with gossip" condition where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

3.2.6 Effects of the Maximum Influence of a Piece of Gossip (*indirW*)

I also examined the effects of the maximum influence of gossip (*indirW*). This parameter can be interpreted as the extent to which individuals rely on gossip to form their belief of another person. Figure 12 shows that for a broad range of *indirW*, the existence of gossip increases information accuracy and cooperation. There is also a trend that the effects of gossip reliance is curvilinear. For gossip to be most effective, 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 of Step 1 hold robust that over a broad range of *indirW*, gossip benefits information accuracy and cooperation.

Figure 12 Effects of the Influence of Gossip

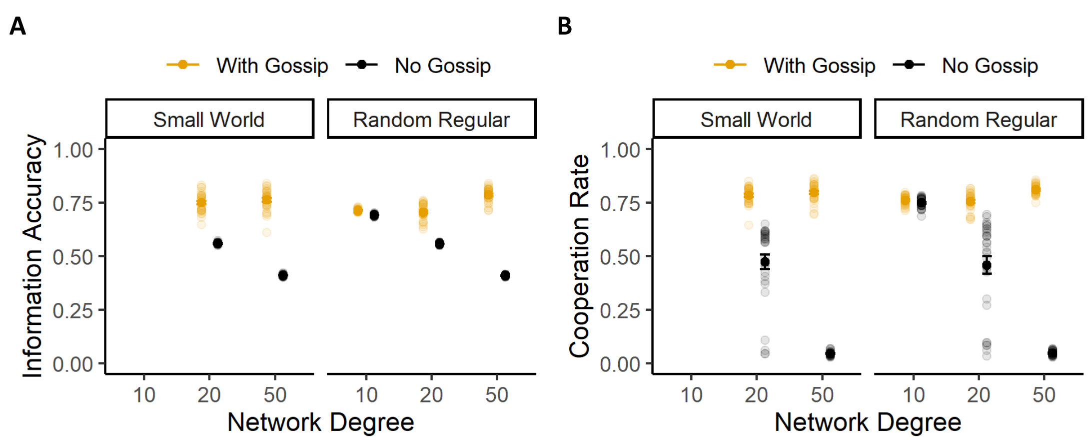


Note. On the left of each plot are conditions with gossip (yellow, *talkF* = 10) and with different levels of reliance on gossip (*indirW*). On the right is the condition without gossip (black, *talkF* = 0) as the control condition. For a broad range of *indirW*, the existence of gossip increases information accuracy and cooperation.

3.2.7 Effects of Network Structures

I also examined the effects of network structures. To do that, I tested a small world network with a higher average degree (i.e., average number of neighbors, *swK* = 50). I also tested a random regular network with different levels of degree (*d* = [10, 20, 50]). Figure 13 shows that, in general, gossip increases information accuracy and cooperation across a variety of network structures. The only exception happens when the degree of a network is very low (i.e., *d* = 10 in a random regular network). This is because when agents have few neighbors, they can get sufficient information just from direct interactions. In this case, the effect of gossip is limited. Overall, these results support the robustness of the model.

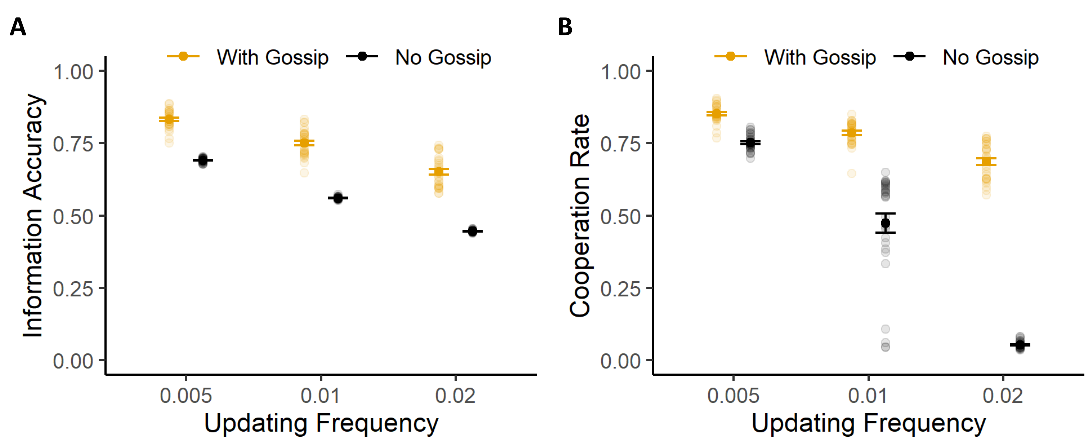
Figure 13 Effects of Network Structures



3.2.8 Effects of the Frequency of Strategy Updating (*updF*)

Finally, I examined the effects of the frequency of strategy updating. This can be interpreted as the speed of evolution. Figure 14 shows that the existence of gossip increases information accuracy and cooperation across all the conditions that have been tested, supporting the robustness of the results.

Figure 14 Effects of Updating Frequency



3.2.9 Conclusion

Overall, the robustness tests show that when reputation accessibility is sufficiently high, more accurate information leads to more cooperation in the population. Thus, the information function of gossip will benefit cooperation as long as gossip can effectively boost information accuracy. However, gossip can lead to more accurate information only when individuals are biased toward more confident gossip. If so, gossip will increase reputation accessibility and thus benefit the evolution of cooperation. These results hold robust over a variety of model choices.

However, in none of the simulations mentioned above, does evolution favor either gossipers or non-gossipers. Thus, the current model cannot explain the mechanism of why gossipers evolve. The mechanism of the evolution of gossipers is examined in Step 2.

3.3 Step 2: Both the Information and Influence Functions of Gossip

In this section, two additional cooperation strategies, hypocritical (GC) and reverse-hypocritical (GD), were added. A 2 (with vs. without gossip) × 2 (with vs. without reputation management) contrast was made to examine the information function, the influence function, and their interaction. The first variable (i.e., with vs. without gossip) corresponds to the information function of gossip, as elaborated in Step 1. The second variable (i.e., with vs. without reputation management) corresponds to the influence function of gossip. In the "with reputation management" condition, gossiper sensitive agents (i.e., GCs and GDs) can manage their reputations in gossip by behaving differently in front of gossipers vs. non-gossipers, manifesting the influence function of gossip. On the contrary, in the "no reputation management" condition, gossiper sensitive agents cannot manage their reputations, and the influence function is "blocked."

Figure 15 shows the effects of the two variables on reputation accessibility, cooperation, and the evolution of gossipers. Plot A shows that in general, the existence of gossip increases information accuracy through the information function of gossip, as found in Step 1 (main effect of gossip: $F(1, 116) = 721.75$, $p < 0.001$). Though there is an interaction between the information and the influence functions of gossip ($F(1, 116) = 8.37$, $p = 0.005$), in general, allowing agents to manage their reputation in front of gossipers *decreases* information accuracy (simple main effects: with gossip, $t(58) = -4.24$, $p < 0.001$; no gossip, $t(37) = -8.54$, $p < 0.001$). This is because when individuals can manage their reputations, their true reputations become less accessible.

Interestingly, Plot B shows that though the information accuracy is compromised by reputation management, the cooperation rate is the highest when allowing for *both* reputation management and gossiping. Specifically, if gossiping is allowed, the cooperation rate is significantly higher when agents are also allowed to manage their reputations (simple main effect: $t(44) = 3.08$, $p = 0.004$), though if gossiping is not allowed, reputation management shows no significant effect (simple main effect: $t(57) = -1.57$, $p = 0.122$; interaction effect: $F(1, 116) = 7.18$, $p = 0.008$). These results show that when reputation management is allowed, the information function of gossip is compromised, but the influence function becomes effective in boosting cooperation despite the less accurate information.

