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Does information matter in the commons? Experimental evidence

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Abstract

Common-pool resources (CPRs) typically involve interaction where precise information about payoffs is absent. However, all experimental studies of CPRs we are aware of study environments where the payoff structure is known. In this paper we address the behavioral consequences of two degrees of information on the mapping between decisions and payoffs. We run two treatments, one with complete information on the payoff structure and one with none. Remarkably, aggregate behavior is not significantly different between the two treatments. In both cases the aggregate tendencies converge to the Nash equilibrium. Furthermore, the best-reply dynamics organize individual behavior in both treatments remarkably well.

JEL classification: C72; C91; D83; Q2

Keywords: Common-pool resources; Information; Nash equilibrium; Learning; Experiments

1. Introduction

Examples of common-pool resources (CPRs) include fisheries, groundwater basins, oil fields, irrigation systems, grazing commons, and computer facilities. Gordon (1954), and later Hardin (1968), first theoretically analyzed CPRs. Since then, experimental and field studies of CPRs have mushroomed. Basically, these studies show that the so-called "tragedy

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of the commons" may be mitigated to a significant extent by institutional arrangements that, for example, make possible the effective monitoring of the behavior of users, consider the possibility of sanctioning, have effective mechanisms for the enforcement of rules, favor direct communication between users, or allow users the possibility of voting on different allocation rules.[1]

A common feature of the experimental literature on CPRs is that subjects are always given perfect information on the payoff function. The payoff function may be deterministic (see, e.g., Hackett et al., 1994; Ostrom et al., 1994; Gardner et al., 1997; Herr et al., 1997; Keser and Gardner, 1999; Walker et al., 2000; Casari and Plott, 2003), or stochastic (as in Walker and Gardner, 1992; Budescu et al., 1995), but in both cases, players in the CPR game always know the mapping between decisions and payoffs.

Natural CPRs, however, typically involve repeated interaction in a complex setting where precise information about the payoff structure is absent (see Ostrom, 1990). Experience is the main source of information. Very often, efforts are taken to improve the quality of such information. However, as in the case of the Californian groundwater basins reported in Ostrom (1990), the provision of more accurate information may be highly costly. Consequently, it is important to ascertain empirically the behavioral influence of precise information about the CPR payoff structure. Does a better knowledge of the CPR payoff structure make subjects more conscious of the externalities and then help to avoid the "tragedy of the commons"? Or do subjects use this information to better exploit the resource? The experimental methodology is well suited to answer these questions. By keeping the influence of other variables under control, the experimental analysis is suitable to isolate the behavioral implications of different levels of information about the payoff structure of the CPR. To control for this in field studies is, of course, more difficult, if not impossible.

Hence, in order to parallel field CPRs, in this paper we experimentally analyze a complex CPR game repeated over a long time horizon. We run two treatments, one with complete information and one with no information on the payoff function. Remarkably, the results show that aggregate behavior is not significantly different between the two treatments and in both cases converges to the unique Nash equilibrium. Furthermore, in both cases the best-reply dynamics tend to organize behavior remarkably well. At the beginning of the experiment the predictive success of best-reply in the treatment with no information on the payoff structure is more erratic than in the complete information treatment. However, this difference vanishes with time. Even when players do not have information on the payoff structure, if they are given enough time they learn to behave according to best-reply. Of course, before reaching definitive conclusions more research must be conducted. However, the results here suggest that costly enterprises with the aim of improving the quality of information on the payoff structure of a CPR may not be profitable.

In Section 5, we contrast our results with the recent experimental literature on games with severely limited information (see Mookherjee and Sopher, 1994; Van Huyck et al., 2001; Nagel and Vriend, 1999; Oechssler and Schipper, 2003). In line with our results, we will see that in a variety of different games, players with very incomplete knowledge of the payoff structure tend at the aggregate level to reach a Nash equilibrium. We believe that

[1] For reviews, see Ostrom (1990,1998,2000), Ostrom et al. (1994), and Carpenter (2000).

this is a highly relevant under-researched area, and we hope that this paper will contribute to gain insights to develop a game theory under limited information.

