Selection Criteria in Coordination Games: Some Experimental Results

By Russell W. Cooper, Douglas V. DeJong, Robert Forsythe, and Thomas W. Ross*

A weakness of the Nash equilibrium concept for noncooperative games is that it may not generate a unique outcome. In this case, it must be augmented by a hypothesis refining the beliefs of players about the strategies selected by their opponents. As beliefs are inherently unobservable, one means of evaluating these hypotheses is through inferences based upon the observed play of participants in experimental games.

We study a class of symmetric, simultaneous move, complete information games called *coordination games*. This term refers to games which exhibit multiple Nash equilibria which are Pareto-rankable.[1] That is, all players are better off in one equilibrium relative to another yet may be unable to explicitly coordinate their strategies to achieve the preferred outcome. When this occurs, a coordination failure arises.

These games characterize strategic interactions in a large number of settings. Schelling (1960, 1978) provides an overview of social environments in which coordination games naturally arise. Coordination games are at the heart of a number of recent models in industrial organization and macroeconomics. These include models of network externalities (Michael Katz and Carl Shapiro, 1985), product warranties under bilateral moral hazard (Cooper-Ross, 1985), team production (John Bryant, 1983); and macroeconomic models of imperfect competition (Walter Heller, 1986 and Nobuhiro Kiyotaki, 1988) and search (Peter Diamond, 1982).[2]

For these games, extant refinement criteria proposed for sequential games of incomplete information (see for example In-Koo Cho and David Kreps, 1987) do not directly apply. Furthermore, in the coordination games we consider, the equilibria will generally be proper (Roger Myerson, 1978) and perfect (Reinhard Selten, 1974). Nevertheless, a number of selection criteria have been proposed for games of this nature and these are reviewed in the next section. These criteria provide a number of hypotheses regarding equilibrium selection in coordination games.

The goal of this experiment is to address the following questions. First, is Nash equilibrium a good predictor of observed behavior in strategic or game settings? Second, when there are multiple Nash equilibria does

*Cooper, DeJong, and Forsythe: College of Business Administration, University of Iowa, Iowa City, IA 52242; Ross: Department of Economics, Carleton University, Ottawa, ON K1S 5B6, Canada. We thank Adil Abdalla for his help in conducting the experiments and Robert Pearson for his programming assistance. Helpful comments were received from seminar participants at the California Institute of Technology and the Universities of British Columbia, Illinois, Minnesota, California at Berkeley, California at Los Angeles and California at San Diego, Stanford University and Texas A&M University, as well as Raymond Battalio, Andrew Daughety, Paul Milgrom, Tom Palfrey, Richard Young and two anonymous referees. Financial support from the National Science Foundation, Price Waterhouse, University of Iowa, the Hoover Institution and the Social Sciences and Humanities Research Council of Canada is gratefully acknowledged.

[1]This term has been used by Thomas Schelling (1960, ch. 4) to refer to games with multiple Nash equilibria yielding identical payoffs. He also used the term "collaboration games" for the same purpose. A standard example involves two automobiles approaching on a road. Each driver must select a side on which to drive. Equilibrium obtains when they select opposite sides. There are two such equilibria with identical payoffs. Here, we consider games in which the Nash equilibria are Pareto ranked, admitting a further need for coordination; namely, to select the "best" equilibrium.

[2]A slightly more extended discussion of these examples is included in Cooper, DeJong, Forsythe, and Ross (1989a).

one arise "naturally" as the outcome? That is, are there any particular characteristics of a game which tend to focus the players' attention on one of the equilibria?

The experimental design used to investigate these questions is discussed in Section I. The main results from our experiment are presented in Section II and can be summarized as follows. First, we find that the observed pattern of play is accurately predicted by the Nash equilibrium concept. Second, we find that the Pareto-dominant Nash equilibrium is not always the experimental outcome. This result is important in light of the argument often advanced that the Pareto-dominant outcome is a natural focal point. Instead, coordination failures can emerge in which the outcome is a Pareto-inferior Nash equilibrium.

We also provide evidence that dominated, cooperative strategies may influence the selection of an outcome from the set of Nash equilibria. Hence, the common practice of eliminating dominated strategies from a normal form game (discussed, for example, by Elon Kohlberg and Jean-Francois Mertens, 1986) may not be inconsequential. Section III provides an interpretation of our results.

I. Selection Criteria for Coordination Games

The critical element in coordination games is a "complementarity" between the strategy choice of a single agent and the strategy choice(s) of the other agent(s) (see Cooper and Andrew John, 1988). A specific game which illustrates a coordination problem is given in Figure 1. In this game, there are three strategies and two players with the payoff to the row player in each cell of the matrix. Since the game is symmetric, the payoff matrix for the column player is the transpose of this matrix. The pure strategy Nash equilibria are for the players to each choose strategy one, that is, (1,1), or for each to select strategy two, that is, (2,2). In these ordered pairs, the first element represents the strategy choice of the row player. These are both equilibria in that given the strategy chosen by the other player, neither player can profitably deviate. Note that at equilibrium (1,1), both players are worse off than at

Row Player's Payoff Matrix

		Column Player 1	2	3
Row Player	1	350	350	700
	2	250	550	1000
	3	0	0	600

FIGURE 1. ROW PLAYER'S PAYOFF MATRIX

(2,2) though neither, acting independently, can do better. This is a coordination failure.

If the players could cooperate and thus jointly determine their strategies, the best symmetric solution is for them to play strategy 3. Hereafter, we call strategy 3 the cooperative strategy and term (3,3) the cooperative outcome. Note also that strategy 3 is dominated by strategy 2 for the game in Figure 1.

The game in Figure 1 is representative of those in the experiment. It does not capture all of the economic detail in the examples of coordination failures. Rather, it reflects the essential qualitative properties of the coordination problem. We use this game to outline the alternative equilibrium selection criteria which have been proposed in the literature for games of this type.