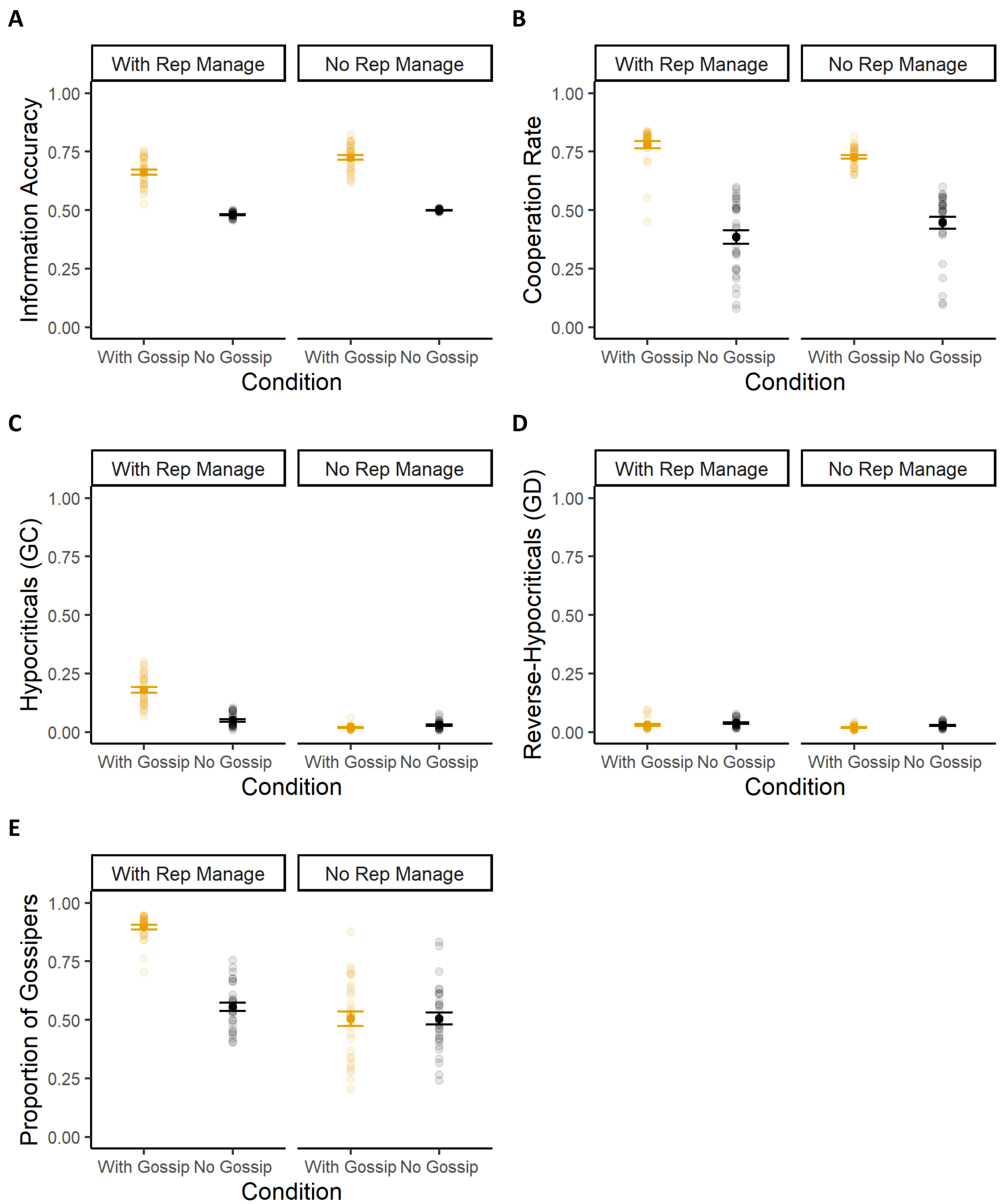
The influence function of gossip is also reflected on the evolution of hypocritical agents (GC). As shown in Plot C in Figure 15, a substantial proportion of agents become hypocritical when they can manage their reputation in gossip and particularly when gossip is transmitted frequently (interaction effect: $F(1, 116) = 103.23$, $p < 0.001$; simple main effects: with gossip, $t(30) = 12.89$, $p < 0.001$; no gossip, $t(46) = 3.31$, $p = 0.002$). On the contrary, there are few reverse-hypocritical agents in any condition (see Plot D). The evolution of hypocritical agents shows that the threat of gossip prevents individuals from defecting at least in front of gossipers. However, the influence function of gossip is only effective when agents *actually* gossip. If the information function is "blocked," gossiping loses its influence function as well.

Most importantly, with the existence of *both* the information and influence functions of gossip, gossipers evolve. Plot E in Figure 15 shows that the majority

(89.69%) of the population evolve to be gossipers if both gossiping and reputation management are allowed (interaction effect: $F(1, 116) = 57.144$, $p < 0.001$; simple main effects: with gossip, $t(35) = 12.05$, $p < 0.001$; no gossip, $t(51) = 1.58$, $p = 0.119$). Moreover, further analyses show that a substantial proportion of gossipers evolve even when gossipers need to spend a cost to gossip (see Figure S3), showing the robustness of the evolution of gossipers under the current model set-up.

Gossipers evolve because of the *joint* effect of the information and influence functions. Specifically, when gossip conveys reputation information, a substantial proportion of reputation sensitive agents evolve. These agents cooperate only with the agents who have cooperative reputations. Thus, it becomes important to have a good reputation in gossip. However, it will be even more beneficial if someone can also act selfishly privately. Thus, hypocritical agents evolve. In particular, these agents cooperate exclusively with gossipers so that they gain both good reputations and extra material payoffs when there is no threat of gossip. The existence of hypocritical agents gives gossipers an advantage over non-gossipers because being able to gossip becomes deterrent and protects them from being exploited by hypocritical agents. This leads to the evolution of gossipers. Moreover, the evolution of gossipers further increases the prevalence of reputation information and thus facilitates the cycle. Eventually, the majority of the population evolve to be gossipers. A substantial proportion of agents become hypocritical. Notably, though the hypocritical agents have the potential to be exploitive, they end up cooperating for most of the time because of the high proportion of gossipers. Thus, gossipers and cooperation coevolve under the joint effect of the information and influence functions of gossip.

Figure 15 The Information and Influence Functions of Gossip



Note. Results from a 2 × 2 contrast. There are 30 simulations in each condition. In the "with gossip" conditions, agents are allowed to have conversations and gossip (*talkF* = 10). In the "no gossip" conditions, no conversation is allowed (*talkF* = 0) and thus the information function of gossip is “blocked.” In the “with rep manage” conditions, gossiper sensitive agents are allowed to manage their reputations by behaving differently in front of gossipers vs. non-gossipers. In the “no rep manage” condition, agents cannot manage their reputation and thus the influence function is “blocked.” Plots A and B show that when agents can manage their reputation, reputation information becomes less accurate, but the influence function leads to more cooperation. Plots C and E show that a substantial proportion of agents evolve to be hypocritical and the majority of the population become gossipers as a result of the joint effect of the information and influence functions of gossip.

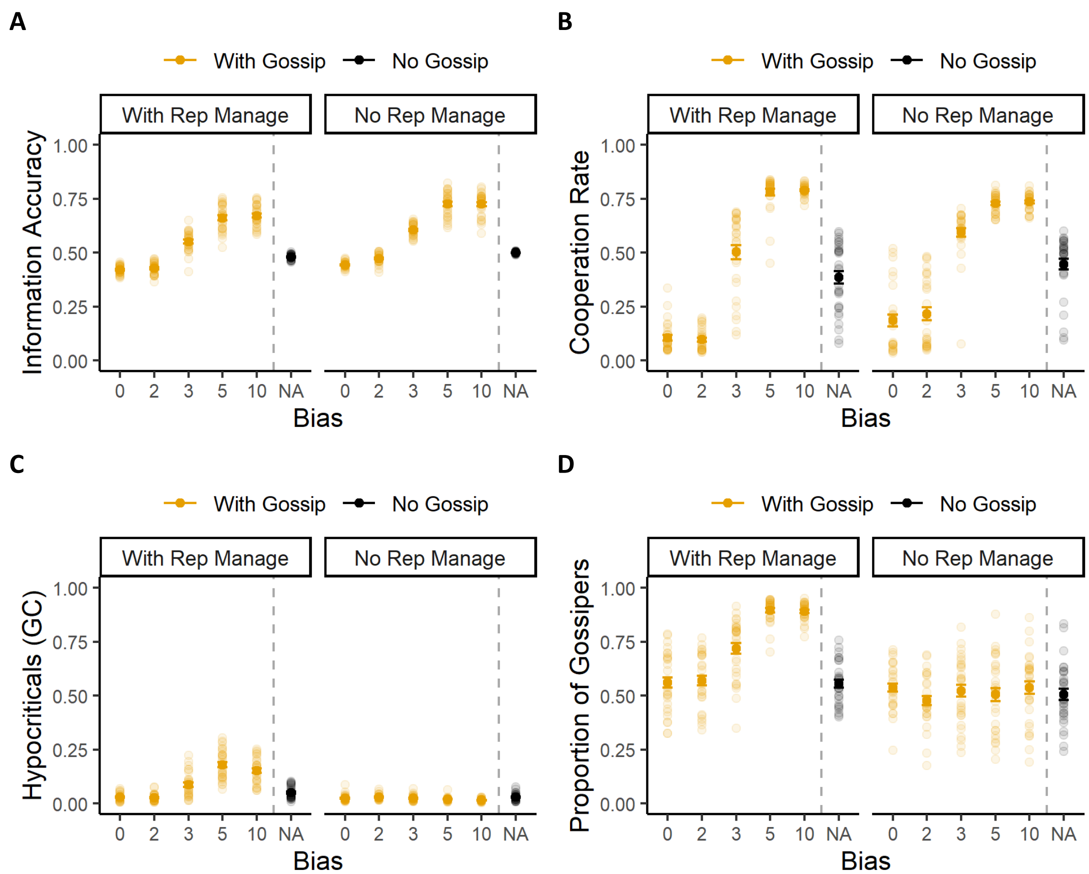
3.4 Step 2: Robustness Tests

In this section, I examined the robustness and boundary conditions of the results in Step 2 by using different model choices. These model choices include: 1) *bias*, bias toward more confident gossip, 2) *intF*, frequency of direct interactions, 3) *talkF*, frequency of conversations, 4) *dirW*, information from one direct interaction, 5) *indirW*, maximum influence of a piece of gossip, 6) network structures, 7) *updF*, frequency of strategy updating, and 8) *m*, mobility. In general, I show that across a variety of model choices, the results in Step 2 hold robust.