The paper is structured as follows. Section 2 introduces the CPR game and derives the theoretical benchmarks, namely the unique Nash equilibrium and the unique symmetric optimal solution. In Section 3, we report the experimental procedure. The experimental data are analyzed in Section 4. Section 5 presents the relation of our results with the literature on games with limited information, and Section 6 concludes. The instructions for the experiment are available from the journal's website.

2. The common-pool resource game

The game to be studied is drawn from the baseline game used in Ostrom et al. For 50 periods, a group of 6 individuals plays a constituent game aimed at representing the appropriation problem in a CPR. Players are aware of the number of periods to be played. The game is symmetric and no communication between players is allowed. In the constituent game, players face the decision problem of distributing a fixed endowment (labeled k) between two markets, the CPR market and a 'private market' (respectively referred to as Markets 1 and 2 in the instructions).

The constituent game is denoted by $\Gamma = (N,X,u)$, where $i \in N = \{1,\ldots,6\}$, x_i is player i's investment in the CPR market, $x_i \in X_i = \{5.00, 5.01, 5.02, \ldots, 30\}$, $x = (x_1, x_2, \ldots, x_6)$, and $X = X_1 \times X_2 \times \cdots \times X_6$. $k = 35$ is the individual endowment; hence $(35 - x_i)$ is player i's investment in the private market.[2] Player i's payoff function is

$$u_i(x) = \left(120\sum_{j=1}^{6} x_j - 1.165\left(\sum_{j=1}^{6} x_j\right)^2\right)\frac{x_i}{\sum_{j=1}^{6} x_j} + (135 - 6(35 - x_i))(35 - x_i). \qquad (1)$$

Then $u(x) = (u_1(x), u_2(x), \ldots, u_6(x))$. The first addend on the right-hand side of (1) represents the CPR market. The payoff derived by any one player from the CPR market not only depends on his/her investment, but also on the investments of the other players. The second addend in (1) represents the private market. The payoff derived by any one player from the private market is contingent only upon his/her own investment decision.

Since the two addends of Eq. (1) are quadratic, the CPR game is relatively complex. Further, since the constituent game is repeated over 50 periods, the time-horizon is relatively long.[3]

2.1. Nash equilibrium and optimal solution

In games where players do not have any information about the payoff structure, standard game theory does not provide any equilibrium prediction. The fol-

[2] The individual action space is limited to the range between 5 and 30 to avoid large negative payoffs.

[3] Note that the typical time horizon is between 10 and 25 periods (see, e.g., Ostrom et al. (1994), Herr et al. (1997), Keser and Gardner (1999), and Walker et al. (2000)). To the best of our knowledge, the maximum number of periods used so far in CPR experiments is 35 (see Casari and Plott, 2003).

lowing argument, therefore, applies only to those games with complete information.

It is shown below that the constituent CPR game has a unique Nash Equilibrium, which happens to be symmetric. By the application of backward induction it can be seen that the equilibrium of the repeated CPR game is at each period to play the symmetric Nash equilibrium (SNE), which constitutes the unique Subgame Perfect Equilibrium of the repeated CPR game.

The SNE of the constituent game is calculated by assuming that the individual strategy space is the continuum between 5 and 30. Consider player i's best-reply function in the constituent game

$$b_i(x_{-i}) = \left\{x_i \in X_i : u_i(x_i, x_{-i}) \geq u_i(x_i', x_{-i}) \text{ for all } x_i' \in X_i\right\}, \quad \text{for all } i \in N, \tag{2}$$

where $x_{-i} = (x_1,\ldots,x_{i-1},x_{i+1},\ldots,x_6)$. The individual best-reply function can be obtained by

$$\frac{\partial u_i(x_i, x_{-i})}{\partial x_i} = 405 - 1.165 \sum_{\substack{j=1 \\ j\neq i}}^{5} x_j - 14.33x_i = 0, \quad \text{for all } i \in N, \tag{3}$$

and hence

$$b_i(x_{-i}) = 28.26 - 0.08 \sum_{\substack{j=1 \\ j\neq i}}^{5} x_j, \quad \text{for all } i \in N. \tag{4}$$