We first allow for the possibility that the outcome is not a Nash equilibrium. For example, players may play the cooperative strategy or may randomly select strategies.

Hypothesis NE: The outcome will be a Nash equilibrium.

In the event that the outcome is in the set of Nash equilibria, one might argue that one of the equilibria is a focal point and hence represents a natural outcome for the game. That is, participants will believe that others will focus on one of the Nash equilibria, making it the outcome of their interaction. The issue of selection then reduces to a search for a "natural" focal point for the game.

Many game theorists (for example, Schelling, 1960 and John Harsanyi and

Selten, 1988) argue that the *Pareto-dominant* equilibrium is a natural focal point.[3] Under this selection hypothesis, coordination failures cannot occur as agents will naturally focus on the Pareto-dominant equilibrium, (2,2), and coordinate their actions to achieve that outcome.

Hypothesis PD: The Pareto-dominant Nash equilibrium will be selected.

We also consider the role of the dominated strategy in influencing the equilibrium selection process. While theorists have generally assumed that strictly dominated strategies can be excluded from the analysis of equilibrium selection (for example, Kohlberg-Mertens, 1986), experimental evidence on repeated prisoner's dilemma games suggests that players will sometimes play the dominated cooperative strategy, (for example, Robyn Dawes, 1980). This behavior may also have important implications for the selection of a Nash equilibrium. Further, to the extent that the selection of an equilibrium is influenced by payoffs associated with a dominated strategy, this provides evidence against any selection criteria which ignore these strategies.[4]

Hypothesis DSI: Dominated strategies are irrelevant to equilibrium selection.

II. The Experiment

In the experiment, players were asked to participate in a complete information, 3×3 bi-matrix game such as the one in Figure 1. Each player was paired with an anonymous opponent. One was designated the "row player" and the other the "column player." Each game was designed to be one of complete information because each player's payoff matrix was common knowledge and the numerical payoffs in each cell of the matrix represented a player's utility if the corresponding strategies were chosen.

We induced payoffs in terms of utility using the procedure introduced by Alvin Roth and Michael Malouf, (1979).[5] With this procedure, each player's payoff was given in points; these points determined the probability of the player's winning a monetary prize. At the end of each period of each game, we conducted a lottery where "winning" players received \$1.00 and "losing" players received \$0.00. The probability of winning, q, was given by dividing the points the player had earned by 1000. Thus, a player's expected utility at the outset of the game is given by:

$$(1)\quad U(\$1)q + U(\$0)(1-q) = q[U(\$1) - U(\$0)] + U(\$0).$$

Since expected utility is invariant with respect to linear transformations, q is a representation of the player's expected utility. Further, since q is linear in points, these points also denote a player's utility.

The experiment was conducted using seven cohorts of players, each consisting of eleven different players. All players were recruited from upper division undergraduate and MBA classes at the University of Iowa. Upon their arrival, players were seated at separate com-

[3]Harsanyi and Selten (1988) uses the term "payoff dominance" to refer to the case in which payoffs are lower in one equilibrium than another for all players. Strictly speaking, Schelling [1960, Appendix C] argues that the Pareto-dominant equilibrium will be a focal point if there is only one combination of strategies yielding that outcome (as in Figure 1). Duncan Luce and Howard Raiffa (1957) go further, eliminating any Pareto-dominated strategy pair as "jointly inadmissible" and by defining a "solution" to be a Nash equilibrium involving only jointly admissible strategy pairs. Finally, Glenn Harrison and Jack Hirshleifer (1989), in an experimental study of public good provision, invoke Pareto dominance as a selection criterion in making their predictions.

[4]For example, Harsanyi and Selten (1988) consider *risk domination* in which the least risky equilibrium is thought to be a natural focal point. The riskiness of an equilibrium strategy is determined without considering strategies not used in any equilibrium. Thus variations in the payoff from the play of dominated strategies should, under this hypothesis, have no influence on the equilibrium that is selected.

[5]Both Roth and Malouf (1979) and Joyce Berg et al. (1986) have employed this procedure to control for risk preferences in experiments where other aspects of behavior were the primary focus of investigation. We have also conducted games similar to the games in this paper in which payoffs were in dollars rather than points. No apparent difference in behavior was noted.

puter terminals and each was given a copy of the instructions for the experiment. These instructions are reproduced in Appendix A. Since these instructions were also read aloud, we assume that the information contained in them is common knowledge.

Each player participated in a sequence of one-shot games against different anonymous opponents within his cohort. All pairing of players was done through the computer using a procedure described below. Since players reported their strategy choices through computer terminals, no player knew the identity of the player with whom he was currently paired, or the history of decisions made by any of the other players in the cohort.

Each cohort participated in two separate sessions.[6] In Session I, all players participated in ten symmetric one-shot dominant strategy games. The payoff matrix used in each of these games is shown in Game 1 in Figure 2. Since this game is symmetric, only the row player's payoff matrix is shown. During Session I, each player played one game against every other player. Since there was an odd number of players, one sat out in each period. Thus, Session I consisted of eleven periods. Also, players alternated being row and column players during the periods in which they were active participants. Game 1 was conducted for three reasons: first, to provide players with experience with experimental procedures, second, to see how well the dominant strategy equilibrium prediction performed, and finally, to inform players about the rationality of their opponents.

In Session II, all players participated in twenty additional one-shot games which differed from the game played in Session I. Each played against each other player twice: once as a row player and once as a column player. As in Session I, one player sat out in each period and players alternated between being row and column players during the periods in which they were participating.[7]

Row Player's Payoff Matrix

		Column Player 1	2	3
Row Player	1	320	440	500
	2	420	600	660
	3	180	360	420

Dominant Strategy Equilibrium at (2,2)

FIGURE 2. GAME 1 DOMINANT STRATEGY MATRIX

Thus, Session II consisted of twenty-two periods.