3.4.1 Effects of Bias (*bias*)

Figure 16 shows the effects of bias on information accuracy, cooperation rate, and the evolution of hypocritical agents and gossipers. Plot A replicates the results in Step 1 that a sufficiently high bias is essential for agents to figure out accurate information through gossip. By comparing the "with rep mange" condition with the "no rep manage" condition, it also supports the results in Step 2 that information accuracy is compromised when agents can manage their reputation in gossip. Plot B shows that gossip benefits cooperation only when bias is high enough. Moreover, a sufficiently high bias is particularly important when reputation management is allowed. Plots C and D show that hypocritical agents and gossipers evolve only when both the information and influence functions of gossip exist and when bias is high enough. In general, these results support the main results of Step 2 as well as emphasize the importance of bias in the functions of gossip and the evolution of gossipers.

Figure 16 Effects of Bias



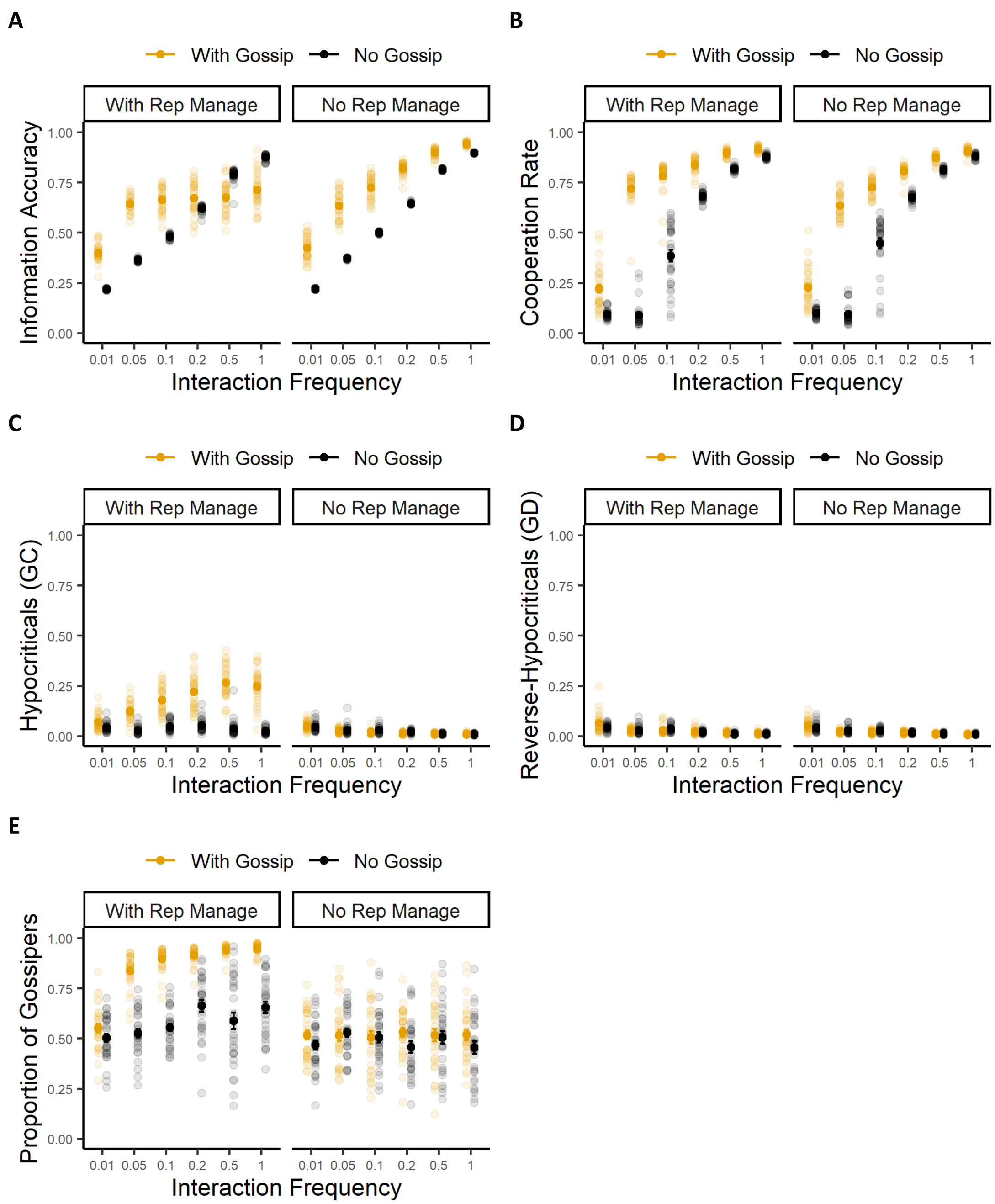
Note. On the left of each subplot are conditions with gossip (yellow, *talkF* = 10) and with different levels of bias. On the right is the condition without gossip (black, *talkF* = 0) as the control condition.

3.4.2 Effects of the Frequency of Direct Interactions (*intF*)

Figure 17 shows how interaction frequency moderates the results. In general, the main results of Step 2 are supported. Plot A shows that when agents can manage their reputation, the information function is compromised, especially when interactions are frequent. This is because the manipulation of reputation happens during direct interactions. Plot B shows that though the information function is compromised, the cooperation is the highest when agents manage their reputations. The results are robust across a wide range of values of interaction frequency, supporting the influence function of gossip. Plot C shows the evolution of hypocritical agents when both gossiping and reputation management are allowed and the proportion of hypocritical agents is particularly high when direct interactions are frequent. Finally, Plot E shows that the majority of the population evolve to be gossipers when both gossiping and reputation management are allowed, as long as the interaction frequency is not so low, replicating the main results in Step 2.

However, I also noticed that some gossipers evolve even when they do not actually gossip, as long as reputation management is allowed, especially when the interaction frequency is high (statistics from two-way ANOVA among conditions without gossip: main effect of reputation management: $F(1, 348) = 37.83$, $p < 0.001$; interaction effect between reputation management and interaction frequency: $F(5, 348) = 5.32$, $p < 0.001$). This is probability because hypocritical agents (GC) have a slight advantage over reverse-hypocritical agents (GD) (see Plots C and D) and that gives gossipers some advantage over non-gossipers. Nevertheless, the main findings in Step 2 hold robust that the influence function of gossip and the deterrent power that gossipers have on hypocritical agents are the key to the evolution of gossipers.

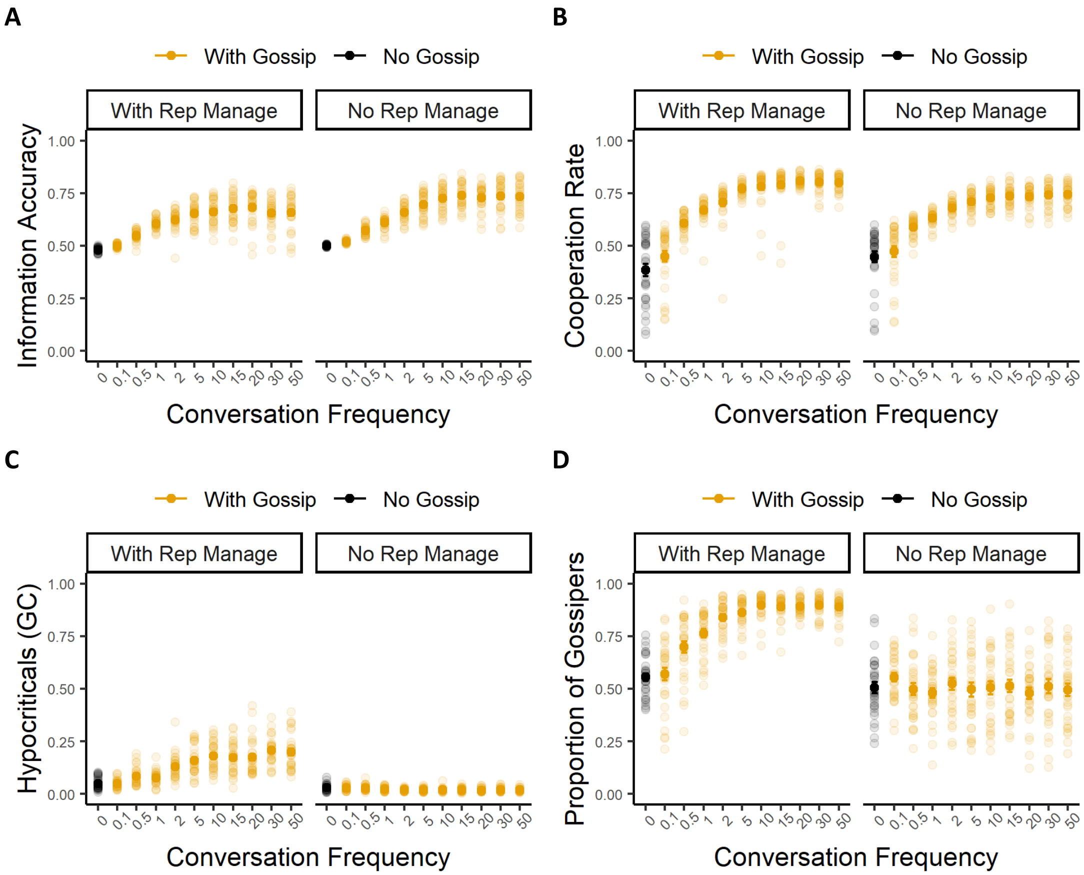
Figure 17 Effects of Interaction Frequency



3.4.3 Effects of the Frequency of Conversations (*talkF*)

In this section, I examined how the frequency of conversations moderates the results. Frequency of conversations (*talkF*) controls how many agents are selected per iteration to speak. Thus, the amount of gossip per iteration depends jointly on the conversation frequency and the proportion of gossipers. Figure 18 supports the robustness of the results in Step 2. Plots A and B show that reputation management in front of gossipers compromises information accuracy but increases cooperation. Plot C shows the evolution of hypocritical agents when they can manage their reputation in front of gossipers and particularly when conversations are frequent. Plot D shows that the majority evolve to be gossipers when reputation management is allowed.