The SNE is obtained by solving the equation system (4). Therefore, regarding the Complete-information treatment, the theoretical prediction for each of the 50 periods is the SNE that calls for every player to invest $x_i^* = 20$ and gives 279 talers of payoff per individual and per period.[4]

To infer the optimal solution first consider the "optimal-reply function" of the constituent game. By the optimal-reply function it is meant that function that gives the individual investment in the CPR market that maximizes group payoffs. That is, for all $i \in N$, the optimal-reply function of the constituent game is

$$p_i(x_{-i}) = \left\{x_i \in X_i : \sum_{j=1}^{6} u_j(x_i, x_{-i}) \geq \sum_{j=1}^{6} u_j(x_i', x_{-i}) \text{ for all } x_i' \in X_i\right\}. \tag{5}$$

Then

$$\frac{\partial \sum_{j=1}^{6} u_j(x_i, x_{-i})}{\partial x_i} = 405 - 2.33 \sum_{\substack{j=1 \\ j\neq i}}^{5} x_j - 14.33x_i = 0, \tag{6}$$

[4] Note that $x_i^* = 20$, $i \in N$, is the integer part of the exact solution of equation system (4).

and hence

$$p_i(x_{-i}) = \max\left\{5, 28.26 - 0.16\sum_{\substack{j=1\\ j\neq i}}^{5} x_j\right\}. \tag{7}$$

The symmetric optimal solution $x_i^{\mathrm{O}} = 15$ is obtained by solving (7) under symmetry. This gives a total of 531 payoffs per individual and period.

3. Experimental procedure

The experiments to be reported were conducted at the Laboratory for Experimental Economics at the University of Bonn. Volunteer subjects, recruited through posters on campus, were primarily undergraduate economics and law students, but also students from other disciplines such as computer science and mathematics. The computerized program was developed using RatImage (Abbink and Sadrieh, 1995). Two treatments were conducted. In Treatment I six groups of six participants played the repeated CPR game under complete information (Complete-information Treatment). In Treatment II another six groups of six participants played the repeated CPR game but with no information about the relation between decisions and payoffs (Minimal-information Treatment).

Instructions were handed out to subjects and read aloud. An English translation of the instructions for the Complete-information Treatment is shown in Supplementary data. Instructions for the Minimal-information Treatment were analogous to those of the Complete-information Treatment, but all information regarding the structure of payoffs was omitted. The following qualitative information was given to participants in the Minimal-information Treatment: “The payoffs you receive from Market 1 depend not only on the amount you invest but also on the amount invested by the remaining members of your group. In Market 2 the payoffs you receive on investments depend only on the amount you invest in Market 2. The payoffs of each Market period are independent of decisions in other market periods, and there is no randomness of any kind in the payoffs.”

The period-by-period information about outcomes was the same in both treatments. That is, players in both treatments were informed of the previous group investment level in the CPR market, and each of his/her own total, average, and marginal payoffs in both markets, own total payoffs for that period, and finally own cumulative payoffs. Furthermore, players in both treatments were told that by clicking on “History,” they would have access to this information for every past period.

The main computer screen, the one where players had to enter their investment decisions, was presented and explained to subjects. Subjects were told that individual decisions remained anonymous to the group and that the game was symmetric. After instructions had been read and questions answered, subjects were randomly assigned to independent and visually isolated cubicles equipped with computer terminals. No communication between subjects was allowed. No time restrictions were imposed. On average, a session, including the instructions phase, lasted less than 1 h and 40 min. Players were privately paid in cash directly after completing the 50 experimental periods. The capital balance was 4000 talers in the Complete-information Treatment, and 8000 talers in the Minimal-information Treatment. The exchange rate was € 0.00125. Average earnings were around € 27.

4. Experimental results

4.1. Does information matter?

We begin by addressing the main question posed in this pape: does precise information on the payoff structure provoke a significant difference in behavior? To this end we compare the Complete-information Treatment with the Minimal-information Treatment.

See the time–series of average investments per treatment (Fig. 1), the distribution of investment decisions per treatment (Fig. 2), and Table 1 where some descriptive statistics are reported.

Result 1. There is no significant difference between the investment decisions at the aggregate level in the two treatments.

