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REGULAR ARTICLE

# Modeling collective adaptive agent design and its analysis in Barnga game

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**Abstract** This paper explores the collective adaptive agent that adapts to a *group* in contrast with the individual adaptive agent that adapts to a *single user*. For this purpose, this paper starts by defining the collective adaptive situation through an analysis of the subject experiments in the playing card game, Barnga, and investigates the factors that lead the group to the collective adaptive situation. Intensive simulations using Barnga agents have revealed the following implications: (1) the leader who takes account of other players' opinions contributes to guide players to the collective adaptation situation, and (2) an appropriate role balance among players (i.e., the leader, the claiming and quiet players, which make the most and least number of corrections of the leader's decision) is required to derive the collective adaptive situation.

**Keywords** Agent-based simulation · Collective adaptive situation · Barnga · Cross-cultural interaction · Leader

## 1 Introduction

Agent-based simulation (ABS) (Axelrod 1997; Gilbert and Troitzsch 2005) contributes to enriching the understanding of the social complex systems and phenomena

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in a variety of areas such as economics, organization, science, and business context (See details in Shen et al. 2006). Eric Bonabeau mentioned that one of the benefits of ABS over other methods is that ABS provides an emergent behavior (Bonabeau 2002) caused by the interactions among agents. Such interactions are indispensable in the real society as our human society is based on the *cross-cultural* interaction where humans with different characteristics interact with many persons in a variety of situations.

However, the conventional agent models proposed in ABS do not directly and explicitly consider the cross-cultural interactions (Arthur et al. 1997; Prietula et al. 1998). Although the study by Erev and Roth (1998) explored the model of the agent that can produce the similar result with humans in the context of *experimental economics* (Friedman and Sunder 1994; Kagel 1995), which is one of the methodologies in *behavioral economics* (Wilkinson 2008), their result is based on the assumption that the actions of agents are predetermined, which can only investigate a certain aspect of human behaviors. If we take an examples of *bargaining game* (Rubinstein 1982), which has been studied in the context of *bargaining theory* (Muthoo 1999, 2000), the players only have to select one of the predetermined actions (e.g., 10 ways of offers which range from 10 to 100%). Such limitation enables us to calculate the equilibrium theoretically or mathematically. However, when we consider the cross-cultural interactions such as an adaptation to a cross-cultural group where there is no fixed number of actions for agents and no clear Nash equilibrium, it is quite difficult to model the agent that can cope with such situations due to its complexity and ambiguity.

Despite of the fact that the cross-cultural interactions are indispensable in our real society, only a few researches addressed such interactions in ABS until now. Yamada and Takadama (2004) tried to model the interactions with multiple agents by considering the adaptation to a group, which was defined as the collective adaptation. Yamada defined its situation as the balance between adaptation (i.e., the change of one's mind to others) and diversity (i.e., the recognition of difference from other's mind). However, this decision makes it hard to determine the appropriate balance of the collective adaptive situation. In addition, Omura designed the social adaptive agent which tried to adapt the group (Omura et al. 2008), but did not find any conditions that enable the agents to lead the collective adaptation. As other related works, Oumi et al. (2006) proposed an agent model that could reach consensus and analyzed characteristics of agents in the consensus situation. However, this model did not deal with a leader required to derive the collective adaptive situation and the effect of the leader, which have attracted much attention in the area of *group dynamics* (Cartwright and Zander 1968) and *organizational behavior* (Hersey et al. 1977), in which intensive researches on the theory of a leader have been done.

To overcome these problems, this paper aims at defining the situation of collective adaptation through subject experiments in the playing card game called Barnga Thiagarajan and Steinwachs (1990), which is based on the cross-cultural interaction among players. This paper then explores the model of the collective adaptive agents and investigates the factors that lead the group to the collective adaptive situations in the computer simulations.

This paper is organized as follows: Sect. 2 introduces the playing card game Barnga. The collective adaptive situation is defined in Sect. 3 according to the subject experiments on the Barnga. The Barnga agent is designed in Sect. 4, and the results of two simulations on the Barnga are presented in the Sects. 5 and 6. Finally, Sect. 7 gives our conclusion of this research.

## 2 Barnga: cross-cultural communication game

*Barnga* is a playing card game, developed by Thiagarajan and Steinwachs (1990) in the area of *gaming simulation* (Greenblat 1988) and is used for a variety of areas such as computer science (Leon Suematsu et al. 2005; Yamada and Takadama 2004; Omura et al. 2008), social science (Hoy 2001), education (Gallavan and Webster-Smith 2009), nursing (Koskinen et al. 2008), and etc. In Barnga game, the players experience how they should behave in the cross-cultural situation. Barnga is played as the following sequence: (1) the players divided by the number of tables have several cards that range from A to 7; (2) they put one card in turn, and decide the winner who puts the strongest card. In the basic rule, the larger a number is, the stronger a card is. Barnga has the trump card (i.e., heart or diamond) and ace-strong/weak rule. The trump card becomes the strongest when the card is put, while the ace-strong/weak rule determines that the ace is the strongest/weakest number. For example, the strong order in the ace-strong rule is “A”, “7”, “6” “5”, “4”, “3” “2” while the one in the ace-weak rule is “7”, “6” “5”, “4”, “3” “2”, “A”; (3) a winner is determined among the players; This is a whole sequence of Barnga and can be counted as one game.