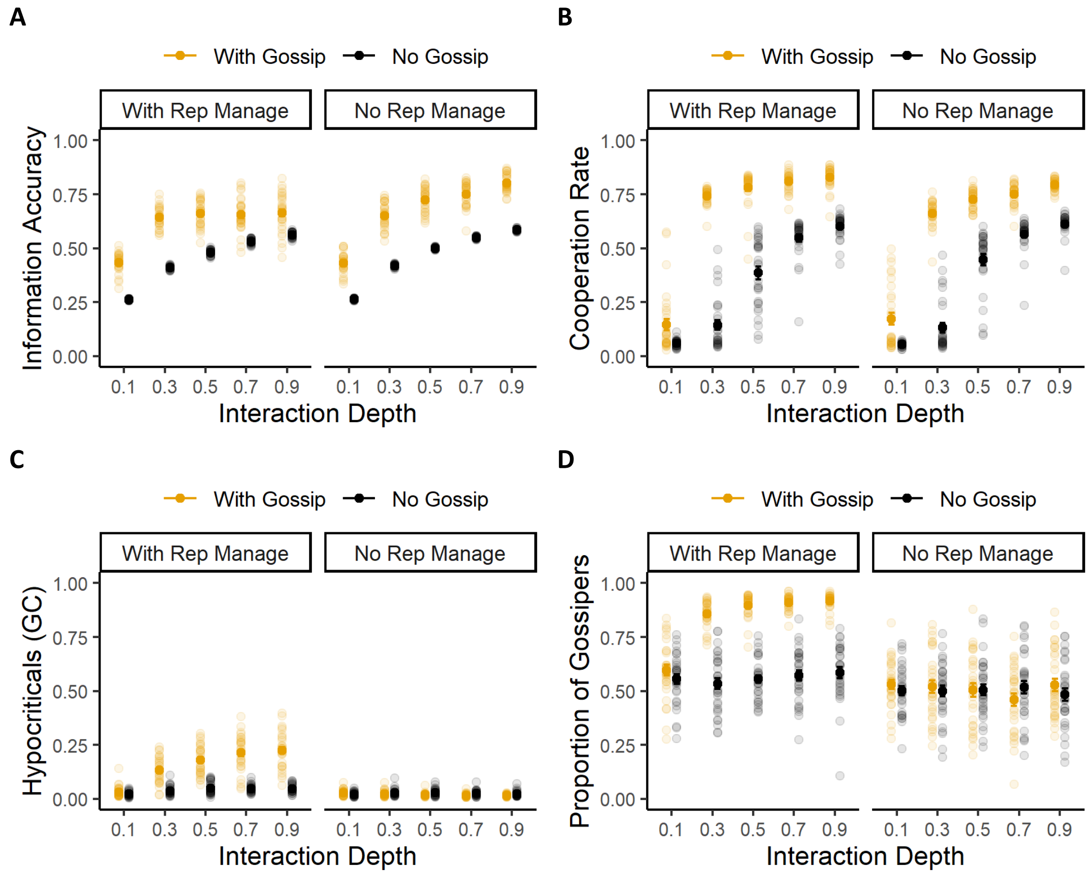
Figure 18 Effects of Conversation Frequency



3.4.4 Effects of the Amount of Information From Direct Interaction (*dirW*)

Figure 19 shows the robustness of the results across a variety of choices of interaction depth. Plots A and B show that reputation management in front of gossipers compromises information accuracy but increases cooperation rate, as a result of the influence function of gossip. Plot C shows the evolution of hypocritical agents when they can manage their reputation in front of gossipers. Plot D shows that the majority evolve to be gossipers when both reputation management and gossiping are allowed. Again, I noticed a slight trend for the evolution of gossipers even when gossipers are not allowed to gossip (statistics from two-way ANOVA among conditions without gossip: main effect of reputation management: $F(1, 290) = 14.42$, $p < 0.001$).

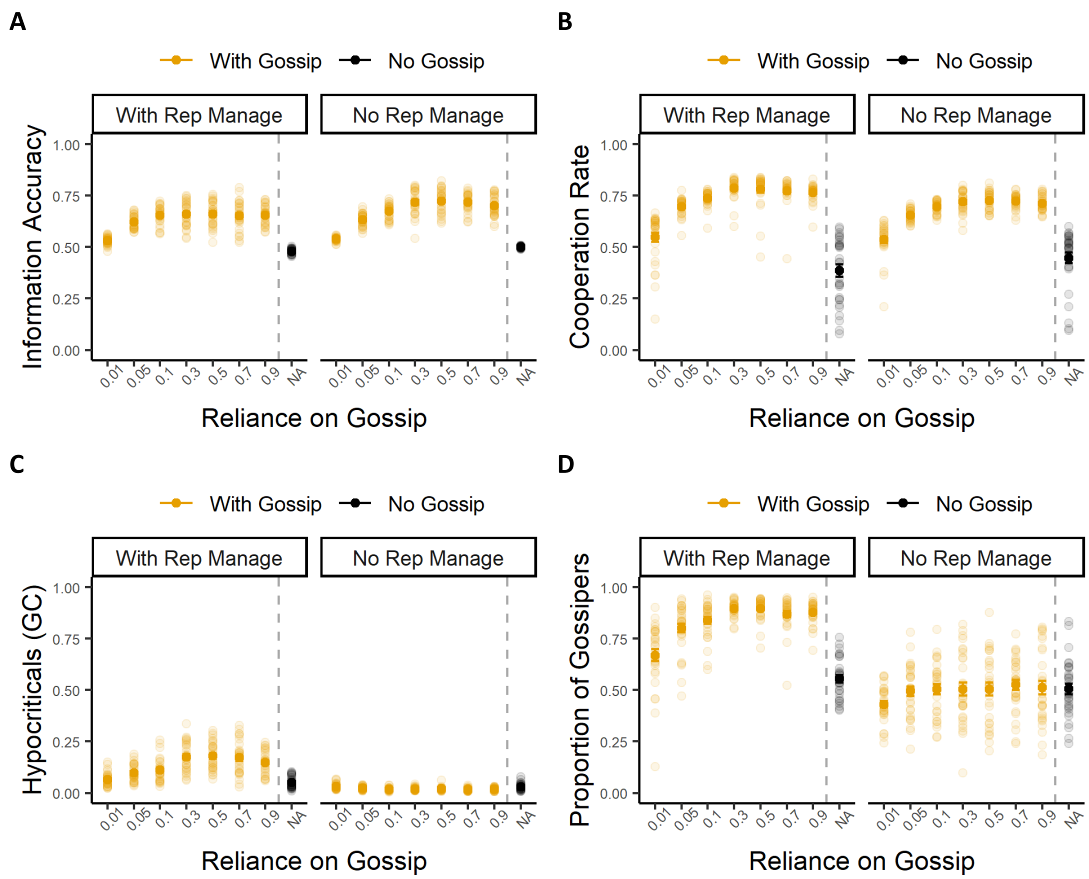
Figure 19 Effects of Interaction Depth



3.4.5 Effects of the Maximum Influence of a Piece of Gossip (*indirW*)

Figure 20 shows the robustness of the results across a variety of choices of the maximum influence of gossip. Once again, Plots A and B show that reputation management in front of gossipers compromises information accuracy but increases cooperation rate, as a result of the influence function of gossip. Same as in Step 1, there is a slight trend that the effect of gossip reliance is curvilinear. For gossip to be most effective in boosting cooperation, individuals need to rely neither too much nor too little on gossip. Plot C shows the evolution of hypocritical agents when they can manage their reputation in front of gossipers. Plot D shows that the majority evolve to be gossipers when reputation management is allowed.