Figs. 1 and 2 and Table 1 clearly show that average investments in both treatments are markedly similar. In order to check statistically the Complete-information Treatment against the Minimal-information Treatment, the average of the investment decisions in the CPR market at the group level are considered. Hence, there are two samples each with six independent observations. The permutation test[5] shows that the difference in the

[5] See Siegel and Castellan (1988) for a reference on the statistical tests used in this paper.

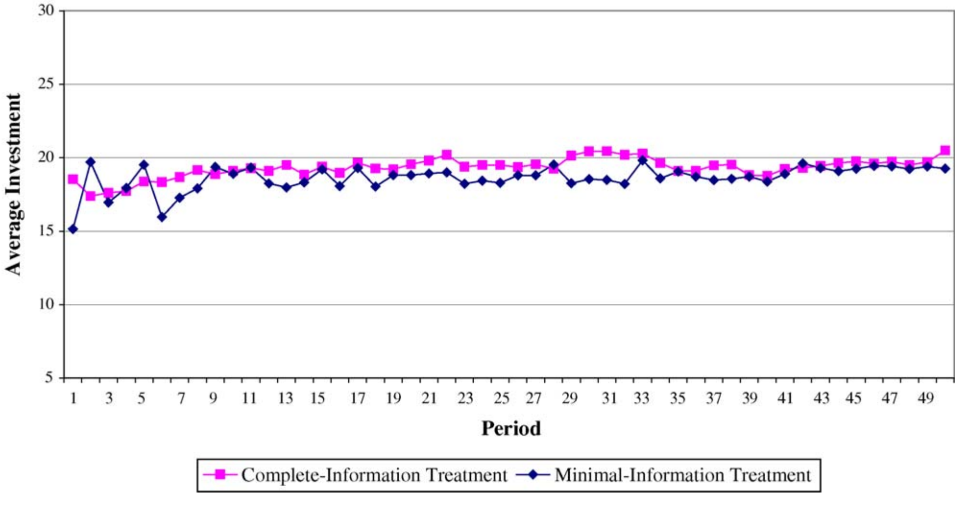

Fig. 1. Time series of average investment by treatment.

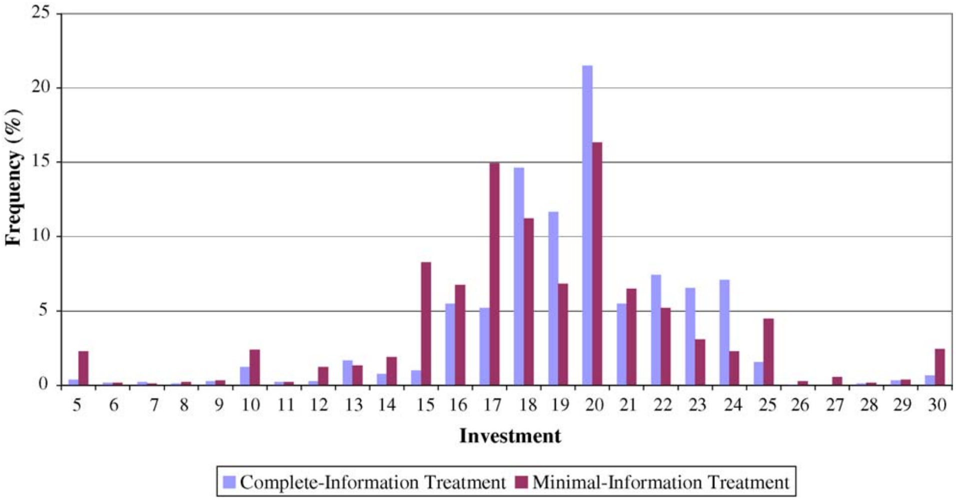

Fig. 2. Distribution of investment decisions by treatment.

average investments taking all the 50 periods between both treatments is not significant ($p = .1298$, two-sided). Moreover, the same conclusion is reached when the two treatments are contrasted by considering the first, middle, and final third of the data separately (the p-values are respectively .3658, .1082, and .2640; two-sided).

Hence, we may conclude that there are not significant differences between the two treatments with respect to location (i.e., central tendency). To test whether the two treatments differ in the respective distributions we compute the two-tailed Kolmogorov–Smirnov two-sample test. We may conclude that neither when we take the entire experimental data nor when we consider the first, middle, or final third of the data separately are there significant differences between the two treatments (the p-values are .20 in the four cases).

