

Persistent Heterogeneous Identities and Evolutionarily Stable Parochial Cooperation*

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Abstract: In tag-based evolutionary Prisoner's Dilemma games, while believing that in-group members are more likely to help each others, agents cooperate with tolerably similar others, and otherwise defect. Current research concludes that when parents leave offspring in proportion to their payoffs, cooperation can emerge and be sustained, but tolerance decreases as societies become more homogenized. Emergent societies based on parochial cooperation are not evolutionarily stable in the presence of mutant free-riders with tolerably similar tags. Instead of genetic inheritance in existing studies, the present research proposes a model of cultural evolution of cooperation in which agents learn tolerance from more successful neighbors and imitate their tags. Two societies are examined: all agents have one non-negotiable identity at the same dimension; and all agents have one non-negotiable identity in different dimensions. We find that agents adapt themselves to increased heterogeneity in both societies so that higher levels of tolerance can be achieved. However, it is in the latter that parochial cooperation can be stably institutionalized in spite of repeated invasions by mutant defectors.

Keywords: group membership identity, parochial cooperation, persistent heterogeneity, loose coupling.

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INTRODUCTION

Many studies have identified a set of conditions that facilitate society-wide and stable cooperation in multi-agent Prisoner's Dilemma games. If people have highest levels of trust toward others and they always cooperate with each other, then such societies are vulnerable to defectors. Human societies are based on lower levels of trust toward others. Parochialism as a preference for favoring the members of one's group is a nearly universal human predisposition.

How can society-wide cooperation at the global level emerge from local interactions of human agents who may have limited tolerance for cooperating with others who they see as different from themselves, then? If people cooperate only with similar others by reading observable traits, called 'tags,' without selection pressure, then within-group cooperation and between-group non-cooperation result in low levels of global cooperation. However, if parents with higher levels of fitness leave more offspring with their genetic traits in the next generation, then the population becomes more composed of those who take more discriminating actions against out-group as societies become more homogenized. In spite of a continuous erosion of tolerance, high levels of global cooperation can be maintained in increasingly homogeneous populations (e.g., 'mechanical solidarity' in a Durkheimian sense).

The stability of this tag-based parochial cooperation, given that tolerance is not an observable trait, depends on whether or not shared beliefs about tags predicting each other's behavior – 'in-group members will reciprocate their cooperation' – continue. The consequence is that tag-based cooperative societies are not robust against mutant free-riders with tolerably similar tags because they are predisposed to defect, but existing cooperators recognize them as in-group to cooperate toward them. Once the shared belief is broken, cooperation as an institutional order (i.e., behavioral regularities) turns into cascades of non-cooperation (i.e., deinstitutionalization followed by a society of mutual betrayal).

Given these weaknesses in tag-based cooperative societies, the present study seeks to find alternative societies in which parochialism is not strong, tag diversity is not wiped out, and cooperation is evolutionarily stable. Existing models of tag-based cooperation are based on the idea of

genetic inheritance: human agents have tags and tolerance as inheritable traits; they are copied from parents to offspring with a small amount of mutation; and parents leave offspring in proportion to their fitness measured by payoffs in the previous generation. The key issue here is that tags are completely changeable in both processes of genetic copying and mutation. This is one major reason for the vulnerability of parochial cooperators to invasion by indistinguishable mutant defectors.

The present study highlights differences between genetic transmission and cultural transmission. In models of cultural evolution of cooperation, agents (i.e., the same set of individuals over time instead of parents and offspring) learn tolerance and imitate tags from successful others with a small amount of learning errors (i.e., instead of mutation) after playing the Prisoner's Dilemma game at every round. In our model of cultural evolution of cooperation, tags are conceptualized as cultural markers (i.e., simple forms of identities) with different levels of changeability. In alternative tag-based societies, each agent has one core identity which is not subject to both learning and its error: all agents have such a core identity at the same dimension in one society, like a caste society, but in different dimensions in the other society, like a modern society. We compare the dynamics of tag-based parochial cooperation among models of genetic and cultural transmission – the likelihood of the emergence of universal cooperation, the characteristic levels of tolerance and tag diversity, and the stability of cooperative clusters in the presence of mutation.