In both sessions, players were paired using a table which specified that in each eleven period sequence, each player would play every other player exactly once and would alternate between being the row and column player during the periods in which he was participating. The ordering of the players and consequently the pair assignments was randomized at the beginning of each session. This randomization procedure was adopted to prevent players from playing against the same opponent in the same order within each session. In the instructions players were told that they would play each other player once in Session I and twice in Session II (once as a row player and once as a column player).

Each cohort was given a different game to play in Session II. The payoff matrices for these games, called Games 2–8, are reported in Figures 3 and 4. Game 2 (see Figure 3) was asymmetric with a unique Nash equilibrium. This game was played to see if a unique Nash equilibrium, not supported by dominant strategies, is a good predictor of observed behavior. Therefore, the outcome for this game, as well as that from the dominant strategy game in Session I, provides evidence on Hypothesis NE.

[6]Each cohort completed the two sessions in about one hour. Payments to participants ranged from \$5 to \$20.

[7]We wanted the pairings to satisfy two conditions: (i) players were to alternate being row and column players and (ii) each player was to play each of the other players twice (in Session II). It is impossible to satisfy these two conditions with an even number of players. Having the player who sits out draw the lottery ticket may have also served the purpose of convincing players of the credibility of the lottery procedure.

Row Player's Payoff Matrix

		Column Player 1	2	3
Row Player	1	525	555	585
	2	505	625	700
	3	385	550	625

Column Player's Payoff Matrix

		Column Player 1	2	3
Row Player	1	20	60	0
	2	110	420	495
	3	200	645	720

Nash Equilibrium at (2,3)

FIGURE 3. GAME 2 UNIQUE NASH EQUILIBRIUM MATRIX

Game 3

Row Player's Payoff Matrix

		Column Player 1	2	3
Row Player	1	350	350	1000
	2	250	550	0
	3	0	0	600

Nash Equilibria at (1,1) and (2,2)

Game 4

Row Player's Payoff Matrix

		Column Player 1	2	3
Row Player	1	350	350	700
	2	250	550	0
	3	0	0	600

Nash Equilibria at (1,1) and (2,2)

Game 5

Row Player's Payoff Matrix

		Column Player 1	2	3
Row Player	1	350	350	700
	2	250	550	1000
	3	0	0	600

Nash Equilibria at (1,1) and (2,2)

Game 6

Row Player's Payoff Matrix

		Column Player 1	2	3
Row Player	1	350	350	700
	2	250	550	650
	3	0	0	600

Nash Equilibria at (1,1) and (2,2)

Game 7

Row Player's Payoff Matrix

		Column Player 1	2	3
Row Player	1	350	350	700
	2	250	550	0
	3	0	0	500

Nash Equilibria at (1,1) and (2,2)

Game 8

Row Player's Payoff Matrix

		Column Player 1	2	3
Row Player	1	350	350	1000
	2	250	550	0
	3	0	0	500

Nash Equilibria at (1,1) and (2,2)

FIGURE 4. MULTIPLE NASH EQUILIBRIUM GAMES

Games 3–8 (see Figure 4) are symmetric coordination games. These games were constructed to test the specific hypotheses given in the previous section. In coordination Games 3–8, the elements in each player's 2×2 principal minor are the same. Payoffs associated with a rival's play of strategy 3 vary from game to game, but strategy 3 is always dominated by strategy 1. The pure strategy Nash equilibria are at (1,1) and (2,2) and (2,2) dominates (1,1) in all cases. In Games 3–6, the cooperative outcome occurs at (3,3) and in Games 7 and 8, it occurs at (2,2).

With this design in mind, we can outline our tests of the hypotheses presented in the previous section. Hypothesis NE will not be rejected if we observe Nash equilibria in each of our games. Should we fail to reject this hypothesis, we will test the alternative selection criteria. Hypothesis PD will be rejected if (1,1) is observed. Evidence that dominated strategies matter in the selection of an equilibrium will serve to refute Hypothesis DSI and, consequently, selection criteria which require that outcomes be independent of payoffs from dominated strategies.

III. Results

We present our results in several parts. First, we examine the behavior in games with unique equilibria (Games 1 and 2). Second, we analyze the data from the coordination games, Games 3–6, and examine the predictive ability of the selection criteria presented in Section II. Games 7 and 8 are discussed in the following section.[8]

A. *Games 1–2*

The data from Games 1 and 2 are presented in the upper and lower panels of Figure 5. Since Game 1 is a symmetric game, we tested to see if row players chose different strategies than column players. Using Fisher's exact probability test for player differences,[9] we found no effects approaching any reasonable level of significance; therefore, we pooled the data across row and column players. Since Game 2 is an asymmetric game, we attempted no such pooling. The row players' choices in this game are presented on the right-hand side of panel b and the column players' choices are shown on the left.[10] We next tested to see if the observed pattern of play was independent from one period to the next. Again using a Fisher's exact test, we were unable to reject the null hypothesis of independence at any reasonable level of significance. Thus, the remaining analysis pools the results within each of these two games.

From Figure 5 it is apparent that there is strong support for the dominant strategy prediction in Game 1 and the Nash equilibrium prediction in Game 2. From the outset, players almost always chose their Nash equilibrium strategies in these two games.