Furthermore, two more groups were run to ascertain whether this finding could be attributed to the fact that players in both treatments had information about average and marginal payoffs in both markets after each decision period. These two new groups (groups 13 and 14) had an experimental design analogous to those already reported. In group 13 six players had the same information as in the Minimal-information Treatment. Players in group 14, however, had information only about the past group investment decisions and about his/her own total payoffs on each market. Fig. 3 shows that the average time series of the groups are again remarkably similar.

Result 2. In the first third of the experiment, dispersion in the pattern of individual investment decisions in the Minimal-information Treatment is greater than that observed in the Complete-information Treatment.

A permutation test on the basis of the standard deviation of individual decisions in the first third of the experiment for the individual groups shows that this result is significant at the .01 level ($p = .0021$; two-sided). However, the difference is not significant

Table 1
Descriptive statistics

Group	1	2	3	4	5	6	Treat I
All periods							
Average investment	19.2	19.67	19.23	19.83	19.76	18.15	19.31
S.D.	2.571	2.778	3.258	3.53	3.975	3.764	3.395
First third							
Average investment	18.52	19.93	17.69	20.08	19.24	16.96	18.73
S.D.	3.121	3.673	4.135	4.255	4.186	4.427	3.966
Middle third							
Average investment	19.33	19.91	20.01	21.34	20.27	17.65	19.75
S.D.	2.182	2.271	2.464	3.027	3.539	3.696	2.863
Final third							
Average investment	19.75	19.2	20.04	18.15	19.81	19.81	19.46
S.D.	2.131	2.04	2.226	2.253	4.118	2.242	2.502
GROUP	7	8	9	10	11	12	Treat II
All periods							
Average investment	17.93	19.5	18.5	18.1	19.51	18.25	18.63
S.D.	4.889	3.79	3.37	4.76	4.443	4.51	4.368
First third							
Average investment	17.2	19.04	17.62	17.9	19.2	18.1	18.18
S.D.	6.437	5.491	4.668	5.52	6.29	4.65	5.509
Middle third							
Average investment	18.18	19.75	18.84	18	19.5	17.8	18.68
S.D.	4.008	2.661	2.107	4.93	3.71	4.57	3.664
Final third							
Average investment	18.41	19.64	19.16	18.3	19.8	18.8	19.02
S.D.	3.659	2.306	2.519	3.71	2.37	4.3	3.146

when taking the second and final third of the experiment (the p-values are respectively .1515, and .1904; two-sided). It seems that at the beginning of the experiment subjects in the Minimal-information Treatment widely explore the consequences of different appropriation levels in order to get a sense of the payoff structure and then reach a relatively stable pattern of behavior that produces no significant difference with the behavior of those subjects that had full information on the payoff structure. Obviously, players in the Complete-information Treatment do not need such an initial exploratory process. The fact that there is a significant difference at the beginning of the experiment between the two treatments suggests that even though the CPR game is relatively complex, those subjects who were provided information on the payoff structure scrutinized ex ante the payoffs consequences of choice and identified the relevant subset of the action space for best-replying.