THEORETICAL BACKGROUND

How to explain cooperation in human societies? Imagine the following simple situation: if Person 1 helps Person 2 at a cost c , Person 2 receives a benefit b ; and if Person 1 does not help, both individuals receive zero payoff. If $b > c > 0$, then this situation is the same as the Prisoner's Dilemma game. Since the payoff of cooperation, $b - c$, is smaller than the payoff of defection, b , the classical game theory contends that if both individuals are self-interested, then they are worse off.

Evolutionary game theory has tackled cooperation in the Prisoner's Dilemma game from a different angle of Darwinian selection. Given genetic predispositions toward certain patterns of

human behaviors – whether or not to help others, a cooperative society is impossible if agents interact with randomly matched others, and parents leave their offspring in proportion to their fitness measured by their payoffs because the payoffs of defectors are higher than the payoffs of cooperators. For example, once a mutant defector (or an immigrant free-rider) receives a higher payoff than any other member in a society purely composed of those who always cooperate with others, the number of defectors increases over time. They finally constitute the population.

Nowak and May (1992) validate that if cooperators, although they always help others, locally group together to gain disproportionate benefits while avoiding defectors, then there can exist dynamic equilibria in which cooperators co-exist with defectors. Natural selection favors defectors over cooperators in unstructured populations, but global cooperation can be enhanced under the very simple condition of ‘viscosity (Hamilton 1964)’ – limited dispersal of offspring in the neighborhood, not their random dispersal, through which cooperators can benefit from more interactions with their own kind and less interactions with defectors.

However, there are some problems in this idea of ‘spatial reciprocity.’ First, it is assumed that agents are supposed to always cooperate with all neighbors (‘the good guy’) or always defect toward them (‘the bad guy’). In other words, they have either highest or lowest levels of trust. The second problem is the sensitivity to the payoff change: the benefit-to-cost ratio (b/c) should be higher than the average degree of network, that is, the average number of adjacent neighbors (Ohtsuki, Hauert, Lieberman, and Nowak 2006). Otherwise, unconditional cooperators cannot survive in the presence of unconditional defectors. Note that in reality either the incentives for cooperation are relatively low or the number of interaction partners in social networks is relatively high, or both.

Recent research has highlighted the roles of discriminators in the evolution of cooperation in human societies. The question is what if there were not only unconditional cooperators and unconditional defectors but also conditional cooperators, who have intermediate levels of trust and therefore cooperate only with reliable partners. The related question is how human agents are able to know who are more likely to cooperate and who are not.

Existing studies on kinship-based altruism (Hamilton 1964), direct reciprocity (Trivers 1971;

Axelrod 1984), and indirect reciprocity (Nowak and Sigmund 1998) can be reinterpreted in the context of ‘cue-based cooperation’ we call. The kinship hypothesis is that the propensity to cooperate between two individuals is affected by how much genes they share. The more genetically related, the more reliable, and the more cooperation. The behavior of an opponent on the previous round serves as a cue in the ‘Tit-for-Tat’ strategy, according to the theory of direct reciprocity between the same two individuals. An individual’s image score is a cue in an indirect form of reciprocity, that is, ‘your cooperative behavior will be rewarded by third parties (i.e., not necessarily the recipient of your help) reading your increased reputation.’ The established finding is that if human agents read cues to cooperate conditionally with acceptable partners, then cooperation can be maintained even in unstructured populations at a broad range of the benefit-to-cost ratios.

The present study is interested in observable markers called ‘tags’ because we intend to explain the evolution of cooperation among genetically unrelated multi agents with minimal cognitive requisites for partner identification. Human agents have tags as the phenotype of “memes (Dawkins 1976)” – to form “memetic kin” (Heylighen and Campbell 1995). Reading tags enables humans to make distinctions between in-group members and ‘others.’ This tag-based partner identification, called ‘tagging,’ is consonant with socio-psychological theories of group membership as social identities (Hoggs 2007) through categorization (Tajfel 1974).

Recent research on tag-based systems reports that tag-based discriminating actions among randomly selected agents significantly enhance the level of global cooperation in multi-agent Prisoner’s Dilemma games (Riolo, Cohen, and Axelrod 2001). Agents may display “in-group favoritism (Hammond and Axelrod 2006),” “parochialism (Bowles and Gintis 2004)” in choosing how to interact, based on their tolerance of differences with others.