Figure 20 Effects of the Influence of Gossip

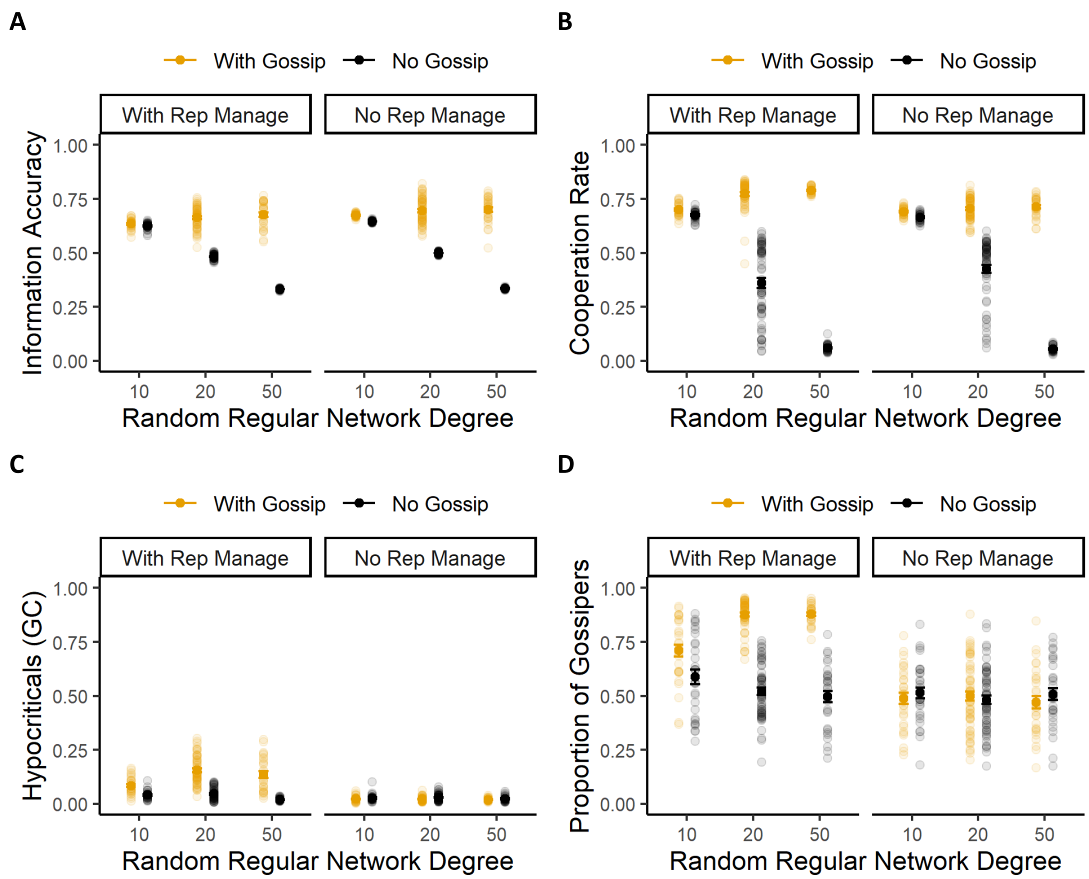


Note. On the left of each plot are conditions with gossip (yellow, *talkF* = 10) and with different levels of reliance on gossip (*indirW*). On the right is the condition without gossip (black, *talkF* = 0) as the control condition. There are 30 simulations in each condition, except for when *indirW* = 0.1 in the "with rep manage" condition, where there are only 29 simulations due to computer error.

3.4.6 Effects of Network Structures

I also tested the model on a random regular network with different levels of degree (d = [10, 20, 50]). Figure 21 shows that, across various network choices, the results in Step 2 are replicated. Plots A shows that reputation management in front of gossipers compromises information accuracy (statistics from two-way ANOVA among conditions with gossip: main effect of reputation management: $F(1, 233) = 25.39$, $p < 0.001$). Plot B shows that reputation management increases cooperation when gossiping is enabled. Plots C and D show the evolution of hypocritical agents and gossipers as a result of the joint impact of the information and influence functions of gossip. Moreover, the proportion of hypocritical agents and gossipers are particularly high when the network degree is high. This is because as agents have more neighbors, they have to learn the reputation of many targets. It becomes increasingly important to learn about these neighbors' reputation from gossip. Thus, the functions of gossip are enhanced.

Figure 21 Effects of Network Structures

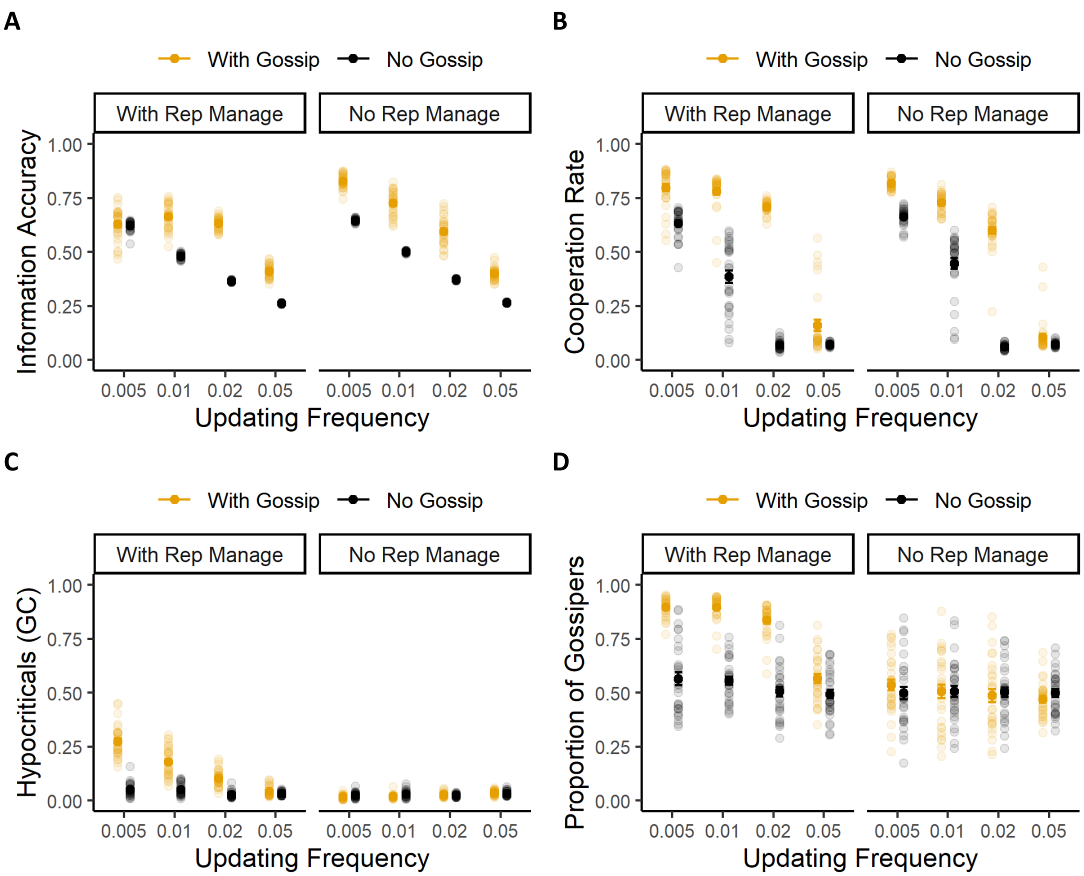


Note. All the results in this figure are drawn from populations embedded in random regular networks with different levels of average degree (*d*). There are 30 simulations in each condition, except for when *d* = 50 in the "with rep manage" and "with gossip" condition, where there are only 29 simulations due to computer error.

3.4.7 Effects of the Frequency of Strategy Updating (*updF*)

I also examined how the frequency of strategy updating (*updF*) moderates the effects of gossip as well as the evolution of gossipers. Plots C and D in Figure 22 show that the evolution of hypocritical agents and gossipers only happen when updating frequency is low. From an evolutionary perspective, this means that for gossipers to evolve, the evolution has to happen slowly so that an individual can live long enough to have many chances to interact and gossip with others. As a result, the results in Step 2 hold robust only when updating frequency is low.

Figure 22 Effects of Updating Frequency



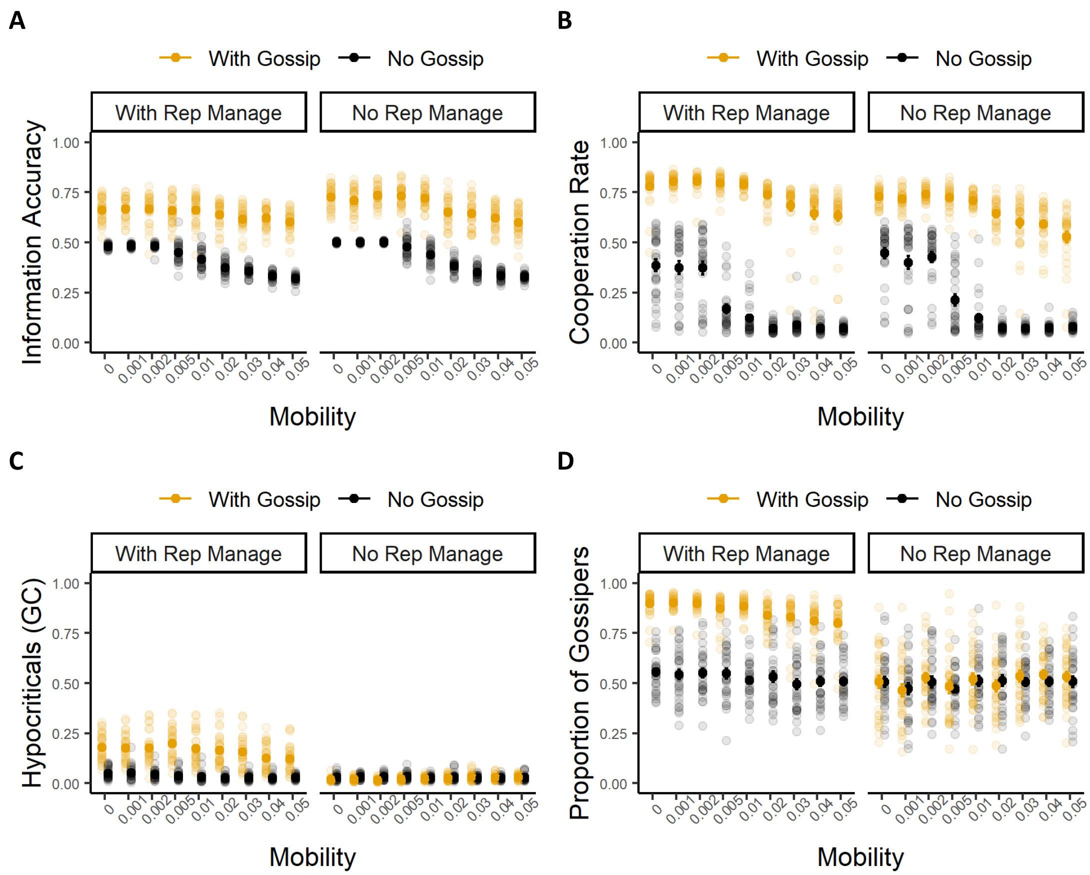
3.4.8 Effects of Network Mobility (m)

Finally, I examined how network mobility moderates the effects of gossip as well as the evolution of gossipers. To implement different levels of network mobility (m), at the end of each iteration, $N \times m$ agents are randomly selected to move.[3] If an agent moves, they cut their connections with their original neighbors and build connections with a new neighborhood, as explained in the Method section.