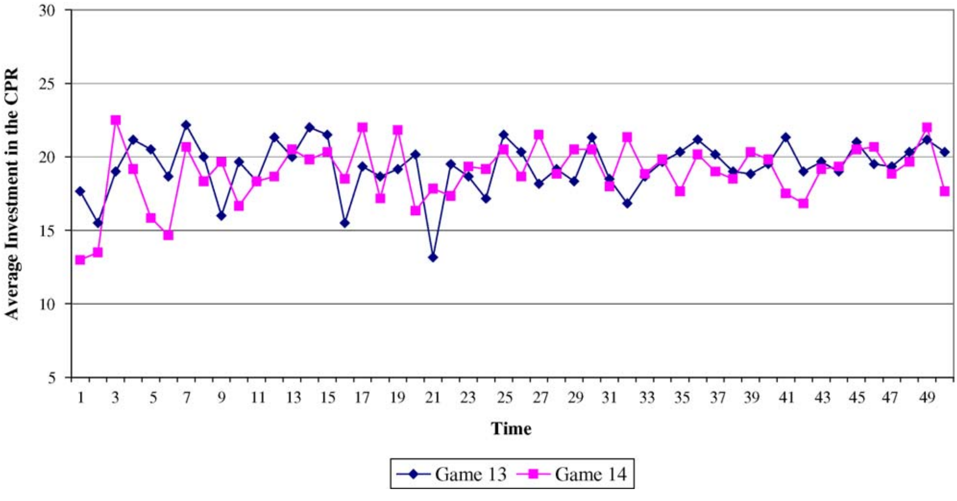

Fig. 3. Time series of average investment in groups 13 and 14.

4.2. Adequacy with equilibrium predictions

Recall that the unique Nash equilibrium (SNE), which is symmetric, predicts an appropriation level of 20 talers. Fig. 1 shows that aggregate behavior tends to converge to the SNE in both treatments. Further, Fig. 2 shows that the modal decision in both treatments is an allocation level of 20. Hence, we can conclude that

Result 3. At the aggregate level the SNE organizes the data in both treatments.

We study now whether the most common learning model, namely the best-reply dynamics, organizes the data. Best-reply is probably one of the first learning models (for an overview, see Fudenberg and Levine, 1998), and it has the advantage of being parameter-free.[6] Therefore, we calculate at each period for every player the predicted investment level by the best-reply function, taking the observed investment level of the opponents. Namely, we calculate:

$$b_{it}(x_{-i,t-1}) = 28.26 - 0.08 \sum_{\substack{j=1 \\ j\neq i}}^{5} x_{j,t-1} \tag{8}$$

by taking the observed value of $x_{-i,t-1}$. By known results on the global stability of dynamic systems in difference equations (see, e.g., Ortega and Rheinboldt, 1970), it can be guaranteed that the SNE is globally stable with respect to the process of iteration described in (8).

[6] Learning models that have proved to be very successful but that make use of parameters are Erev and Roth (1998) reinforcement model, Camerer and Ho (1999) EWA model, and Sarin and Vahid (2001) payoff assessment model.

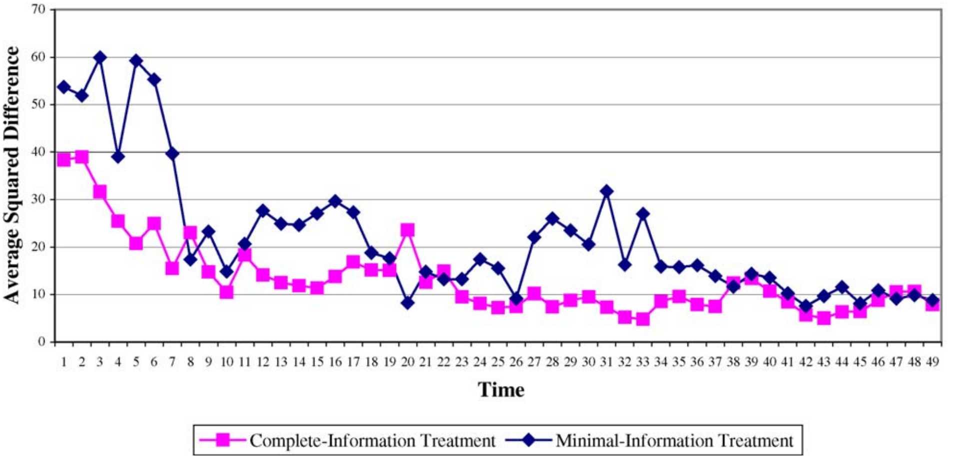

Fig. 4. Time series of the average squared differences between individually observed and predicted investments by the best-reply function.

Fig. 4 plots the time series of the average squared differences between the observed data and the prediction of Eq. (8) for both treatments separately. Interestingly, Fig. 4 shows that at the beginning of the experiment the squared differences of the Minimal-information Treatment are greater than those of the Complete-information Treatment. However, by the end of the experiment both treatments show an average squared difference that tends to zero.