Note that (i) each table has the slightly different rule (except for the basic rule). Figure 1 shows an example of the situation where players have different rules. Due to such differences, the players think of the different card that is the strongest in the game, which leads to conflicts of the opinions; (ii) every player does not know such differences among the tables, which represents the cross-cultural situations, some players are swapped within tables every several migration process, and then the players meet other players who have different rules after the migration as shown Fig. 2. Plus, what should be noted here is that conversation among the players is not allowed during the

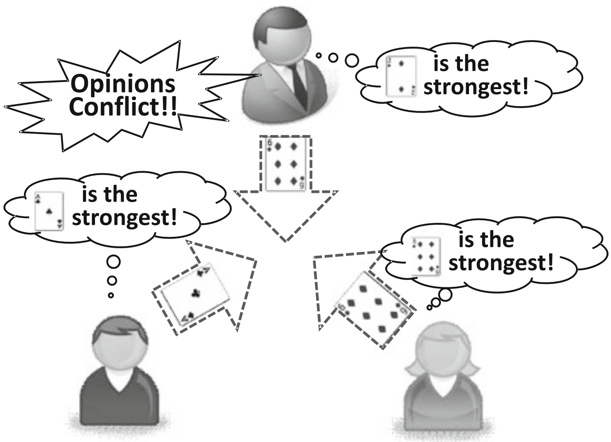



**Fig. 1** Situation of players with different rules in a group

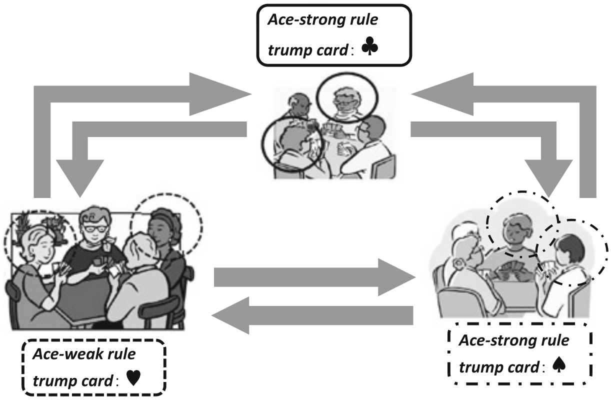



**Fig. 2** Migration process

game, which force the players to interact with non-verbal communication like body languages to determine the winner. Barnga differs from bargaining game or prisoner's dilemma (Poundstone 1993) in experimental economics, in the sense that the players are required to negotiate the decision of the game without oral communication. This indicates that there is no fixed number of negotiation strategy and that such interactions in Barnga game are more complex than that of experimental economics. Under this circumstance, the players have to play the games smoothly to adapt to the situations, i.e., they need to play games without any conflicts. Here, we define the *smooth game* as the one which is played without any conflicts.

## 3 Collective adaptation in Barnga

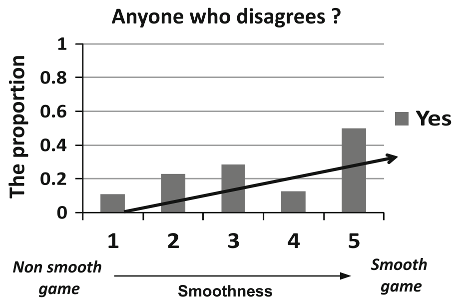
This section analyzes the subject experiment of Barnga to identify the smooth game. Note that the smooth games are normally played in the situation where the players adapt to other players.

### 3.1 Subject experiments and results

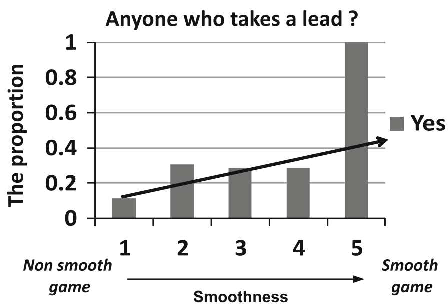
The examinees played Barnga game and the results were analyzed from the viewpoint of the smooth games. Concretely, we investigate the answers to the questionnaire such as "Do you think the smooth games occurred (the score for the smoothness from 1 to 5. 5 is the smoothest)?", "Why (not) do you think so?". For this purpose, two times of experiments were conducted with four tables with 4 players. 14 games (i.e. a winner is determined 14 times) were played in one round and there was the migration process after one round. Such round is played 3 times (i.e. 2 times of migration).

Figure 3 shows the results of the subject experiments. The graphs indicate the proportion of (a) a *leader* who decided the winner to reach consensus decision when two or more different winners were nominated, (b) the *claiming player* who often corrected the different opinions of other players, and (c) the *quiet player* who rarely corrected them. In particular, the leader was selected from the players in each table. In Fig. 3, the vertical axis indicates the proportion of three roles, while the horizontal axis describes


**(a)** The proportion of the number of quiet players




**(b)** The proportion of the number of claiming player




**(c)** The proportion of the number of leader

**Fig. 3** Results of subject experiments

how smooth the games proceed, which ranges from 1 to 5. According to the results, as the smoothness increases, the proportions also all arise. This indicates that there is a correlation between three roles and the smooth game. What should be noted here is that the number of the player who disagrees is not zero when the players think the games go smoothly.