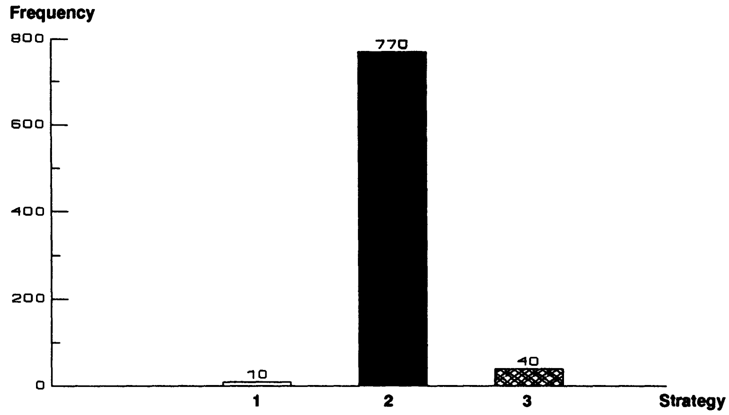
B. *Games 3–6*

We next analyze the first four coordination games. Recall that these are all symmetric games. As with Game 1, we tested whether row players behaved differently than column players. Since we again found no significant differences, we pooled the data across both types of players. The data are not independent across periods, however. Using Fisher's exact test, we can reject the hypothesis that the data from the first 11 periods is the same as the data from the last 11 periods at the 0.05 level. Using only the last half of the

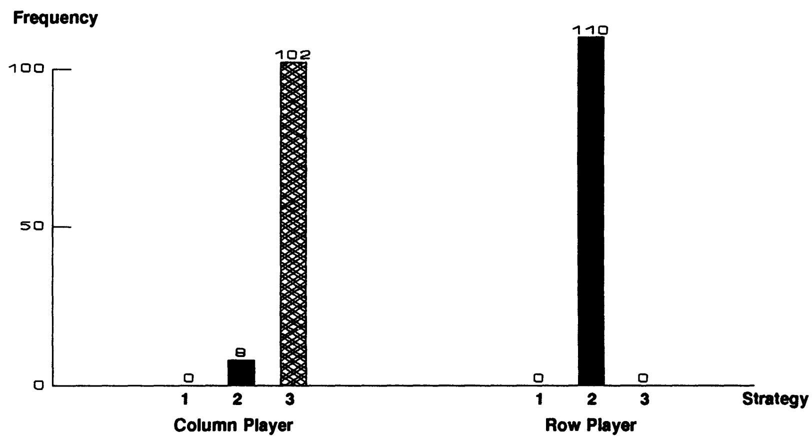
[8]The complete history of play for each game is available from the authors upon request.

[9]We use Fisher's exact test throughout this paper to test for the statistical significance of differences (see Kendall and Stuart, Vol. II (1979) 584–86). For example, in Game 3, the strategies 1, 2, and 3 were chosen 157, 44, and 19 times, respectively. The row players choose these strategies 79, 33, and 8 time, respectively. We ask how likely we are to see these choices if they are independent of whether the player was designated a row or column player. The exact probability of observing this data is 0.737.

[10]Throughout the discussion of results, we describe individual play rather than equilibrium outcomes as strategy choices are independent of rivals' identities given the information structure.



a. Game 1



b. Game 2

FIGURE 5a. GAME 1, b. GAME 2

data from each game, this time independence hypothesis cannot be rejected at a significance level of 0.05. However, since Game 4 barely passed this test, we examined the data from the last five periods of each game. In this latter case, we find that the time independence hypothesis cannot be rejected at any significance level up to 0.40. Thus, we report our data in two ways: pooled over the last eleven periods and pooled over the last five periods.

These pooled data are summarized in Figure 6. From this figure it can be seen that players overwhelmingly chose a single strategy in each of these games: strategy 1 in Games 3 and 4 and strategy 2 in Games 5

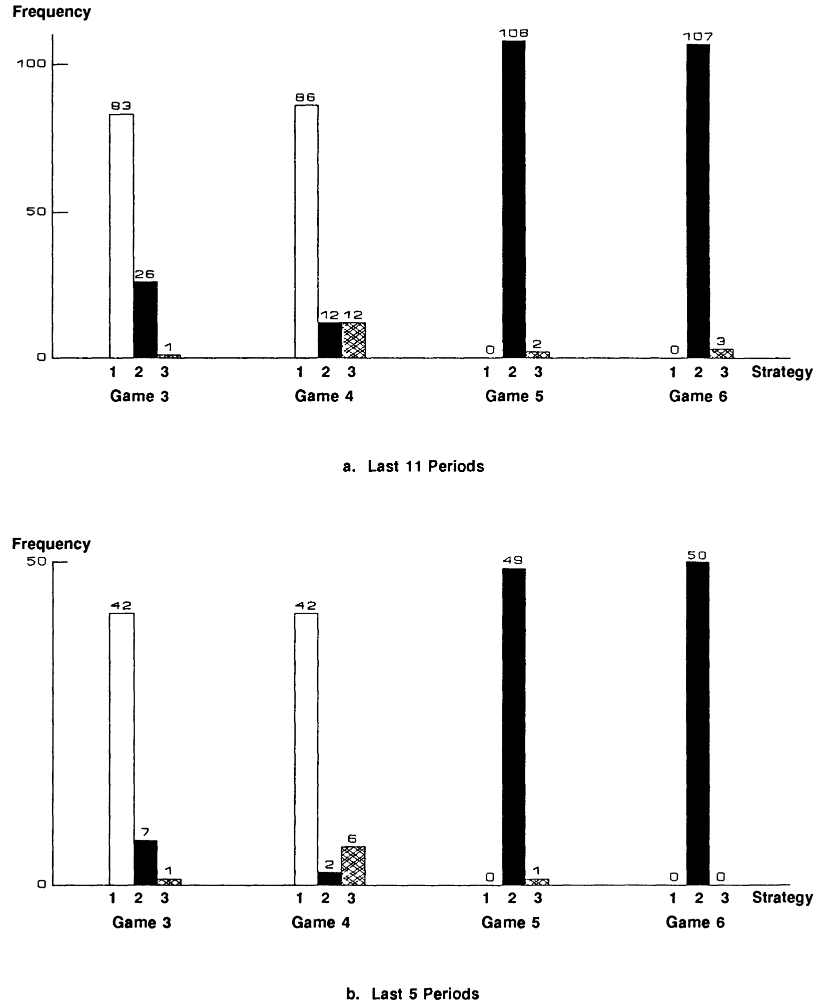


FIGURE 6a. LAST 11 PERIODS, b. LAST 5 PERIODS

and 6. These data are consistent with the hypothesis that the outcomes will be a Nash equilibrium.[11,12]

We can use the data to refute several additional hypotheses. Consider first Hypothesis PD and recall that (2,2) is the Pareto-dominant Nash equilibrium strategy in these games. The data from Games 3 and 4 can be used to reject the hypothesis. Further, the data support the hypothesis that

[11]A more formal test of the hypotheses presented in the previous section can be found in Cooper, DeJong, Forsythe, and Ross (1989a). For each of the respective games, we were unable to reject the hypothesis that strategy 1 was chosen at least 95 percent of the time in Games 3 and 4 and strategy 2 was chosen at least 95 percent of the time in Games 5 and 6 in the last five periods of play.