We have seen throughout the analysis that both treatments show markedly similar aggregate behavior. However, this impression may be treacherous. It may well be that this is the result of averaging over quite heterogeneous behavior at the individual level. In fact, it is common in the experimental literature on CPR games, Cournot games, and games with unique mixed strategy Nash equilibria that the aggregate data fits the equilibrium prediction well, but that the individual choices look quite different. In the present case, both information conditions yield similar aggregate results, which could result from quite different individual behavior. To check against this conjecture we classify individual players in the two treatments separately on the basis of the distance (squared difference) between the observed individual behavior and the behavior predicted by Eq. (8). We take the data of the last third of the experiment, when some stabilization at the aggregate level seems to emerge in both treatments. Fig. 5 reports the distribution of individual players in the two treatments separately. Fig. 5 suggests a slight difference between the two information conditions. It seems that the distribution of individual players in the complete information treatment is more to the left than that of the minimal information treatment, showing smaller deviations from best-reply. However, the two-tailed Kolmogorov–Smirnov two-sample test cannot reject the null hypothesis of equal distributions at any standard significance level. Therefore, we may conclude that it seems that players learn to behave according to best-reply in both treatments. Remarkably, even when players do not have information on the payoff structure, if they are given enough time, they learn the structure.

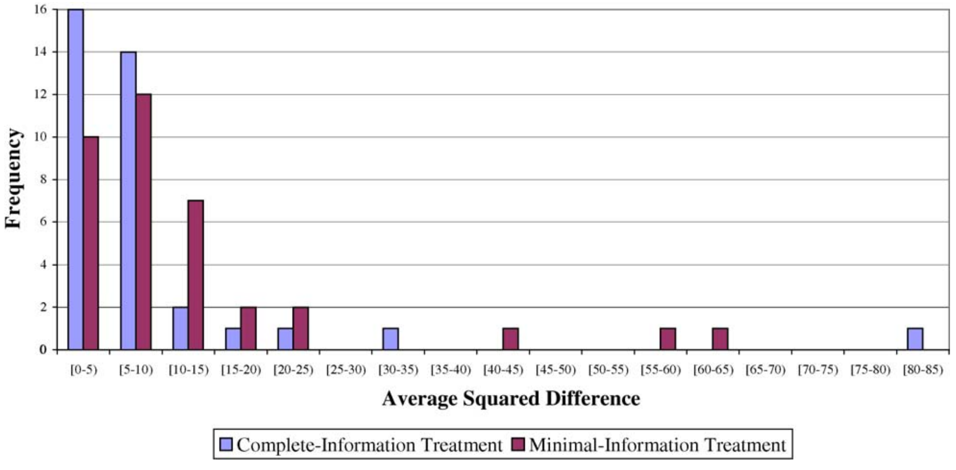

Fig. 5. Distribution of individual players on the basis of the average squared differences between individually observed and predicted investments by the best-reply function.

5. Experimental literature on games with minimal information

There is a growing interest on the study of behavior in games where players are given very little information on the payoff structure. The first paper we are aware of that compares the behavior of fully informed subjects with the behavior of subjects who had no information on the payoff structure is Mookherjee and Sopher (1994) who implement a simple 2×2 game, a matching pennies game, repeated over 40 periods under two treatments. In treatment I players were informed only about their own past payoffs and decisions. In treatment II players were informed also about the payoff function and the decisions of their opponents. Players knew that they were playing always against the same opponent. At the aggregate level the authors observe that average choice frequencies are strikingly similar in both treatments and correspond with the unique Nash equilibrium of the game. Mookherjee and Sopher note that there are a number of behavioral differences between the two treatments (e.g., in the degree of randomness, inertia, and predictability of behavior), but it is remarkable that average frequencies of choices in the two treatments are very close to the unique Nash equilibrium.

Van Huyck et al. (2001) study the coordination game of Van Huyck et al. (1994) in a minimal information treatment. The coordination game studied is a complex game involving 5 players, repeated over 75 periods. In their minimal information treatments players knew the number of players, that they always played against the same opponents, the number of periods and, the history of own decisions and payoffs, but they did not get information on the payoff structure. Again, the authors observe that players in the complete information treatments of Van Huyck et al. (1994) and those in the minimal information treatment of Van Huyck et al. (2001) converge to the unique interior equilibrium.