Riolo et al. (2001) has become a classical study for modeling of tag-based cooperative societies. In their study, what action an ego chooses is contingent on whether or not her perceived social distance to an opponent is less than or equal to her tolerance level. They demonstrate that if agents cooperate only with others with tolerably similar tags and they leave offspring in proportion to their fitness, then societies reach high levels of cooperation. However, both tolerance and tag diversity

decrease drastically as the average level of cooperation increases rapidly.

Tag-based parochial cooperation in emergent societies is not evolutionarily stable. If a mutant agent is introduced who is sufficiently similar to the majority of parochial cooperators, but who are less tolerant than them, global cooperation can disintegrate. Nonetheless, once more tolerant agents with similar tags are born through mutation and they help each other, another transition is possible along with an increase in the average tolerance. This is why Riolo et al. (2001: 442) observe endless cycles of cooperative societies and betrayal societies to conclude: “in our model, the cycle of increasing and decreasing tolerance could reflect, for example, a loss of sensory discrimination in a population when there is little selection pressure to retain it, followed by a recovery when a more discriminating individual succeeds.”

Are there mechanisms that might enable a society to establish robust parochial cooperation without a great amount of erosion of diversity and tolerance, then? The evolutionary instability of parochial cooperation is due, in part, because agents are born through mutation who have both the lowest level of tolerance (i.e., they are predisposed to defect) and tolerably similar tags (i.e., they are recognized as in-group members). Given this point, the present study should point out that existing models underscore genetic evolution of cooperation to assume tags are completely changeable.

In one study on the co-evolution of cooperation and linguistic codes associated with group membership, Nettle and Dunbar (1997: 98) bring up more sociological concepts of cultural markers as simple identities: “The free-rider... could not possibly survive in populations where each local group had its own language or dialect. Each group would be able to tell by his speech that he was an outsider and where he came from. This is not to imply, of course, that social identity is an unchanging, clear-cut matter. In real life, it is always being renegotiated and redefined and loses or gains significance according to the situation at hand.” In other words, some markers are less changeable (e.g., skin color), while others are more changeable (e.g., linguistic codes, attitudes, and opinions).

We therefore propose an alternative model of cultural evolution of cooperation in which tags as cultural markers and simple identities have different levels of changeability: tags and tolerance are learned from more successful neighbors with a small amount of mistake. This payoff-based trait

updating is equivalent to the rule that tags and tolerance are genetically transmitted from parents to offspring with a small amount of copying errors (i.e., mutation); and each agent in alternative societies is assumed to have one core identity which is not subject to both learning and its error.

We want to compare the evolutionary dynamics of tag-based parochial cooperation across three models: the baseline model of genetic evolution of cooperation (Baseline Model); a caste society in which each agent has such a core identity at the same dimension, and therefore the society as a whole does have one unchangeable master culture (Model 1); and a modern society in which each agent has such a core identity in different dimensions, and the society as a whole does not have any master culture (Model 2).

THE MODEL

We use the NetLogo Version 4.0.2 (Wilrensky 1999). The baseline model of genetic evolution of cooperation (Model 1) consists of the following six steps:

1) at the beginning, 49 agents with randomly assigned genetic traits – both tags and tolerance – are located on a torus with the Moore Neighborhood. For agent i , tags $t_i \in \{0, 1\}^L$ and tolerance $T_i \in \{0, 1, \dots, L + 1\}$. Here, L stands for the tag length;

2) if $L = 0$, agents cannot make a distinction between ‘us’ and ‘them’; otherwise, they perceive dissimilarity based on the Hamming Distance defined by $HD_{ij} = \sum_{k=1}^L |t_{ik} - t_{jk}|$. Therefore, $\text{Min}(HD) = 0$ and $\text{Max}(HD) = L$;

3) agents locally interact with adjacent neighbors. If $HD_{ij} < T_i$, agent i cooperates with j ; otherwise, defect. Suffice to say here that agent i can take different discriminating strategies across her eight local alters, for instance [CDCDDCD];

4) each agent’s payoff is calculated after all interactions in the population (Table 1) If an ego cooperate, she pays cost c to produce benefit b . If she defects, she can take b without c . Table 1

satisfies two conditions for the Prisoner's Dilemma game, $T > R > P > S$ and $2R > T + S$ when R, T, S, and P stands for Reward for Mutual Cooperation, Temptation to Defect, Sucker's payoff, and Punishment for Defection, respectively;