[12]We focus here on pure strategy Nash equilibria. In all of Games 3–8 there is a unique mixed strategy equilibrium in which each player plays strategy one with probability 2/3 and strategy two with probability 1/3. The data presented in Figure 6 reveal that we can reject this as the outcome over the last 11 and last 5 periods in all of these games.

(1,1) is the experimental outcome. Thus, Games 3 and 4 provide examples of coordination failures.[13]

Hypothesis DSI can be tested by comparing the outcomes from these games. According to this hypothesis, the experimental outcomes should be the same in Games 3 to 6, since they differ only in the payoffs a player receives when his opponent plays a dominated strategy. However, the Pareto-inferior Nash equilibrium outcome was observed in Games 3 and 4, while the Pareto-superior Nash equilibrium outcome was observed in Games 5 and 6.[14] Thus, comparing these outcomes leads us to reject Hypothesis DSI: dominated strategies can influence the selection of an outcome from the set of Nash equilibria.

IV. Interpretation

These results provide evidence against Pareto-dominance as a selection criteria for coordination games and indicate that the cooperative, dominated strategy influences equilibrium selection. That is, by varying the payoffs associated with a rival's play of strategy 3, we can induce variations in the selection of an equilibrium. At the very least, the evidence implies that at some point during the play of these games, some participants placed positive probability on an opponent playing the cooperative, dominated strategy. If this was not the case, then variations in the payoff associated with an opponent playing this strategy could not have affected the outcome. From these observations, two questions arise. First, why is strategy 3 so important in these games? Second, how did the play evolve toward the equilibrium that was selected?

We investigated whether strategy 3 is important because it is the cooperative strategy or whether players place prior probability weight on a dominated strategy even when it does not support the cooperative outcome. That is, a player might believe that his opponent will be "cooperative" or will be "irrational" where the latter term refers to the play of a dominated strategy by a self-interested player.[15]

To separate the two explanations for our observations in Games 3–6, we designed Games 7 and 8 (see Figure 4) in which the cooperative outcome was not supported by dominated strategies. Game 7 (8) was constructed from Game 4 (3) by reducing each player's payoff from playing strategy 3 when his opponent plays strategy 3 from 600 to 500. For each of these games, this moves the cooperative outcome from (3,3) to (2,2) which is also a Nash equilibrium. If players place the same prior probability on their opponent playing the dominated strategy in Game 7 (8) as they did in Game 4 (3), the outcome observed in these two games should be the same. On the other hand, if players place positive probability on their opponent playing the cooperative strategy rather than the dominated strategy, players should expect that their opponent is more likely to play (2,2) in Game 7 (8) than in Game 4 (3). This should increase the likelihood that (2,2) is observed in Games 7 and 8.

The pooled data for Games 7 and 8 are summarized in Figure 7. The Pareto-superior Nash equilibrium, (2,2), was observed in

[13]Since running these initial treatments, we have replicated the results for Game 3 two additional times. In an experiment based on Bryant's (1983) model of coordination failures, John Van Huyck et al. (1987) also find that the Pareto-inferior Nash equilibrium may be selected.

However, we want to indicate a word of caution about the saliency of the $1 lottery prize. Since conducting the initial treatment and replications (about two years ago), we've obtained identical results in four replications using a $2 prize. With a $1 price, the results are qualitatively similar but not identical.

[14]The Pareto-superior outcome was also obtained in an additional game we conducted using the 2×2 principal minor of Games 3–6. For the 22 periods, players selected strategy 2 108 out of 110 opportunities. When compared with Games 3–4, this game provides additional evidence regarding the influence of a dominated strategy on equilibrium selection.

[15]This should be distinguished from the play of a cooperative, dominated strategy by a player whose utility depends, in part, on the payoffs of others.