Nagel and Vriend explore a quite complex 6-player oligopoly game repeated about 150 times. Nagel and Vriend did not run a complete information treatment. In their incomplete information treatments, subjects had only partial information on the profit function and did not either know the number of firms or the number of periods. The authors conclude that aggregate behavior is close to the unique symmetric stationary equilibrium of the complete information version of the game.

In a recent paper, Oechssler and Schipper study the behavior of subjects in three different 2×2 games: a coordination game, a game with a unique equilibrium which is in mixed strategies, and a prisoners' dilemma game. Players in the experiments of Oechssler and Schipper knew their own payoff functions, but not those of their opponents. Subjects knew that they were playing a 2×2 game, repeated over 20 periods, against the same opponent. The novelty of this study is that subjects, after playing 15 periods, were asked to estimate the payoff function of their opponents. Surprisingly, although players did not correctly perceive the payoff matrix, they played quite close to the Nash equilibria of the respective games.

We see, therefore, that in quite a broad class of games (simple and complex coordination games, 2×2 games with a unique equilibrium that is in mixed strategies, prisoners' dilemma games, complex oligopoly games, and in the present case of a CPR game), even when players are given very little information on the payoff structure they nevertheless learn to play according to Nash. It remains as a question for future research to assess the consistency of these results. For example, an obvious direction is to address this question in other games such us public goods games or pricing games. Further, the present study and all those reported here involve repeated interaction between the same group of players. It may be interesting to evaluate whether players with very little information on the payoff structure learn to play Nash when interacting with different opponents.[7]

6. Concluding remarks

In this paper we have analyzed the influence on behavior of providing precise information about the payoff structure of a common-pool resource (CPR) game. It has been argued that, typically, field CPR environments involve repeated interaction in complex strategic settings where accurate information on the payoff structure is not available (see Ostrom, 1990). Since technical studies that have the aim of improving the knowledge on the relation between decisions and payoffs in CPR settings may be highly costly, it is a crucial question, relevant for policy-making, to evaluate the behavioral usefulness of these studies.

With this aim we have designed an experiment to compare the behavior of subjects in a relatively complex CPR game repeated over a long time horizon under two extreme informational conditions. In the first one subjects had complete information on the payoff structure (Complete-information Treatment), while in the second one they had none (Minimal-information Treatment).

Surprisingly, we find that there is no significant difference in the investment decisions at the aggregate level between those groups in the Complete-information Treatment, and

[7] The experimental literature on imitation often implement treatments where players have no information on the payoff structure, but know the actions and payoffs of (some of) their opponents (see Huck et al., 1999; Bosch-Domènech and Vriend, 2003; Apesteguia et al., 2005; Selten and Apesteguia, 2005). Since these studies are conductive for imitation, we do not review them here, but see Selten and Apesteguia (2005).

those in the Minimal-information Treatment. It emerges that at the beginning of the experiment subjects in the latter treatment widely explore the consequences on payoffs of their decisions; players use the first periods to get a sense of the payoff structure. Of course, in the Complete-information Treatment the first exploratory phase is not necessary since information is directly given to them. What is remarkable is that after some time players in both treatments seem to reach the same overview of the payoff structure. In fact, we have shown that aggregate behavior tends to the unique Nash equilibrium of the CPR game in both cases. While at the beginning of the experiment the average squared difference between the observed behavior and that predicted by best-reply in the Minimal-information Treatment is much more erratic than in the Complete-information Treatment, by the end of the experiment the difference tends to zero in both treatments. This indicates that if players in a CPR game are given a sufficiently long time-horizon they do approach the Nash equilibrium by best-replying.

The results of this paper suggest that the priorities in the CPR institutional agenda may have to be reconsidered. Enterprises with the aim of providing more precise information on the payoff structure of CPRs may not be worth their cost.

Finally, we have shown that our results are in line with those in the experimental literature on the study of behavior under severely limited information conditions. It emerges that in a variety of games players with minimal information on the payoff structure end up playing Nash. This is a remarkable and surprising result that deserves close attention in future experimental and theoretical research. In this respect, we have outlined some possible directions.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jebo.2004.08.002.

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