### 3.2 Roles in a group

Figure 3 brought three important roles for the smooth games; (a) leader, (b) claiming player, and (c) quiet player. Since the smooth games normally appeared in the

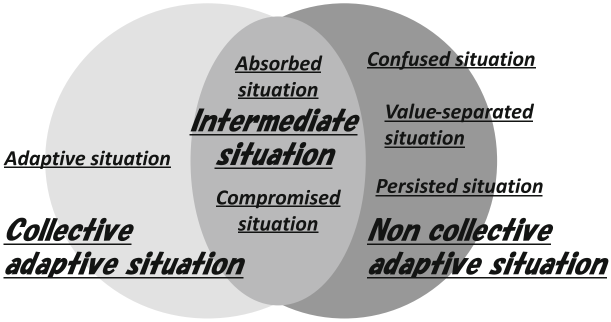



**Fig. 4** Categorization of collective adaptive situation according to subject experiments

collective adaptive situation, the appropriate role balance among players (i.e., the leader, claiming, and quiet players) is important for the collective adaptive situation. From this point of view, it is worth to explore the balance among the roles. Furthermore, as a result of roles' being played, the players modify their rules and reach an agreement to share a certain rule such as diamond or heart. From the analysis of the subject experiments, it can be concluded that the definition of the collective adaptive situation is the case of (1) the proper role balance among the players and (2) the smooth game with the rules being shared among players.

### 3.3 Group classification

The three group categorizations can be made according to the results of the subject experiments, which help to clarify the concept of the collective adaptive situation. We start by classifying the groups obtained from the experiments into the following categories as shown in Fig. 4.

1. **Collective adaptive situation**
   As defined previously, the most of the players change their rule (i.e., the trump card and ace-strong/weak rules) to share other rules with each other. Such situation derives the smooth games.
2. **Non-collective adaptive situation**
   This situation is divided into the following situations.
   – **Confused situation** : Because of the players who are puzzled with the slightly different rules, the players change their rules repeatedly when faced with the rules that the players find different from the one they think it is.
   – **Value-separated situation** : The players do not change their rules despite of the ones completely different from each other, which results in the non-smooth game.
   – **Persisted situation** : The player persists his rule, which is different from others, in order to force other players to agree with the player for the consensus among the players.
3. **Intermediate situation**
   This situation has the features of both the collective and non-collective adaptive situation, and is divided into the following situations.

- **Compromised situation** : The players change their rules but do not share one certain rule with each other. This is different from the collective adaptive situation. Such a compromise can be regarded *negatively* because all the players lose their rules, while this can be considered *positively* because the players try to reach the agreement.
- **Absorbed situation**: The opinion of one player is absorbed by the multiple players'. Since a rule is shared and a smooth game is played in the situation, this situation seems to be *positively* regarded as collective adaptive situation. However, the different aspect from collective adaptive situation is no correction in this situation because the minority cannot complain, which brought it being not satisfied with the rule. This difference suggests that this situation can be classified *negatively* as the non-collective adaptive situation. This analysis found that the collective adaptive situation requires several numbers of the corrections from other players. Otherwise, it can be regarded as the absorbed situation.

## 4 Agent model for barnga game

Considering the results of the subject experiments, we model Barnga agent, who corresponds to the player in the subject experiment. The proposed agent is composed of the memory and action modules.

### 4.1 Memory module

(1) **Leader aptitude L:** $L(X)$, which ranges from 0 to 100, shows how appropriate the agent $X$ is as the leader and is used to select the leader. If the agent has the high value it means that it has high possibility to be elected. $L(X)$ is changed by $+a$ or $-b$, according to the correction as shown in Eq. (1). When other agents stop to correct the leader's decision, $L(X)$ is reset to the one before the game starts defined as $preL(X)$ and is added by $+a$. We introduce $preL(X)$ because the updates for that leader during the game can be excluded once the leader is accepted. No correction to the leader's decision means that his action is accepted by the other agents. So such updates for the previous corrections by the other agents to the leader can be excluded. In this equation, $a$, and $b$ are coefficients, which are set to 5 and 1 in our simulation, respectively.

$$L(X) = \begin{cases} preL(X) + a\,(No\,correction) \\ L(X) - b\,(Correction\,to\,the\,leader's\,decision) \end{cases} \tag{1}$$

(2) **Opponent reliability W:** $W(X, Y)$, which ranges from 0 to 100, shows how much the agent $X$ relies on the agent $Y$ and is updated as shown in Eq. (2). In this equation, $R$ and $\alpha$ are respectively the reward and the learning rate, where $R$ is set as shown in Eq. (3), and $\alpha$ is set to 0.2 in the simulation. If there is no correction during the game, the player is 100% sure about the winner and the more corrections made, the less the player belives in the winner. The parameter