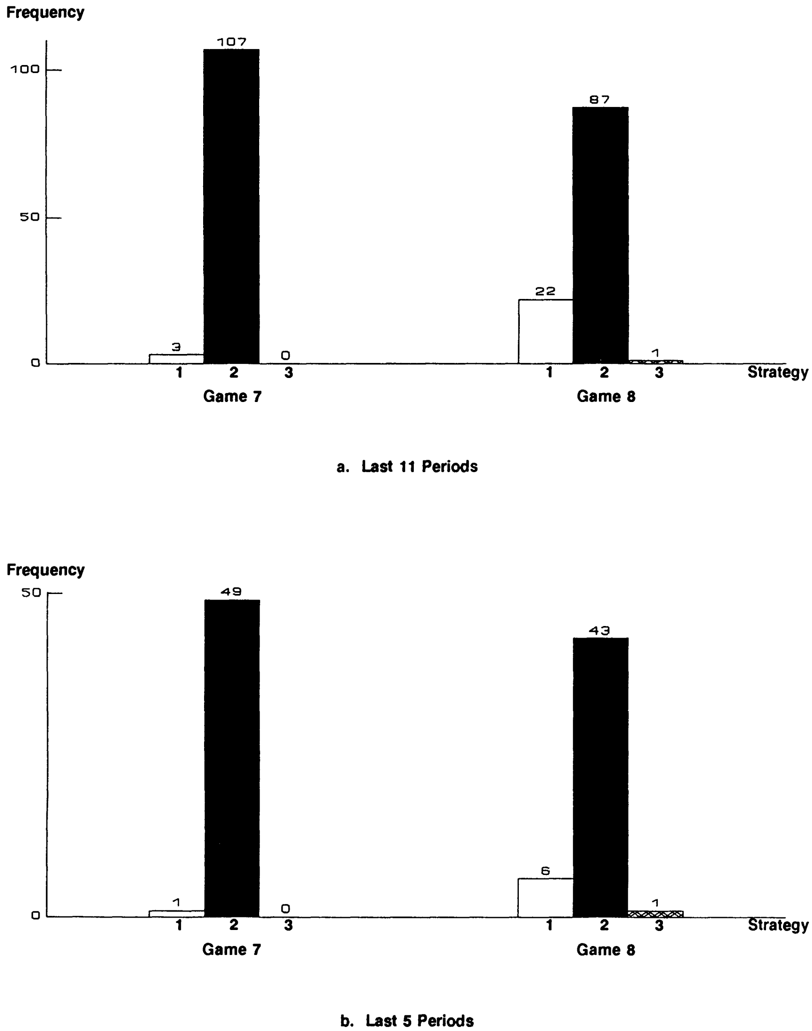


FIGURE 7a. LAST 11 PERIODS, b. LAST 5 PERIODS

these games.[16] Thus, when strategy 3 no longer supports the cooperative outcome, players evidently place a lower probability on its play by their rival. This is verified by the observed play: in all 22 periods of Games 3–6 the cooperative, dominated strategy is chosen 11 percent of the time while in Games 7–8, the dominated strategy is played only 1.8 percent of the time.

To better understand the observed differences in play in Games 3–6, Figure 8 presents the data for all 22 periods of play in each game. The play of strategy 3 occurs more frequently in early periods of all four games. As indicated by the figure, this play tends to disappear in all games except Game

[16]There are some differences in play between these two games. In particular, strategy 1 was played 22 times in Game 8 but only 3 times in Game 7 in the last 11 periods.

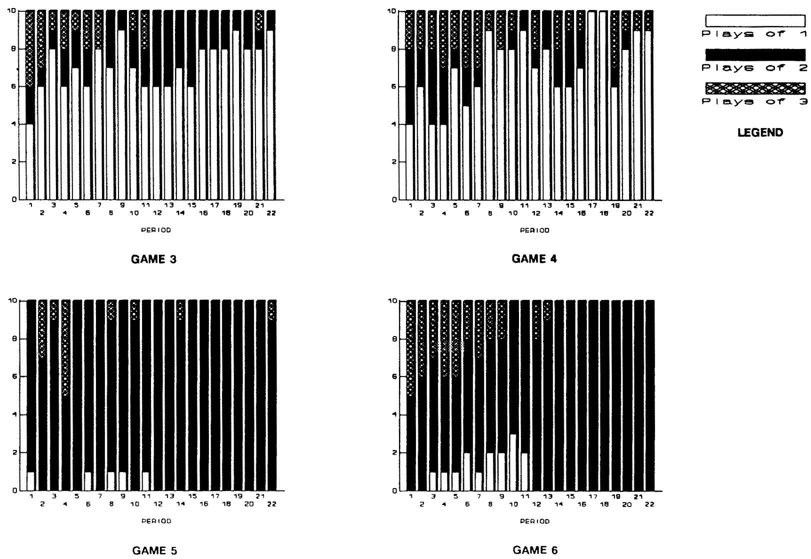


FIGURE 8. GAMES 3, 4, 5, AND 6

TABLE 1—FREQUENCY OF STRATEGY CHOICES BY OPPONENT'S PLAY IN PREVIOUS PERIOD: Periods 2–11, Games 3–6

		Opponent's Play in Previous Period			
Game	Strategy	1	2	3	Total
	1	48	9	12	69
3	2	11	4	1	16
	3	8	3	3	14
	Total	67	16	16	99
	1	44	8	13	65
4	2	8	5	2	15
	3	8	5	6	19
	Total	60	18	21	99
	1	0	4	0	4
5	2	4	72	9	85
	3	0	8	2	10
	Total	4	84	11	99
	1	2	9	4	15
6	2	8	35	17	60
	3	3	13	8	24
	Total	13	57	29	99

4 in which strategy 3 is played a number of times in later periods. There is little initial play of strategy 2 (1) in Games 3 and 4 (5 and 6). In Games 3 and 4, the play of strategy 1 increases over time. In Games 5 and 6, the play of strategy 2 increases over time and strategy 1 is never observed in the last 11 periods of play.

Table 1 summarizes individual play in the first 11 periods conditional on opponents' play in the previous period.[17] The point of this table is to illustrate the evolution of play to strategy 1 (2) in Games 3 and 4 (5 and 6). For Games 3 and 4, an opponent's play of strategy 3 appears to lead to the play of strategy 1 in the next period. Similarly, in Games 5 and 6, an opponent's play of 3 leads to the play of strategy 2 in the next period.

A model consistent with these observations must explain the observed play of the cooperative strategy and the selection process. One model assumes the presence of some altruistic players.[18] Suppose, for example, that altruists want to maximize the minimum element of the payoff pair so that strategy 3 becomes a best response to a rival's play of strategy 3, and outcome (3,3) represents an equilibrium for two such players.[19] Equilibrium selection would then depend upon the actual proportion of players who are altruistic as well as the priors players hold about this proportion. For example: self-interested players who expect to meet a sufficient number of altruists playing strategy 3, will respond by playing strategy 1 in Games 3, 4, and 6, and strategy 2 in Game 5. Altruists who find the probability of meeting another altruist playing strategy 3 too low, will switch to whatever the self-interested players are playing, yielding an equilibrium at (1,1) or (2,2). If we use the actual proportion of play observed in the first 11 periods of each game as proxies for the actual beliefs held by players, this model predicts the equilibria observed in Games 3–8.