Figure 23 manifests both the information and the influence functions of gossip under mobility. With respect to the information function of gossip, Plot A shows that when there is no gossip, as mobility increases, reputation accessibility decreases because agents have to interact with new neighbors frequently. However, the existence of gossip maintains reputation accessibility at a relatively high level even when mobility is high. As a result, Plot B shows that the existence of gossip helps maintain a high cooperation rate even under high mobility. Moreover, Plots A and B support the results in Step 2 that reputation management decreases information accuracy but increases cooperation rate. Plots C and D show that hypocritical agents and gossipers evolve across different mobility values as a result of the joint effect of the information and influence functions of gossip. There is a slight trend that the proportion of gossipers is the highest when mobility is low. This is probably because if mobility is too high, the neighborhood changes so fast that the deterrent power of gossipers is compromised. However, overall, the results of Step 2 hold robust across different levels of mobility.

[3] Random sampling with replacement.

Figure 23 Effects of Network Mobility



3.4.9 Conclusion

Overall, I have showed that over a broad range of model choices, being able to manage one's reputation under the threat of gossip compromises information accuracy, but the reputation concern leads to more cooperation across the population, showing the influence function of gossip. Moreover, the majority of the population evolve to be gossipers under the joint impact of the information and influence functions of gossip. The evolution of gossipers is robust across a variety of model choices and even when gossiping is costly. These results show that the influence function of gossip not only increases cooperation but also is the key mechanism for the evolution of gossipers.

Chapter 4: Discussion

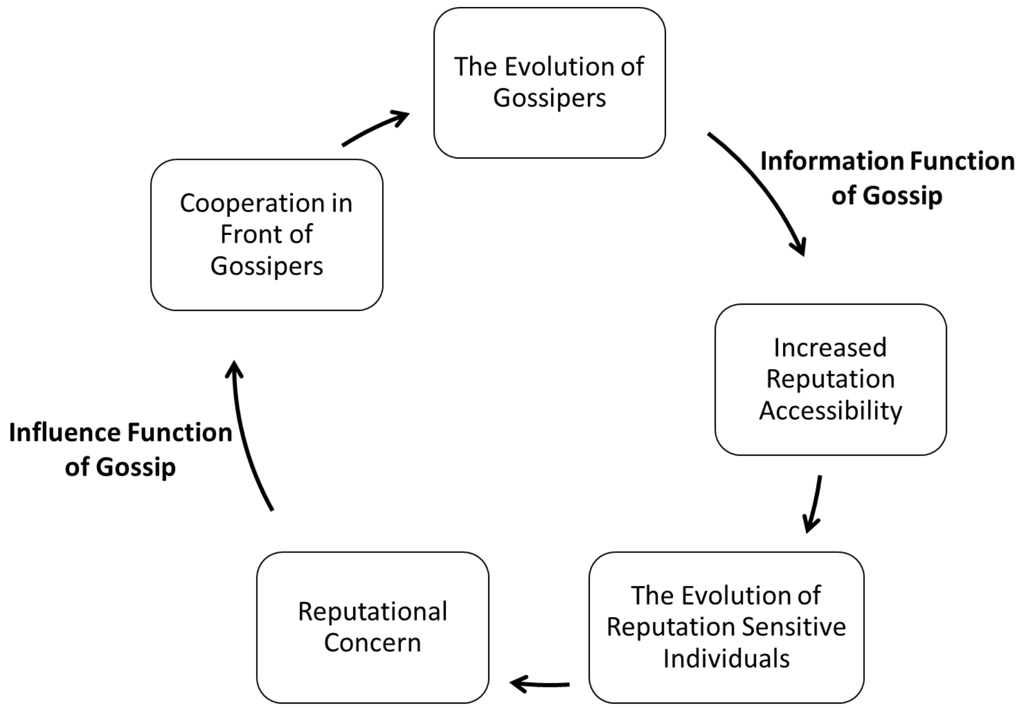
4.1 Summary of Results

This thesis built an agent-based EGT model to examine the functions of gossip in the evolution of cooperation as well as the mechanism of the evolution of gossipers. To do that, in Step 1, I built a model that manifested the information function of gossip. In this model, the existence of gossip increases reputation accessibility. As a result, most agents evolve to utilize reputation information; cooperation increases in the population. These findings are consistent with previous work on indirect reciprocity and the information function of gossip (Enquist & Leimar, 1993; Nowak, 2006; Nowak & Sigmund, 1998a). However, in Step 1, the evolution of gossipers is not observed, which indicates that the information function of gossip alone is not sufficient for explaining why gossipers evolved in the first place.

In Step 2, I built a model that incorporates both the information and the influence functions of gossip. In this model, when agents are able to behave differently in front of gossipers vs. non-gossipers to manage their reputation in gossip, accessibility of agents' true strategies is decreased. Thus, the information function of gossip is compromised. However, a substantial proportion of agents evolve to be susceptible to the influence function of gossip and cooperate when under the threat of gossip. The influence function of gossip leads to more cooperation despite the compromised information function of gossip.

Most importantly, gossipers evolve under the joint impacts of the information and influence functions of gossiper. Specifically, 1) gossipers, 2) the information function of gossip, and 3) the influence function of gossip form a positive feedback loop, which is *sufficient* to sustain the evolution of gossipers (see Figure 24). In the cycle, the existence of gossip increases reputation accessibility through its information function and makes the utilization of reputation information effective and necessary. As reputation becomes more important, individuals are motivated to leave a good reputation in gossip by cooperating with gossipers, in which gossip manifests its influence function. As more individuals cooperate with gossipers, gossipers gain an advantage over non-gossipers and proliferate in the population. The prevalence of gossipers reinforces the importance of reputation and enhances the information and influence functions of gossip. Eventually, most individuals become gossipers and behave cooperatively as a result of the joint impact of the information and influence functions of gossip. Results in Step 2 also show that all the links in this cycle are *necessary* to sustain the evolution of gossipers. If either the information or the influence function of gossip is "blocked," there will not be a substantial proportion of gossipers evolving and the cooperation rate will also be discounted, too.

Figure 24 The Mechanism of the Evolution of Gossipers



4.2 Factors Moderating the Information Function of Gossip

I also examined the factors that moderate the functions of gossip and tested the robustness of the models under a variety of model choices.

First, in Step 1, I examined the factors that moderate the impact of gossip on reputation accessibility. Results show that gossip only increases reputation accessibility when more credible gossip is given more weight in the belief updating process. Moreover, gossip has a stronger impact on reputation accessibility when the amount of information got from direct interactions is not sufficient. Therefore, the information function of gossip is more profound when direct interaction is less frequent, when individuals have more neighbors, and when strategy updating happens more frequently. Furthermore, because gossip only provides secondhand information and there is noise in it, individuals must avoid overusing gossip. Thus, gossip benefits reputation accessibility the most when individuals gossip and rely on gossip neither too little nor too much.

Second, in Step 1, I examined the factors that moderate the impact of gossip on cooperation through its information function. In general, higher reputation accessibility leads to more cooperation, so the situations where gossip is more beneficial for reputation accessibility are also the situations where gossip is more beneficial for cooperation. However, gossip benefits cooperation the most when the information accuracy without gossip is low enough. Thus, gossip has the strongest impact on cooperation through its information function when individuals interact very infrequently, when they only have shallow interactions, when individuals have many neighbors, and when strategy updating happens frequently.

4.3 Factors Moderating the Influence Function of Gossip

I then examined the factors that moderate the influence function of gossip in Step 2. The influence function of gossip can be reflected by the evolution of hypocritical individuals who behave more cooperatively under the threat of gossip. The situations where the influence function is the strongest are *different* from the situations where the information function is the strongest. On the contrary, since the deterrent power from gossipers happens during direct interactions, the influence function of gossip is more prominent when individuals interact frequently and when the interactions are deep. Moreover, the impact of the influence function also depends on whether gossip can convey reputation information effectively. Thus, the influence function is more prominent when bias is high enough, when conversations happen frequently, when individuals have many neighbors, and when individuals rely neither too much nor too little on gossip. Moreover, the influence function is more prominent when the network and individuals' status are relatively steady, i.e., when network mobility is low and when strategy updating is infrequent.