$n$ describes the number of corrections to the leader's decision.

$$W(X,Y) = W(X,Y) + \alpha(R - n * 10 - W(X,Y)) \tag{2}$$

$$R = \begin{cases} 100\,(winner\ that\ agent\ thinks = winner\ selected\ by\ leader) \\ 0\,(winner\ that\ agent\ thinks \neq winner\ selected\ by\ leader) \end{cases} \tag{3}$$

(3) **Rule strength S:** $S(X, r)$, which ranges from 0 to 100, indicates the strength of the rule $r$ that the agent $X$ has (e.g., the heart trump or ace-strong rule), in a sense of how much the agent $X$ thinks the rule $r$ is correct. $S(X, r)$ decreases whenever the agent $X$ corrects the leader's decision. When the game is over, $S(X, r)$ is reset and is updated as shown in Eqs. (4) and (5), where *rNum* is denoted as the number of rules. We introduce the reset mechanism because in the subject experiment, we observed that when conflicts occurred the players struggled with the determination of a winner, which corresponds here to the agents updating Eqs. (4) and (5) during the game. But once a winner was decided, the players seemed to forget about the process of how the winner was decided and tried to follow the actual rule used for the decision of the winner, which corresponds to $S(X, r)$ being reset to the one before the game starts. If the game ends according to the heart trump and the ace-strong rule, for example, the heart trump and ace-strong rule (described in *SelectedRule*) are updated according to the Eq. (4), while the diamond trump, the clover, the spade, and the ace-weak rule (described in *OtherRule*) are updated according to Eq. (5).

$$S(X, SelectedRule) = S(X, SelectedRule) + \alpha(R - S(X, SelectedRule)) \tag{4}$$

$$S(X, OtherRule) = S(X, OtherRule) + \triangle S(X, SelectedRule)/rNum, \tag{5}$$

where $\triangle$S can be written as follows:

$$\triangle S(X, SelectedRule) = \alpha(R - S(X, SelectedRule) \tag{6}$$

## 4.2 Action module

The action module of the agent consists of the following functions: (1) the rule selection, (2) the winner nomination, (3) the winner decision (only for the leader) and (4) the correction of the leader's decision.

(1) **Rule selection:** The agent $X$ selects one rule (e.g., the heart trump or ace-strong rule) according to $S(X, r)$ by the roulette-selection.
(2) **Winner nomination:** Each agent $X$ personally decides the winner in his mind according to the selected rule and determines if the decided winner should be nominated according to $S(X, r)$.

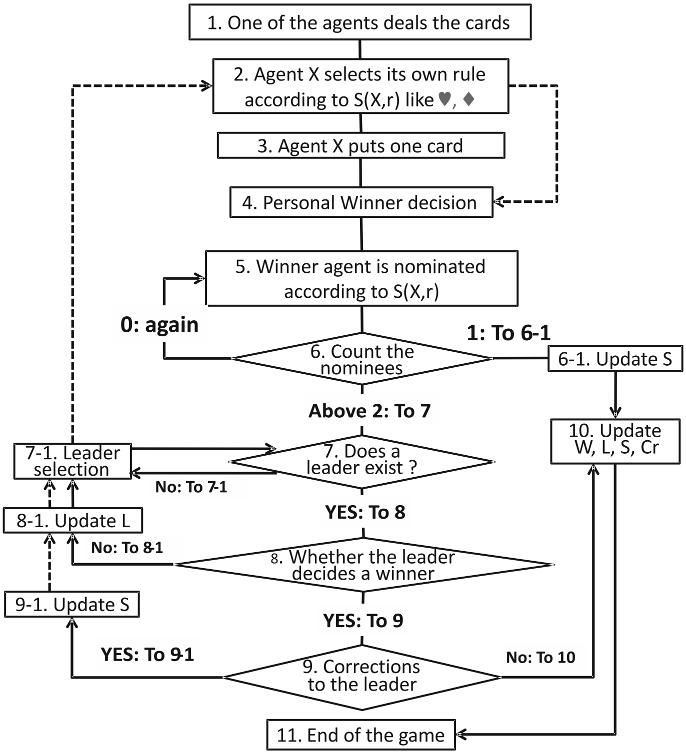



**Fig. 5** A sequence of Barnga Simulation

(3) **Winner decision:** The leader decides the winner agent if two or more agents are nominated as winners. To decide one winner, the following two types of the leader are considered in our model: (a) *Self-centered leader*, who determines the winner that the leader thinks as a winner, and (b) *Other-centered leader*, who determines the winner according to $W(leader, Y)$ where $Y$ is denoted for the agent that nominates a certain winner, in a sense that a leader decides which player to rely on.

(4) **Correction of the leader's decision:** According to $S(X, r)$, the agent $X$ decides whether he corrects the leader's decision.

## 4.3 Simulation sequence

The sequence of Barnga game on the computer simulation shown in Fig. 5 is described as follows.

1 One of the agents deals the cards.

2 Each agent $X$ selects his own rule $r$ (e.g., the heart trump or ace-strong rule) according to $S(X, r)$ by the roulette selection. $S(X, r)$ shows how the agent $X$ believes his rule $r$.