V. Conclusions

Our principal concern in this research was to answer the following question: What happens when players play a noncooperative game with multiple Nash equilibria? We further refined the question by focusing on games with Pareto-rankable equilibria called coordination games. Coordination games are of significant economic interest; they describe the strategic interactions present in models of double moral hazard and networks in the industrial organization field and coordination failures in macroeconomics. In terms of the outcomes in these games, several possibilities suggest themselves. For example, we could observe the Pareto-dominant equilibrium as the outcome, randomized strategies, chaos, or even cooperation.

Our experimental evidence strongly supports the hypothesis that the outcome will be from the set of Nash equilibria. It does not support, however, any of the other proposed hypotheses regarding equilibrium selection. First, the Pareto-dominant equilibrium was not always selected in the games. Second, we found evidence that variations in payoffs from a rival's play of a dominated strategy can influence equilibrium selection. As a result, we can reject the hypotheses based upon Pareto dominance and the irrelevance of dominated strategies; variations in a player's payoff from an opponent's play of a cooperative, dominated strategy influences equilibrium selection.

The importance of cooperative play has also been identified in the experimental literature on finitely repeated prisoner's dilemma games.[20] There are a number of theoretical models which can explain this cooperative play including that discussed by Kreps et al.

[17]This allows us to look at the most naive type of dynamics: best responding to an opponent's play in the previous period.

[18]Alternatively, Kreps et al. explain observed cooperation in finitely repeated prisoner's dilemma games by modeling it as a game of incomplete information. If players believe that there is a small chance their opponent will adopt a tit-for-tat strategy, it may be optimal for them to respond for some time, with a similar strategy, leading to cooperation. The strategies which support this outcome are not feasible in our environment.

[19]This is only one of many ways to model altruistic behavior. Thomas Palfrey and Howard Rosenthal (1987) introduce a different model of altruism in their work on experimental public goods contribution games. In their model, altruists enjoy extra utility from being "cooperative" (in their model by contributing more toward the provision of the public good) which is independent of the choices made by the other players.

[20]See, for example, Dawes (1980), Dawes and John Orbell (1982) and Anatol Rapoport and Albert Chammah (1965).

(1982) and models with altruistic players. We are unaware of any evidence which distinguishes between these competing theories of cooperative play.

A second line of research is to consider the robustness of observed coordination failures to alternative institutions. Joseph Farrell (1987) suggests that nonbinding preplay communication can overcome coordination problems while Kohlberg-Mertens (1986) suggest that allowing one player to choose between playing a coordination game and receiving a certain outcome can lead to play of the Pareto-dominant Nash equilibrium.[21]

APPENDIX A: INSTRUCTIONS

General

You are about to participate in an experiment in the economics of decision making. If you follow these instructions carefully and make good decisions, you might earn a considerable amount of money which will be paid to you in cash at the end of the experiment.

The experiment will consist of a series of separate decision making periods. Each period consists of two phases. In Phase I you will be paired with another person and, based upon your combined actions, you will be able to earn *points*. In Phase II, you will have the opportunity to earn dollars based upon the points you earn in Phase I. We begin by describing Phase II so that you understand how the points you earn affect the number of dollars you earn. Then, we describe Phase I in detail so that you understand how to earn points.

Phase II *Instructions*

At the end of Phase I, you will have earned between 0 and 1000 points according to the rules we will discuss below. The number of dollars you earn in Phase II will depend partly on the number of points you earned in Phase I and partly on chance. Specifically, we have a box which contains lottery tickets numbered 1 to 1000. In Phase II, a ticket will be randomly drawn from the box. If the number on the ticket IS LESS THAN OR EQUAL TO the number of points you have earned in Phase I, you WIN $1.00. If the number on this ticket IS GREATER THAN the number of points you have earned in Phase I, you WIN $0.00. For example, if you have 600 points, you will have a 60 percent chance of winning $1.00. Notice that the more points you have, the larger will be your chance of winning the $1.00 prize.

Phase I *Instructions*

In each decision-making period, you will be paired with another person. One of you will be designated player B and the other will be designated player S. At the beginning of the period, both player B and player S must separately and independently select an action. The combined actions of player B and player S jointly determine the number of points earned by player B and the number of points earned by player S.

You will alternate from being player B to being player S from one period to the next. Since there is not an even number of people participating in this experiment, you will occasionally be required to not participate during a particular period. When this is the case, you will receive a message on your terminal which states:

"FOR PERIOD ____, YOU ARE SITTING OUT."

In the periods in which you are participating you will receive a message stating:

"FOR PERIOD ____, YOU ARE A B PLAYER."

or

"FOR PERIOD ____, YOU ARE AN S PLAYER."

You will be participating in a series of separate sessions during today's experiment. During the current session, you will play against each person once—as either player B or player S. However, you will not know the identification of the person you are playing against in any period. Similarly, nobody in your decision-making pair will know your identification in any period. Further, you will not be told who these people are either during or after the experiment.

In your folder you will find a set of record sheets. On these sheets you will indicate, based on the message previously received on your terminal, whether you are player B, player S, or not participating for each period. The points that you earn in each period will be determined by the rules given below.

Specific Instructions for Player B

In this part of the instructions we will be referring to specific number of points. These numbers are the same as you will be using in the first session of today's experiment.

In those periods in which you are player B, you and player S must separately and independently decide on actions which will jointly determine the number of points earned by you and the number of points earned by player S. As player B, you may either choose action $B1$, action $B2$, or action $B3$. Similarly, player S may choose action $S1$, action $S2$, or action $S3$. The number

[21] Cooper, DeJong, Forsythe, and Ross (1989b) provide some preliminary results indicating that allowing communication in Game 3 may not lead to play of the Pareto-dominant Nash equilibrium. Van Huyck et al. (1989) present results on coordination games with pre-play auctions which support the predictions of Kohlberg-Mertens.

of points earned by you is given by the following table for each pair of actions you and player *S* might select:

NUMBER OF POINTS EARNED BY PLAYER *B*

		S's Actions		
		*S*1	*S*2	*S*3
B's Action	*B*1	320	440	500
	*B*2	420	600	660
	*B*3	180	360	420

To read this table, suppose that you chose action *B*2 and player *S* chose action *S*1. You would then earn 420 points. Similarly, suppose that you chose action *B*1 and player *S* chose action *S*3. You would then earn 500 points. In a like manner, you can use this table to determine the number of points you would earn for all other pairs of actions you and player *S* may select. *S* players also earn points depending upon the type of action they select. These are given in the next section of the instructions.