5) if there is no mutation, given one local neighbor randomly chosen, if her payoff is higher than an ego's payoff, the ego's tags and tolerance are replaced by her tags and tolerance. In the presence of mutation, the ego's tags and tolerance are changed into randomly selected traits; and

6) we store the longitudinal data of the proportion of cooperation, the average tolerance, and the average perceived dissimilarity. As described above, Model 2 is exactly the same with the baseline model except the fact that all agents have one non-negotiable identity at the same dimension. In Model 3, all agents have one unchangeable identity in different dimensions.

We cannot overemphasize the importance of verification in agent-based modeling. Regarding this, there are two points to be addressed here. First, tags and tolerance are assigned randomly to agents from $U [0, 1]$ in Riolo et al. (2001). For agent A and B, if $|t_A - t_B| \leq T_A$, then A cooperate; otherwise, defect. Edmonds and Hales (2003) find that Riolo et al. (2001) would have had lower levels of global cooperation if they had used $|t_A - t_B| < T_A$. Roberts and Sherratt (2002: 500) bring up the same issue of whether cooperation or not when A and B have exactly the same tags and T_A is 0 in Riolo et al. (2001). Agent A will cooperate in their model, but not in the setting that $|t_A - t_B| < T_A$. In our models, Agent A will defect in spite of no difference between two tags as long as T_A is 0 (i.e., "Always defect"). In the same way, C will cooperate as long as T_C is $L + 1$ (i.e., "Always cooperate") because the maximum identity difference is L . Second, Edmonds and Hales (2003) also point out that the selected bias method (i.e., "higher than or equal to") in Riolo et al. (2001) brings about higher levels of cooperation. We use the no bias method (i.e., "higher than") for all three models.

EXPERIMENTAL DESIGN

In a two-way factorial experimental design, the ratio of benefit to cost and the tag length are expressed in columns and rows, respectively (See Table 2). 100 independent repetitions were

implemented for each group G_{ij} . The baseline model has 2,000 cases in total. Since there are no differences among three models when $L = 0$, each of alternative models has 1,500 cases in total. The mutation rate was controlled as 0. Each replication is run during 1,000 time-steps. In the absence of mutation, it is run until societies reach either universal cooperation or universal defection (i.e., the proportion of cooperation is either 1 or 0).

SUMMARY OF FINDINGS

The effects of local interaction without doing distinction (i.e., $L = 0$) are not sufficient for the evolution of cooperation when the b/c ratio is less than 8 (Table 3). This is consistent with Ohtsuki et al. (2006) who substantiate a very simple rule that cooperation can survive if the b/c ratio exceeds the average number of neighbors ($k = 8$ in our study) in a population of unconditional cooperators and defectors regardless of network topology.

However, local interactions based on group membership identities make a very favorable condition for the evolution of parochial cooperation. It is not shown here, but cooperative clusters can survive even at the simplest tag (i.e., $L = 1$) with the chance of 3% when $b/c = 4$, 3% when $b/c = 6$, 8% when $b/c = 8$, and 13% when $b/c = 10$ in the model of genetic inheritance. We find another tendency that the longer tag, the more efficient distinction, the higher chance that cooperative culture survives. Regarding this effect of tag length, it also turns out that five dimensions ($L = 5$) are sufficient to facilitate its stable institutionalization. Overall, there are no average differences across three models in the possibility of the survival of cooperation.

For the first few generations, within-group cooperation and between-group non-cooperation co-exist, but the number of different tag clusters declines over time. As societies become more homogenized, agents become more parochial. Finally, the absolute majority are those who are willing to cooperate only with neighbors who have the exactly same tags. Despite that more tolerant agents can remain at higher b/c ratios, tolerance dramatically decreases to 1 over time at a broad range of the

b/c ratios when $L = 5$ (See Figure 1). However, as the tag length becomes longer (e.g., $L = 10$ or 20) and therefore agents are able to do more fine-grained distinction, the chance that less parochial agents survive increases although agents with the minimum tolerance for cooperation are still the majority (Figure 1). According to the ANOVA test, the levels of averaged tolerance in the models of cultural transmission are higher than that in the model of genetic inheritance. When holding L constant, the average tolerance is highest in Model 2; the second highest in Model 1; and lowest in Baseline Model (See Table 4).