3 Each agent *X* puts one card in turn according to the follow strategy: (i) they try to put a card that satisfies their rule (e.g., if the diamond 5 is on the table and the agent has the diamond 6, it plays the diamond 6 as the stronger card than the diamond 5); (ii) if they do not have any cards to play, the trump card can be used; and (iii) if there is no trump card, they select one card randomly.

4 Each agent *X* decides the winner who puts the strongest card in his mind according to the rules selected in 2. Note that each agent just thinks who the winner agent is, which means that he has not yet expressed his decision to other agents.

5 The winner agent is nominated by expressing the decision of the agents according to the value of $S(X, r)$. In the subject experiment, some players do not express their decisions, even though they have. We model the agents to behave such a quiet behavior.

6 If the number of the nominated agents is one, $S(X, r)$ of the agent *X* is updated in 6-1, and then go to 10. If there is no nominated agent, then return to 5. If the number of the nominated agents is more than one, then go to 7.

7 If a leader does not exist, go to 7-1 to select it and back to 7. If corrections happen (i.e. in the figure, it corresponds to the dahs line), go to 2 to select the agents' own rule instead of going to 7.

8 Since more than two agents are nominated in this situation, the leader *Y* selects one winner, according to the probability of $L(Y)$. If the leader *Y* does not select any winner, go to 8-1 to update $L(Y)$ according to Eq. (1), go to 7-1 to select a new leader according to the value of $L(otherplayer)$, and then return to 7. This cycle comes from the subject experiments results where a leader did not emerge in a group.

9 When the leader *Y* decides the winner, the agent *Z* who thinks that another agent is the winner corrects the leader *Y*'s decision with the probability of $S(Z, r)$. In such a correction case, go to 9-1 to update $S(Y, r)$ temporarily by Eq. (4), proceed to 8-1 to update $L(Y)$ by Eq. (1), and then go to 7-1 to select the leader again. If none of the agents correct the leader's decision, then go to 10.

10 Update *W, L,* and *S* of all agents individually according to Eqs. (1) to (5) and then to go to 11.

11 One game ends. The agents are swapped whenever some numbers of the games are played, and then back to 1.

## 5 Simulation: collective adaptive situation and leader

### 5.1 Simulation setup

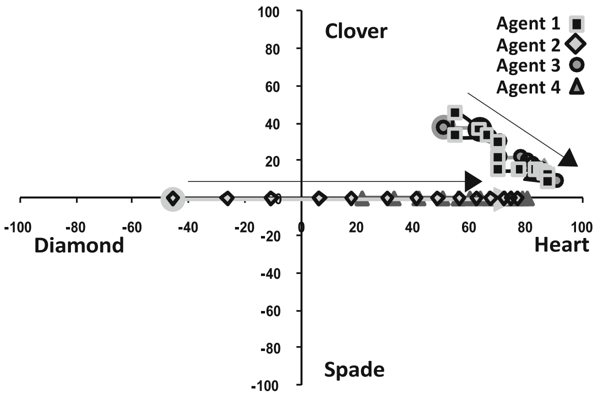
There are four players in one table and three tables in a whole simulation. We conducted the experiments with *four* agents in one table because of the following reasons: (i) with the number of the agents being more than four in one table, it is quite hard to see what kinds of the roles are played among the agents or how a group of the agents evolve over time because games played by a lot of agents in the same table would mostly derive the complicated group (e.g., all agents in a table may have different rules), and (ii) with less than four agents in a table, say 3, on the other hand, it also becomes hard to see the emergent behaviors of the agents. The another reason why we set four as the number of the agents in a table is that the number of players in the subject experiments is also four, which enables us to compare the results of the agent-based simulations with those of the subject experiments to see if our proposed agents work like humans.

At the initial stage, all agents in the same table have the same rules, indicating that there is no variation of the agents. After the several games, the migration process shown in Fig. 2 occurs and the agents encounter the situation where they have to change their rules to adapt to the rule of the other agents.

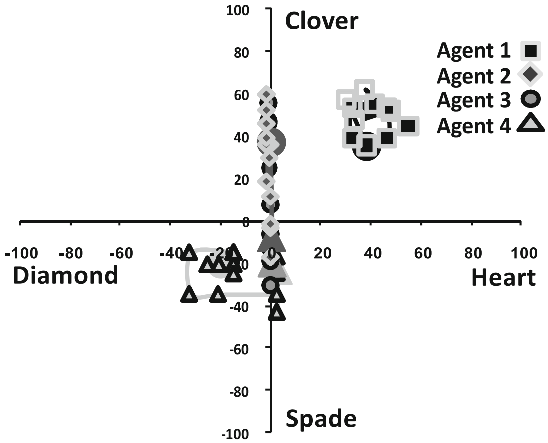
## 5.2 Simulation results

This section investigates the simulation results from the following three evaluation criteria; (1) the emerged group and (2) the leader aptitude L, and (3) the average number of corrections. Shown below are the typical results, although a random seed is changed several times in order to obtain a variety of results. The migration process occurs after every twenty one games and such cycle is repeated eight times.