4.4 Factors Moderating the Evolution of Gossipers

Finally, I examined the factors that moderate the evolution of gossipers. Since hypocritical individuals and gossipers evolve hand in hand, in general, the situations where the influence function of gossip is the most prominent are also the situations where gossipers are most likely to evolve. To summarize, more gossipers evolve 1) when individuals interact frequently, 2) when the interactions are deep (i.e., when one can gain much information about their partner from one single interaction), 3) when bias is high, 4) when conversations happen frequently, 5) when individuals have many neighbors, 6) when individuals rely much on gossip, 7) when network mobility is low, and 8) when strategy updating is infrequent.

4.5 Contributions of This Thesis

This thesis has contributed to gossip research both methodologically and theoretically. Methodologically, I created an EGT modeling framework that incorporates the processes of both cooperation and gossiping, incorporates both the information and the influence functions of gossip, and is able to study the role of gossip in the evolution of cooperation as well as the evolution of gossipers. My modeling framework is novel from the following aspects.

First, compared with research on indirect reciprocity that treated one's reputation as a rating that is public to everyone (e.g., Nowak & Sigmund, 1998a), I assume that reputation is stored in people's minds and everyone may have a unique belief of other's reputation based on their previous experiences. The heterogeneity of information is the precondition for gossip to make a difference to reputation accessibility.

Second, compared with the models that directly assumed that gossip increases reputation accessibility (e.g., Enquist & Leimar, 1993), I implement the specific processes of gossip transmission and examine the effects of gossip on reputation accessibility. I show that gossip can only increase reputation accessibility when people give more weight to more credible gossip. In fact, my model can be applied not only to studying the transmission of gossip but also to studying other information diffusion processes in general.

Third, even compared with previous models that also implemented gossip transmission processes (e.g., Giardini & Vilone, 2016), my model is more flexible and realistic. Previous models usually assumed reputation as a one-dimensional judgment that is either "good" or "bad." However, people can behave differently under different conditions. My model incorporates this in the reputation system by making X's reputation in Y's mind as a strategy that captures the *conditional* behaviors that Y believes X will do under different conditions. The belief of other's strategy resembles the ability of theory of mind in human cognition (Dunbar, 1997; Perner, & Wimmer, 1985) and it is essential for individuals to make conditional decisions based on their beliefs of others.

Fourth, different from many other models that assumed that one can know about someone else's strategy after a single interaction (e.g., Giardini & Vilone, 2016), I assume that learning about a person's strategy is a gradual process and people may make mistakes throughout this process. At the same time, people may start gossiping before they get perfect information. This may lead to inaccuracy in gossip and is also the reason why gossip may not benefit reputation accessibility under some conditions. This assumption not only is more realistic but also opens up new directions to examine the factors that influence the accuracy of gossip.

Fifth, in addition to the strategies often used in models of indirect reciprocity (e.g., Nowak & Sigmund, 1998a), I implement two extra gossiper sensitive strategies (i.e., GC and GD). This set-up has gone beyond previous models on the information function of gossip and enabled me to examine the influence function of gossip.

Sixth, and most importantly, my model examines the evolution of gossipers directly. So far as I know, all previous models have set the proportion of gossipers as an exogenous variable, which made it unable to examine why gossipers appear in the first place. Using an EGT framework, I make gossiping behavior an evolvable strategy and examine the evolution of gossipers as an emerging phenomenon.

Finally, the set-ups in the current model go beyond traditional EGT models that assume minimal cognitive ability of agents and focus mainly on population level processes. Based on psychological theories, my model incorporates various intra- and inter-personal processes into the traditional EGT framework, such as belief representation (Johnson-Laird et al., 1999), metacognition (Dunlosky & Metcalfe, 2008), theory of mind (Dunbar, 1997; Perner, & Wimmer, 1985), communication and information diffusion (Weenig & Midden, 1991), trust and information processing (Jaswal & Malone, 2007), etc. Such integration of individual and population level processes expands the scope of application of EGT approach and enables the model to study more complicated social behaviors that are of interest to psychologists, which can be a promising future direction for EGT approach (Pan et al., in press).

My model has also made several theoretical contributions to psychological research. First, in general, my results support previous findings on the information function of gossip. However, I have extended this research by showing that when people cannot differentiate between credible and incredible gossip, the information function of gossip may have a negative effect on the evolution of cooperation. This finding is applicable not only to gossip research but also to research on information diffusion in general.

Second, my model shows that it is evolutionarily adaptive to develop reputational concerns and behave more cooperatively in front of gossipers. The influence function of gossip has been widely discussed in psychological literatures (e.g., Feinberg et al., 2012; Piazza & Bering, 2008; Wu et al., 2019). While empirical studies usually focus on describing the prevalence of this phenomenon, the current model examines the evolutionary basis of it—whether and under what circumstances are hypocritical strategies evolutionary adaptive. Thus, my model is a useful supplementary to the empirical research on the influence function of gossip and the motivation of reputational concerns.

Third, I show that though the influence function of gossip makes it difficult to figure out what others will do privately, it increases cooperation in general because of the prevalence of gossipers. Moreover, the influence function of gossip only benefits cooperation when gossipers really gossip. If gossipers only have the potential to gossip but do not actually share the information, hypocritical individuals will not evolve as much. Thus, the information and influence functions work together to benefit the evolution of cooperation. Though the similar findings can be inferred from previous empirical research, this thesis tests the interactions between the two functions of gossip directly. While it is easy to "turn off" the information function of gossip in empirical studies by prohibiting participants from gossiping, it is usually hard to completely "turn off" the influence function because people in laboratory settings still face the constraints from social norms, reputational concerns, and social desirability (Nederhof, 1985). As a result, it is difficult for empirical research to examine the interactions between the information and influence functions of gossip.

Thanks to the flexibility of agent-based models, my thesis examines the effects of the influence function of gossip directly and expands the scope of empirical research.

Fourth, and most importantly, I have identified the mechanism for the evolution of gossipers. Though the prevalence of gossipers has been proved by numerous empirical studies, it remains unclear why such behavior has evolved in the first place. With a computational model from an evolutionary perspective, I show that the joint effect of the information and influence functions of gossip can sustain the evolution of gossipers. Admittedly, there might be other mechanisms, such as the entertaining or social bonding functions of gossip. Nevertheless, my findings indicate that the role of gossip in cooperation alone is sufficient to explain the prevalence of gossipers in human society. This thesis, thus, has pushed previous research from the "how" to the "why" questions of gossip (Varnum & Grossmann, 2017).

Finally, I have examined the effects of a variety of variables that moderate the effects of gossip on cooperation as well as the evolution of gossipers. Though there is great between-group diversity on these moderators, many of them are difficult to manipulate in laboratory settings, making it hard to test the causal effects of these moderators directly. My model, however, has provided a handy tool to directly test the effects of these moderators. Combined with archival data, these moderators can be used to understand the variance in gossip across societies. For example, my results show that gossipers are more likely to evolve in a population where people have many neighbors, when they have deep and frequent interactions and frequent conversations, when mobility is low, and when strategy updating is infrequent. This is consistent with empirical evidence showing that gossip is more prevalent in rural communities (Haugen & Villa, 2006). This thesis has also raised many testable hypotheses that, once validated by empirical data, can be valuable for psychological research. For example, I show that the information accuracy is the highest when people gossip neither too little nor too much. This result can be used to understand the dynamics of fact vs. fiction dissemination in social media platforms. I also show that the situations where gossip has the strongest influence function are not necessarily the same situations where it has the strongest information function. For example, gossip has the strongest information function when people interact infrequently but has the strongest influence function when people interact frequently. This may be able to explain the puzzle why sometimes a community can have many gossipers while the gossipers are not bringing incremental information. In general, my thesis has raised many testable hypotheses that is worth studying in future research.

4.6 Limitations

I note that my thesis has some limitations. First, though I try to make the strategy set unbiased toward either cooperators or defectors and unbiased toward either gossipers or non-gossipers, the strategies are still not exhaustive. For example, I assume that two exploitive agents (i.e., CDs) will cooperate with each other based on the assumption that when people believe their partners are shrewd, they will tend to mutually cooperate instead of perishing together. However, I aware that other possibilities exist, and it is implausible to include all of them. Nevertheless, my strategy set has already covered more strategies than previous models (e.g., Nowak & Sigmund, 1998a) and my model is not set up to bias toward the findings.

Another asymmetricity in the strategies is that, in my model, while reverse-hypocritical agents (i.e., GDs) pretend to be unconditional defectors (i.e., ADs) in front of gossipers, hypocritical agents (GCs) pretend to be virtuous cooperators (i.e., CC) instead of unconditional cooperators (i.e., AC). I made this choice because in the pilot study, I found that if hypocritical agents pretend to be unconditional cooperators, they will be exploited by exploitive agents (i.e., CDs) and thus be disadvantageous in the evolution. This indicates that hypocritical individuals not only want to appear "nice" in gossip, but also want to send a signal that they are not easy to be exploited. Although this assumption is reasonable, this has made the strategies asymmetric. One way to overcome this is to implement different versions of hypocritical agents, including those who pretend to be ACs, CCs, CDs, etc., as well as different versions of reverse-hypocritical agents. However, that will expand the strategy set dramatically and make the results hard to interpret. Nevertheless, the goal of the current model is not to create an exhaustive strategy set that covers all the possibilities of human behaviors. Instead, I only want to identify one of the possible mechanisms for the evolution of gossipers based on several justifiable assumptions. Future empirical and modeling studies can examine the heterogeneity among gossiper sensitive individuals and explore the evolution of different versions of hypocritical and reverse-hypocritical individuals.