Not surprisingly, the average of perceived social distances increases in proportional to the number of identity dimensions (Figure 2). Given the same tag length, the degree of cultural diversity is significantly higher in both models of cultural transmission than that in the model of genetic inheritance because of increased heterogeneity given one core identity: the highest heterogeneity in Model 2; the second highest in Model 1; and the lowest in Baseline Model (Table 5).

In the presence of 1% mutation, parochialism-based cooperative societies cannot persist when mutant defectors can exploit surrounding cooperators who perceive those defectors with similar tags as in-group members. As is reported in Riolo et al. (2001: 442), “the vulnerability of the dominant cluster is realized when a mutant’s tag happens to be within the range of tolerance of the typical member of the dominant cluster, but the mutant’s own tolerance range is small enough to prevent its donation to members of the dominant cluster... The result is that the fortunate mutant has many offspring over the next few generations, and soon establishes a new cluster of agents with similar tags and similar (low) tolerances.” The transition rate from a cooperative society to a betrayal society is faster in structured populations than that in unstructured populations (i.e., random matching). It is also possible for parochial cooperative culture to reemerge and spread out as long as agents with $T \geq 1$ can benefit from each other while avoiding interactions with defectors. This shift from a betrayal society to a new cooperative society happens faster among connected agents than otherwise.

There seem to be a couple of solutions for alternative tag-based societies in which human agents are more tolerant of heterogeneous others, but parochial cooperation is significantly stable in spite of

repeated perturbations caused by defectors with tolerably similar tags. First, very high rates of mutation (in both tags and tolerance) could supply enough heterogeneity to enable agents to continue to draw distinctions between ‘us’ and ‘them.’ Particularly, mutant discriminators are more frequently generated and they reciprocate each other’s help before cooperation is completely wiped out (See Figure 3). However, as the amount of copying errors increases, tag-based cooperation can be more robust against invasion by mutant defectors in terms of stability, but the level of global cooperation becomes low in terms of efficiency. Besides, too high and arbitrary mutation rates are not acceptable in evolutionary dynamics.

Second, larger societies would be more likely to display stable cooperation because limited dispersal of offspring in the neighborhood, in other words, assimilative influence through local learning cannot overcome increased diversity in both tags and tolerance (See Figure 4). Increased path lengths in large-sized societies make tag-based cooperation more robust in terms of stability, but with a decrease in the level of global cooperation in terms of efficiency.

We find that the average levels of tolerance and tag diversity are significantly higher in both models of cultural transmission than those in the baseline model. More importantly, however, there is a huge difference between Model 1 (‘caste societies’) and Model 2 (‘modern societies’) in the long-term evolutionary dynamics of parochial cooperation. As Figure 5 shows, parochial cooperation can be very stable only in modern societies although agents in modern societies, on average, are more tolerant of culturally different others (including defectors) than agents in caste societies. It should be noted here that there remain a significant number of tag clusters without penetrating each other in modern societies. Modern societies are based on local convergence but global divergence of cultural identities, while caste societies are characterized by local convergence and global convergence of cultural identities.

DISCUSSION AND CONCLUSIONS

We observe two fundamental problems in tag-based cooperative societies. First, parochial agents

displaying stronger discrimination against out-group are more likely to survive. Nonetheless, they continue to cooperate with each other because the degree of tag diversity in the population decreases over generations. From a view of cultural transmission, we can say that: agents learn intolerance from more successful others as societies become more homogenized under assimilative influence; and high levels of cooperation are still possible in spite of a huge erosion of tolerance because it is more likely that cooperation occurs among more homogeneous agents. Finally, the most discriminating cooperative agents, who cooperate only with identical others, are the majority in the population because they win against defectors, and they are also always as good as more tolerant agents.