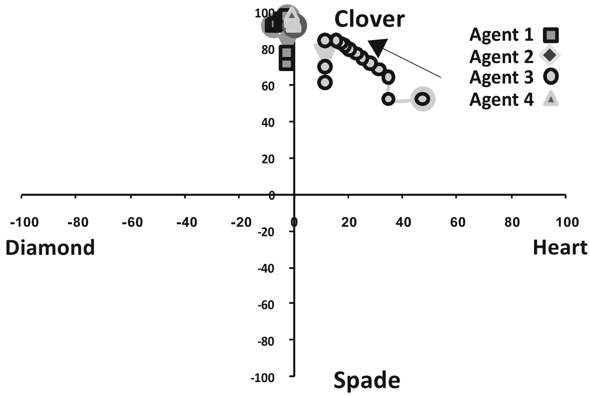
(1) **Emerged group**
Before going to the result, let us explain how we classify the emerged groups. There are three tables and eight rounds in the whole simulation, which provides the 24 results in total. Since the first round is not considered because all agents in each table have the same rules, we exclude it and 21 results become the candidates for the group classification. Note that we changed the random seed 5 times to see if there is any deviation of the results, but such variation did not reveal any significant difference in the result. From this fact, we select one typical result as shown in Fig. 6.
Figure 6 shows the examples of (a) collective adaptive situation, (b) non-collective adaptive situation, and (c) intermediate situation. Each of them illustrates the change of the rule strength $S(X, r)$ of the trump card of four agents during 21 games, where the each edge of the axis corresponds to the maximum value of the rule strength of each trump card. In Fig. 6(a), even in the different rules that the agents have, they adapt to others by modifying the values of the rule strength $S(X, r)$ and to share one rule with each other, which is Heart in this case. From this adaptation, we can classify this situation as the *collective adaptive situation*. In contrast, the case shown in Fig. 6(b) can be categorized as the *non-collective adaptive situation*, because the agent 1 with the black square does not change the value of the rule, remaining in the up-right position, even though the others modify their rules. This indicates that the agents believe their own (different) rules as the correct one due to the conflicts among the agents. Finally, Fig. 6(c) shows the case that can be classified into the *intermediate situation* because the three agents have their beliefs that the correct rule is Clover, while the agent 3 represented by the light gray circle initially thinks that clover or heart would be the correct one. What should be noted is that it is possible to classify the result into the collective adaptive situation because the agents all learn to share the clover rule with each other. However, it is also possible to clas-




**(a)** Collective adaptive situation




**(b)** Non-collective adaptive situation




**(c)** Intermediate situation

**Fig. 6** Examples of situations obtained in the simulation

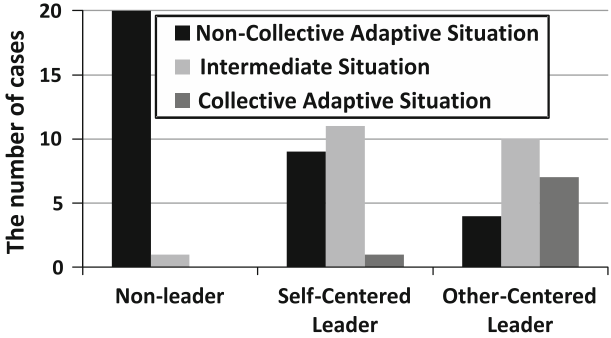



**Fig. 7** Group Classification in two types of agent

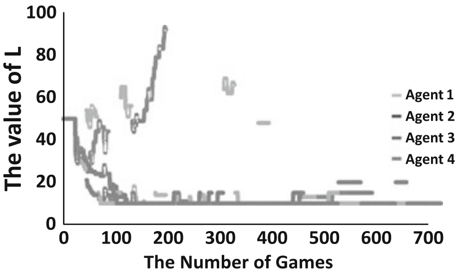
sify as the non-collective adaptive situation because the agent 3 represented by the light gray circle seems to have some objections but cannot complain it due to the majority of the clover rule. By analyzing in this way, we classified all of the results into the three types of the group. It should be noted that our agent model successfully obtains all of the different types of groups categorized in Sect. 3.3 (e.g., the confused situation, the absorbed situation, etc.).

Figure 7 shows the result of the group classifications in the three different types of the leaders (i.e. non-leader, self-centered, leader,and other-centered leader). The black, gray, and light gray box indicates the non-collective adaptive situation, intermediate situation and collective adaptive situation respectively. The horizontal axis indicates the agent types, while the vertical axis indicates the number of the situations from 21 results. The results suggest that non leader agent and the self-centered leader does not/ hardly derive the collective adaptive situation, while the other-centered leader agent causes the largest number of collective adaptive situations.