In addition, in this thesis, I assume that once an agent has updated their strategy, they will be treated as a brand-new person. This resembles the death-birth process in evolution, in which strategy updating happens when an individual dies and a new individual replaces their place. However, an individual may change their strategy in the middle of their lifetime and their old and new reputations may be mixed in people's minds as well as in gossip. The current model does not consider such situation, and this may be examined in future studies.

Moreover, like all the other agent-based models, I extracted only a few procedures from the decision-making processes related to cooperation and gossiping. The way that human beings utilize reputation information and react to gossipers should be much more complicated than captured in the current model. There are also many other factors that influence the results. For example, in additions to the information and influence functions, gossiping is also entertaining and can facilitate friendship (Foster, 2004; Shaw et al., 2011). These functions of gossip may also contribute to the evolution of gossipers and cooperation. Nevertheless, the current model can serve as a starting point for models of increasing complexity and realism. It can also be extended to examine the evolution of various other behaviors under the same framework.

4.7 Future Directions

There are many ways to extend the current model. First, future studies can examine the evolution of different gossiping strategies. In the current model, there are only unconditional gossipers who gossip indiscriminatively and unconditional non-gossipers. Future models can implement conditional gossipers whose gossiping decisions depend on the listeners' reputations or the relationship between the gossipers and the listeners. This will be helpful to understand how people form their "communities" of gossip and how information heterogeneity may emerge as a result (Jadbabaie et al., 2013). Moreover, people can also have different strategies for deciding the content of gossip. In the current study, agents randomly choose their gossip targets, and they always gossip honestly. However, people may prefer to spread positive or negative gossip (Grosser et al., 2010), may exaggerate or downplay their confidence, and may intentionally spread inaccurate information for different reasons (Peters & Fonseca, 2020). Future studies can examine the evolution of these behaviors as well as their impacts on information accuracy and cooperation.

From the gossip perceivers' perspective, future studies can also manipulate how people process reputation information. For example, people may be more influenced by negative gossip than positive gossip (Ito et al., 1998). People may be more likely to trust the gossip from someone they have cooperated with. People may have different assumptions of others' strategies when there is no preexisting knowledge available (Fulmer & Gelfand, 2013). Moreover, when hearing a piece of gossip that is different from their prior belief, people may have different levels of resistance and openness (Kruglanski et al., 1993). The current model framework can be modified to incorporate these factors and examine a variety of questions on gossip and cooperation.

Future studies can also incorporate some other mechanisms to the current framework and examine their impacts on cooperation. For example, punishment and gossip are the two well-studied mechanisms in cooperation, which are often compared against each other (Wu et al., 2016). Kniffin and Wilson (2010) argued that gossip is a substitute for formal punishment when the cost of punishment is too high. Future work can incorporate both gossip and punishment in the same model and examine how the two mechanisms interact. In addition, when someone has a bad reputation, there are two ways that people can treat them—to ostracize them or to also defect with them (Giardini et al., 2014). Future studies may also examine the different roles of gossip in these two situations.

Finally, one of the mechanisms for the evolution of cooperation is group selection—though a cooperator might not do better than their fellow defectors in the same population, a group of cooperators may be more successful than a group of defectors (Nowak, 2006). The same mechanism may explain the evolution of gossipers as well. Future research can implement a multi-level selection model and examine its impact on the evolution of gossipers and cooperation.

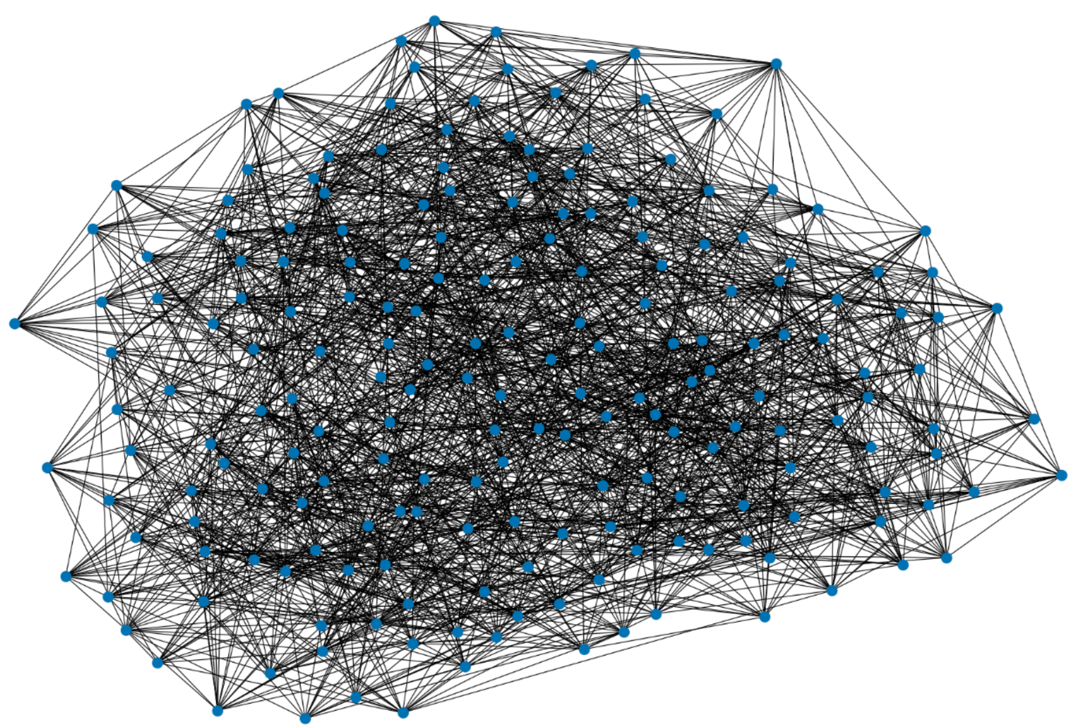
To conclude, this thesis has not only built an agent-based model to examine the functions of gossip and the evolution of gossipers, but also designed an extendable framework that can be used to study a variety of questions on cooperation and gossip in general. Combined with validations from empirical data, my model can be a promising tool for understanding the evolution of cooperation in human society.

Appendices

Model Set-Up: Network Structure

Figure S1 shows an example of the small world network used in the default model. The network has 200 nodes. The average degree of the network, *swK* = 20. The small-world network is generalized with the algorithm in Watts and Strogatz (1998) using the "watts_strogatz_grah(n = 200, k = 20, p = 0.5)" function in NetworkX in Python.

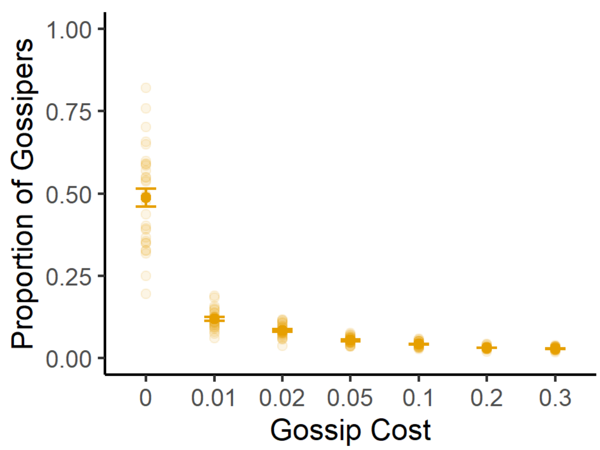
Figure S1 An Example of a Small World Network



Step 1: Effects of Gossiping Cost

Figure S2 shows the evolution of gossipers when gossiping is costly in Step 1. Each condition is got from 30 simulations. In all the conditions, agents talk frequently (*talkF* = 10), but only gossipers gossip. Results show that even if a little cost is implemented to gossiping behavior (e.g., *gCost* = 0.01, which is 1% of the cost of cooperation), it will cause the proportion of gossipers to dramatically decrease. This result shows that the set-up in Step 1 is not sufficient to explain the prevalence of gossipers in human evolution.

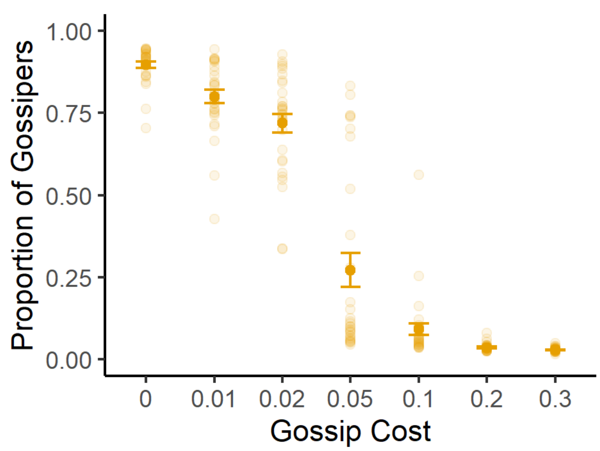
Figure S2 Evolution of Gossipers Under Gossiping Cost in Step 1



Step 2: Effects of Gossiping Cost

Figure S3 shows the evolution of gossipers when gossiping is costly in Step 2. Each condition is got from 30 simulations. 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. 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). These results show that the evolution of gossipers is resistant to moderate cost if both the information and influence functions of gossip are enabled.

Figure S3 Evolution of Gossipers Under Gossiping Cost in Step 2



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