Second, if a mutant who is predisposed to exploit others has tolerably similar tags to existing parochial cooperators, such a mutant earns a higher payoff (i.e. fitness) to invade the population successfully. Therefore, the number of offspring with her tolerance and tags increases over generations. Less parochial agents perceive a broader range of partners as in-group, so they are more likely to be vulnerable to mutant defectors with similar tags. However, even the strongest parochial cooperators are also vulnerable to mutant defectors with exactly the same tags. This is exactly in parallel to the conclusion from some other studies about the emergence of unstable cooperation among agents who cooperate conditionally with acceptable partners by reading ‘cues’ such as image scores (Nowak and Sigmund, 1998), signals (Miller et al., 2002), or linguistic markers (Nettle and Dunbar, 1997). Generally saying, once mutants who are more likely to exploit others perturb an associative co-evolution of cues and behavioral patterns, cue-based cooperation becomes no longer stable.

The evolutionary instability of tag-based parochial cooperation among a small number of agents in the presence of a small amount of mutation has yet to be solved. The present study seeks to find theoretical possibilities for tag-based societies to achieve stable but relatively high levels of cooperation without significant loss of tolerance and tag diversity. We demonstrate the necessary condition for alternative tag-based cooperative societies: parochial cooperators should be able to share a minimal number of core identities that are difficult for defectors to imitate. It is not shown here, but there seems to be another condition given our finding that caste societies (Model 2) are characterized

by local convergence and global convergence of cultural identities, whereas modern societies (Model 3) by local convergence and global divergence. In other words, different tag clusters should be loosely coupled (cf. Perrow 1984) in order for complex systems to be robust in the face of perturbation. Otherwise, cooperative clusters are easily destroyed through cascades of non-cooperation triggered by indistinguishable mutant defectors.

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Table 1. Payoff Matrix in Prisoner's Dilemma Game

	Cooperate	Defect		Cooperate	Defect
C	$b-c, b-c$	$-c, b$	C	$(b/c) - 1$	-1
D	$b, -c$	0, 0	D	b/c	0

Note: Payoff matrix in the right panel is a translated version of the left one for our models.

Table 2. Summary of Experimental Design

	b/c				
L	2	4	6	8	10
0	G_{11}	G_{12}	G_{13}	G_{14}	G_{15}
5	G_{21}	G_{22}	G_{23}	G_{24}	G_{25}
10	G_{31}	G_{32}	G_{33}	G_{34}	G_{35}
20	G_{41}	G_{42}	G_{43}	G_{44}	G_{45}

Table 3. The Possibility of Cooperation

	b/c				
L	2	4	6	8	10
0	0	0	0	0	1
5	94/85/97	98/96/98	95/95/100	96/90/100	94/93/100
10	100/96/99	97/100/100	100/99/100	100/98/100	99/99/100
20	100/100/100	100/100/100	99/100/99	99/100/100	100/100/100

Note: The number in each cell represents how many times cooperative culture survives out of 100 trials in Baseline Model, Model 1, and Model 2 from the left to the right. For examples, when $L = 5$ and $b/c = 4$, that chance is 98% in Baseline Model, 96% in Model 1, and 98% in Model 2.