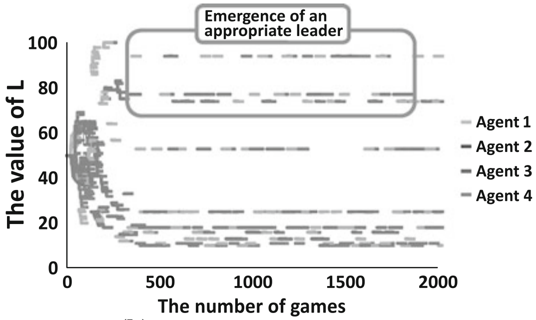
(2) **Leader Aptitude L** Fig. 8 shows the change of the leader aptitude L over 700 games, where the horizontal axis indicates the number of the games, while the vertical axis indicates the leader aptitude L. Figure 8(a) shows the result of the self-centered leader agent, while Fig. 8(b) shows that of the other centered leader agent. These figures show the typical results which are confirmed that the simulation results do not drastically change according to the random seeds. Since the migration process occurs every 21 games, the dots which represent the values of L of agents are disconnected. The important aspect is that the distributed points are different between Fig. 8(a) and (b). In detail, the dots of the other-centered leader shown Fig. 8(b) are mapped in the upper area of the graph, which indicates the agents with the high values of L, while in the self-centered leader shown Fig. 8(a), the dots are mostly mapped in the bottom, which indicates the agents with the lower values of L. This difference suggests that the other-centered leader agents are encouraged to be emerged because such a leader is relied on by other agents and is needed to derive the collective adaptive situation.

(3) **Average number of corrections**

Figure 9 shows the average number of the corrections in 147 games (i.e. (8-1)




**(a)** Self-centered leader agent




**(b)** Other-centered leader agent

**Fig. 8** Distribution of leader aptitude L over 700 games

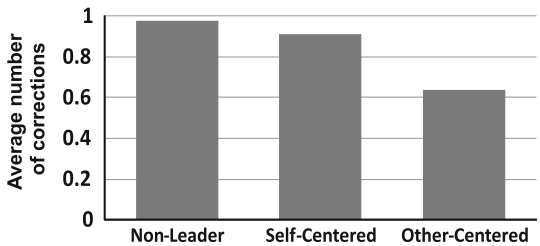



**Fig. 9** Average number of corrections in three types of agent

round * 21 games), where the horizontal axis indicates the three types of the agents, while the vertical axis indicates the average number of the correction $N_{avg}$. We define $N_{avg}$ as follows:

$$N_{avg} = \frac{N_i}{N_{all}}, \tag{7}$$

where $N_i$ is the total number of corrections in $i$th game, and $N_{all}$ is the number of corrections for 147 games. The figure shows that the non-leader agent receives the largest number of the corrections, the self-centered leader agent follows, and the other-centered leader agent receives the smallest numbers of the corrections. Note that the result indicates that a certain number of corrections is required even for the other-centered leader agent, which has the largest number of situations classified as the collective adaptive situation in Fig. 7(a). As mentioned in Sect. 3.3, the collective adaptive situation requires an appropriate number of corrections to derive smooth games. The simulation result obtained is consistent with the subject experiment.

### 5.3 Discussion

None/a few of the collective adaptive situations are observed in the non-leader/self-centered leader as shown in Fig. 7 and the leader aptitude L of the self-centered agent decreases as the games proceeds as shown in Fig. 8(a). These results suggest that the self-centered leader and no-leader agents are not likely to derive the collective adaptive situation. In contrast to them, the largest number of the collective adaptation is observed in the other-centered leader agents as shown in Fig. 7 and the high leader aptitude L is kept in comparison with the self-centered leader as shown in Fig. 8(a). From these points of view, the other-centered leader agents have the great potential of deriving the collective adaptive situation.

This result is supported by the Leader-Member Exchange (LMX) theory. The LMX theory represents that the relationship between a leader and followers is important for a leader to perform their tasks (Liden et al. 1997), which indicates the result that the other centered leader outperforms the self-centered leader has consistency with this theory because the other centered leader takes followers into consideration.

## 6 Simulation: conditions toward a collective adaptive situation

To find conditions that transfer the group from non-collective adaptive to collective adaptive, we modify the leader aptitude L of the agent. Since the results of the previous simulation reveal that a leader facilitates the collective adaptive situation, we modified the L (agent 4) from 40 to 80 in this simulation, which corresponds to the situation, where an appropriate leader emerges.

### 6.1 Simulation results

Figure 10 shows the typical simulation results. The upper graphs show the change of the leader aptitude L of each agent in one table like Fig. 8(a) and (b). The four types of the shapes represent four agents in one table. The middle graph indicates which and when the agents corrects, where the horizontal axis indicates the agent and the vertical axis describes the number of games. The lower graphs show the change of $S(X, r)$ during 21 games, where the each edge of axis corresponds to the maximum value of each trump card. In this case, the left side of the figure illustrates the confused situation because a large number of the corrections and the different rules among the agents, while the right side of the figure, on the other hand, shows that the number of the corrections decreases and that the rule of each agent is moved toward the heart trump card by modifying their values to share the heart trump card. From this point

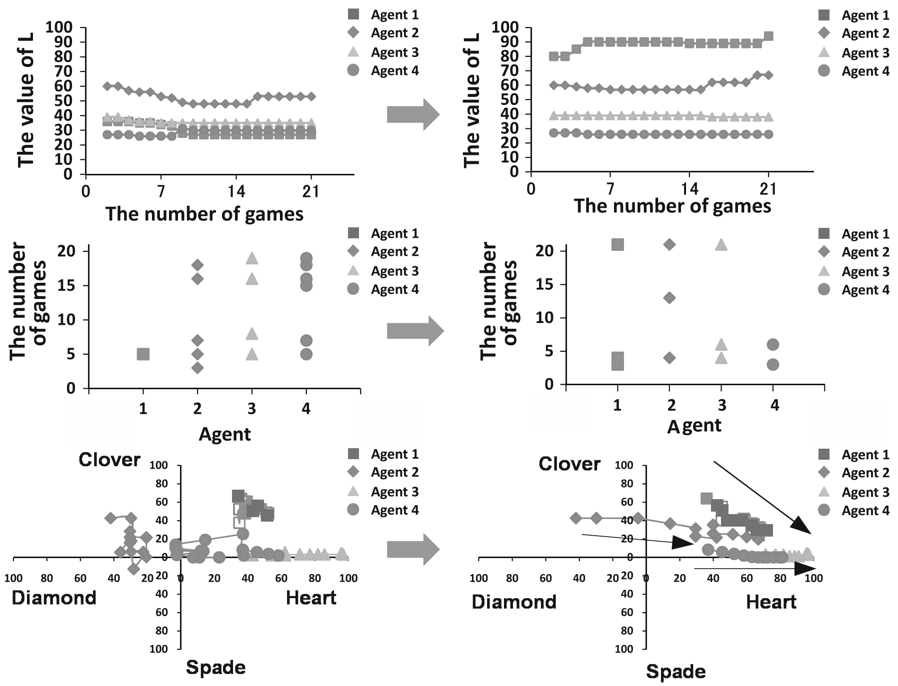



**Fig. 10** Transition from non-collective adaptive situation to collective adaptive one

of view, it can be concluded that these graphs suggest the change of L derive the collective adaptive situation because the correction number decreases (but not zero) after the modification and all the agents get to share one rule (the heart trump card), which is the definition of the collective adaptation described in Sect. 3.

## 6.2 Discussion

For revealing the specific condition of the collective adaptive situation, the seven collective adaptive cases and ten non-collective adaptive cases in the other centered leader agent are analyzed. In detail, we (a) explore something in common with the collective adaptive situation and the non collective adaptive situation and (b) figure out what differentiates between them. Through the analysis, the following insights that satisfy (a) and (b) are obtained; (i) the leader aptitude L has to be more than 60, and (ii) the ratio of the corrections is less than 3:1 between the claiming and the quiet agent. From the computer point of view, the claiming agent would be defined as the one who makes corrections the most, while the quiet agent could be regarded as the one who corrects the least. In the middle of the left figure the agent 1 can be regarded as the quiet agent and the agent 4 can be considered as the claiming agent. This case does not show the smooth game because of the unbalanced corrections, whose ratio is 5:1, indicating that some agents corrects many times and others do not. In the middle of the right figure, however, the agent 4 corrects twice over a period of 21 games, while the other agents correct three times. This indicates that the ratio between them is less than 3:1. From these analysis, the following hypothesis can be made in this circumstance, because of no leader, the quiet player has to follow the claiming player, which derives the non-collective adaptive situation. An appropriate leader, however, tries to bring the opinions together, which results in the decrease of the number of the total corrections by promoting the claiming player to make less corrections, which means that the correction balance among agents is adjusted. From this point of view, it can be concluded that the appropriate roles among agents (the leader, quiet and claiming agent) is required to bring them to the collective adaptive situation by sharing the new rule (e.g., the heart becomes the trump card in Fig. 10).

These results can be applied the situation, where humans and an agent(s) play this game together. The agent perceives what is happening and figures out the best solution (e.g., give up, insist of its opinion, or take a lead to avoid conflicts) to derive the collective adaptive situation.

## 7 Conclusion

This paper explored the collective adaptive agent that adapts to a *group* in contrast with individual adaptive agent that interacts only with a *single* user. For hits purpose, this research defined the collective adaptive situation as the smooth games by sharing the rule among the players as a result of an appropriate role balance through the analysis of the subject experiments in Barnga. The other situations were also classified into the several categories, which could not be clarified by other previous works. The simulations of Barnga revealed the following insights for the collective adaptive situation: (1) the leader who takes an account of other players' decisions on the winner contributes to the collective adaptive situation, and (2) the appropriate balance in roles is required, i.e. the balance among the leader, the claiming agent who makes corrections frequently and the quiet agent who corrects the least times. In detail, the following specific conditions were found out to be indispensable for the collective adaptive situation: (a) the emergence of the leader whose value of the Leader Aptitude is more than 60 and (b) the ratio in the correction numbers between the claiming and quiet agents is less than 3:1.

Although we should generalize the above conditions and apply it to a real society, (1) an investigation of Barnga in which both humans and agents play together, (2) a precise analysis of the conditions for leading the collective adaptive situation, and (3) the comparisons of the performance with other related works should be done for the future works.

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