Figure 1. Means of Final Tolerance

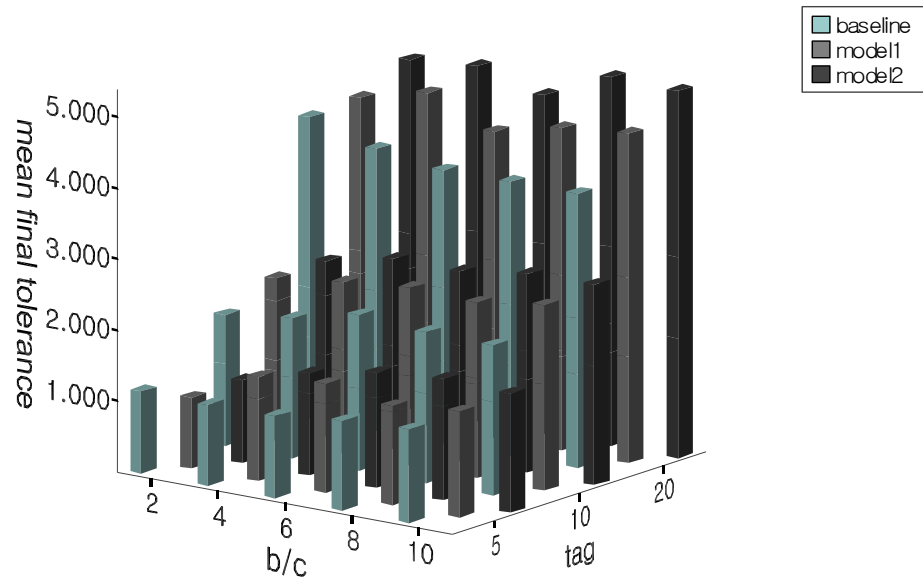


Table 4. ANOVA Test on Average of Final Tolerance

<i>L</i>	Baseline Model	Model 1	Model 2	<i>p</i> -value	Post-hoc test (Scheffe)
5	1.2605(.4629)	1.4986(.5404)	1.5374(.5111)	0.000***	Baseline-Model 1*** Baseline-Model 2***
10	2.0628(.9644)	2.4923(.7357)	2.6853(.7204)	0.000***	All pairs***
20	3.9650(2.0360)	4.5197(1.8026)	5.0065(1.5626)	0.000***	All pairs***

* $p < .05$ ** $p < .01$ *** $p < .001$ (two-tailed tests)

Figure 2. Means of Final Average Dissimilarity

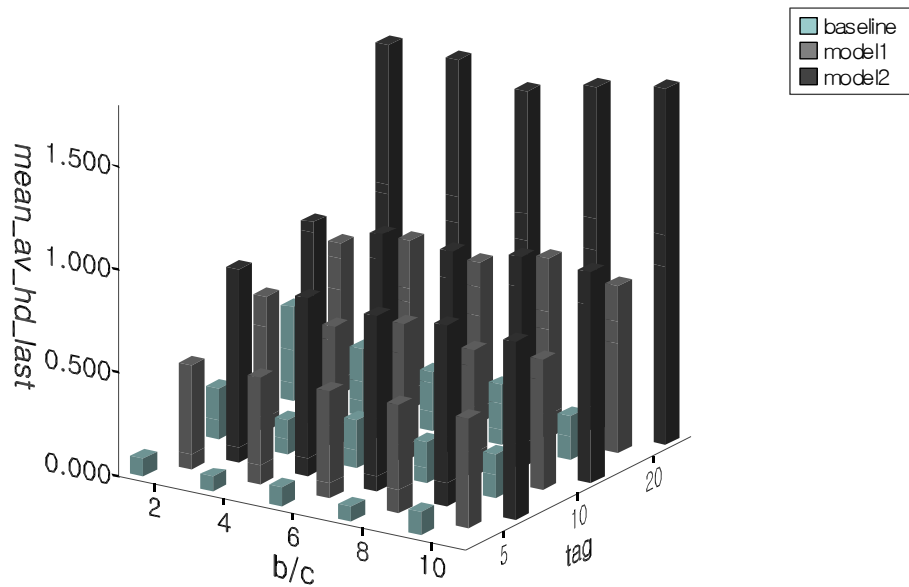
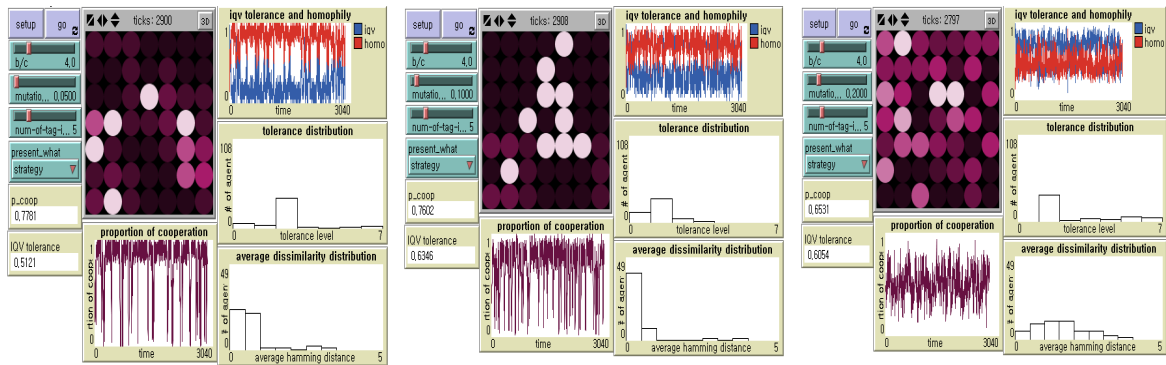


Table 5. ANOVA Test on Average Final Dissimilarity

<i>L</i>	Baseline Model	Model 1	Model 2	<i>p</i> -value	Post-hoc test (Scheffe)
5	.0870(.2128)	.5183(.1087)	.8754(.1690)	0.000***	All pairs***
10	.2102(.4283)	.6265(.3234)	.9969(.2081)	0.000***	All pairs***
20	.3138(.7545)	.7994(.7379)	1.7633(.5546)	0.000***	All pairs***

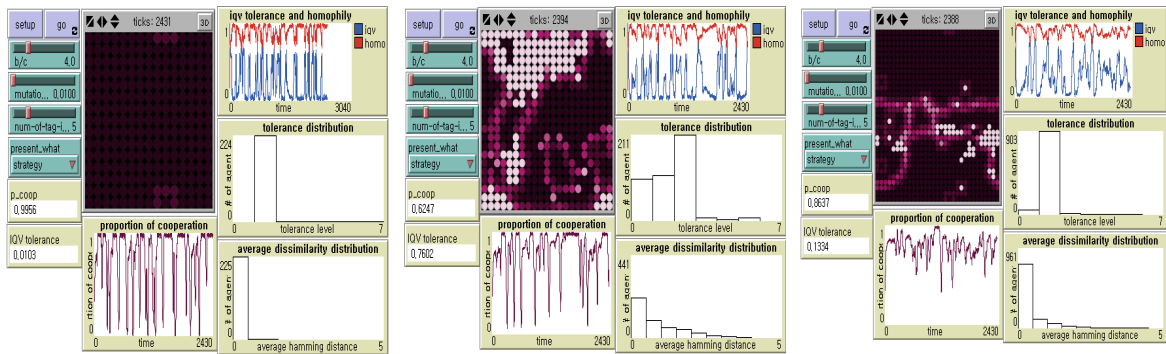
* $p < .05$ ** $p < .01$ *** $p < .001$ (two-tailed tests)

Figure 3. Dynamics of Tag-based Cooperation with Varying Mutation Rates



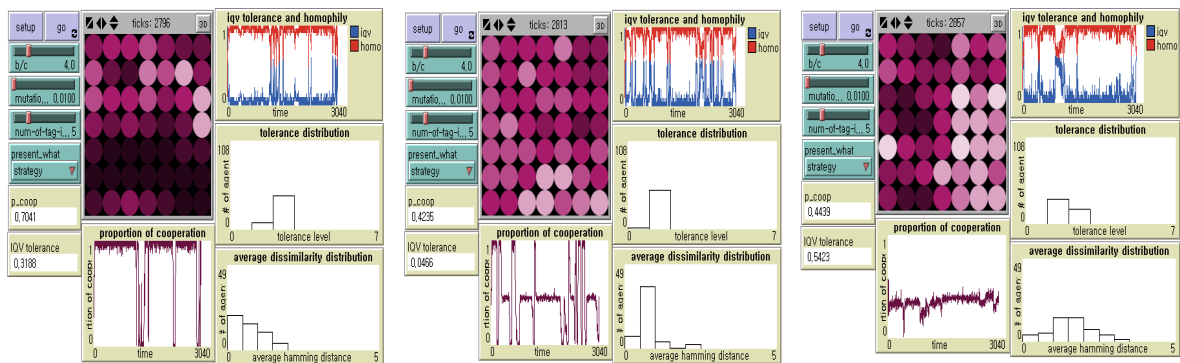
Note: Baseline Model. The mutation rate is 0.05 (Left); 0.1 (Middle); 0.2 (Right), holding $b/c = 4$ and $L = 5$ constant.

Figure 4. Dynamics of Tag-based Cooperation with Varying Population Sizes



Note: Baseline Model. The number of agents is $225 = 15 \times 15$ (Left); $441 = 21 \times 21$ (Middle); $961 = 31 \times 31$ (Right), holding $b/c = 4$, $L = 5$, and the mutation rate = 0.01 constant.

Figure 5. Dynamics of Tag-based Cooperation in the Presence of Mutation



Note: Baseline Model (Left); Model 1 (Middle); Model 2 (Right), holding $b/c = 4$, $L = 5$, and the mutation rate = 0.01 constant.