When you select an action, enter the action chosen into the computer via your terminal and record the action chosen on your record sheet. Once both you and player *S* have selected your actions and entered them into the computer via your terminals, the computer will determine the number of points earned by you based on the table given above. The result is then sent to you via your terminal. The message will look like the one below:

PERIOD POINTS ARE ____.

At the end of the period, you are to record your point earnings for Phase I on your record sheet. Make sure you check your earnings in points against the computer's calculations. The computer will also inform you about the action taken by player *S*. Make sure you record this information on your record sheet.

Specific Instructions to Player S

In those periods in which you are player *S*, you and player *B* must separately and independently decide on actions which will jointly determine the number of points earned by you and the number of points earned by player *B*. As player *S*, you may either choose action *S*1, action *S*2, or action *S*3. The number of points earned by you is given by the following table for each pair of actions you and player *B* might select:

NUMBER OF POINTS EARNED BY PLAYER *S*

		S's Action		
		*S*1	*S*2	*S*3
B's Action	*B*1	320	420	180
	*B*2	440	600	360
	*B*3	500	660	420

To read this table, suppose that player *B* chose action *B*2 and you chose action *S*1. You would then earn 440 points. Similarly, suppose that player *B* chose action *B*1 and you chose action *S*3. You would then earn 180 points.

When you select an action, enter the action chosen into the computer via your terminal and record the action chosen on your record sheet. Once both you and player *B* have selected your actions and entered them into the computer via your terminals, the computer will determine the number of points earned by you based on the table given above. The result is sent to you via your terminal. The message will look like the one below:

PERIODS POINTS ARE ____.

At the end of the period, you are to record your point earnings for Phase I on your record sheet. Make sure you check your earnings in points against the computer's calculations. The computer will also inform you of the action taken by player *B*. Make sure you record this information on your record sheet.

Phase II *Recording Rules*

After completing your Phase I record sheet for a given decision-making period, you are to use your profit sheet to record the dollars you earn in Phase II. First, record your Phase I point earnings in the row corresponding to the number of the period that is currently being conducted. The person who sat out in this period will then be asked to draw a lottery ticket from the box. Before he/she returns the ticket to the box, the number on the ticket will be announced. You should record the number of the ticket in the second column of your profit sheet. If the number drawn IS LESS THAN OR EQUAL TO the number of points earned in Phase I, circle $1.00 in the next column; otherwise circle $0.00 in that column. Pay careful attention to what you circle. Any erasure will invalidate your earnings for the period. If you do make a mistake and circle the wrong number, call it to the experimenter's attention.

At the end of the session, add up your total profit in dollars and record this sum in row 23 of your profit sheet. All dollars on hand at the end of the session in excess of $2.00 dollars are yours to keep. Subtract this number, which is on row 24, from your total dollars on row 23 and record this difference on row 25. This is the amount of dollars you have earned in this session.

In summary, your earnings in the experiment will be the total of the amounts you win in all Phase II lotteries. The amount of money you earn will depend partly upon luck and partly upon whether you have made good decisions in Phase I. Notice that the more points you earn in Phase I, the more likely you will win in Phase II. Are there any questions?

Instructions for Session II

This session of the experiment will again consist of a series of separate decision-making periods. The session will be conducted in exactly the same way as the previous session except you will play against each person twice, once as player *S* and once as player *B*.

All dollars you earn in this session in excess of $0.00 dollars are yours to keep.

SAMPLE INFORMATION SHEET

Player B

Number of Points Earned by Player B

		S's Action		
		*S*1	*S*2	*S*3
B's Action	*B*1	320	440	500
	*B*2	420	600	660
	*B*3	180	360	420

Player S

Number of Points Earned by Player *S*

		S's Action		
		*S*1	*S*2	*S*3
B's Action	*B*1	320	420	180
	*B*2	440	600	360
	*B*3	500	660	420

REFERENCES

Berg, Joyce E. et al., "Controlling Preferences for Lotteries on Units of Experimental Exchange," *Quarterly Journal of Economics*, May 1986, *101*, 281–306.

Bryant, John, "A Simple Rational Expectations Keynes-Type Model," *Quarterly Journal of Economics*, August 1983, *98*, 525–59.

Cho, In-Koo and Kreps, David, "Signalling Games and Stable Equilibria," *Quarterly Journal of Economics*, May 1987, *102*, 179–222.

Conover, W. J., *Practical Nonparametric Statistics*, New York: Wiley & Sons, 1971.

Cooper, Russell et al., (1989a) "Selection Criteria in Coordination Games: Some Experimental Results," University of Iowa Working Paper, 1989.

______, (1989b) "Communication in Coordination Games," University of Iowa, mimeo., 1989.

Cooper, Russell and John, Andrew, "Coordinating Coordination Failures in Keynesian Models," *Quarterly Journal of Economics*, August 1988, *103*, 441–63.

______ **and Ross, Thomas, W.**, "Product Warranties and Double Moral Hazard," *Rand Journal of Economics*, Spring 1985, *16*, 103–113.

Dawes, Robyn M., "Social Dilemmas," *Annual Review of Psychology*, 1980, *31*, 169–93.

______ **and Orbell, John M.**, "Cooperation in Social Dilemma Situations: Thinking About It Doesn't Help," in *Research in Experimental Economics, Volume II*, Vernon L. Smith, ed., Greenwich: JAI Press, 1982, 167–73.

Diamond, Peter, "Aggregate Demand Management in Search Equilibrium," *Journal of Political Economy*, October 1982, *90*, 881–94.

Farrell, Joseph, "Cheap Talk, Coordination, and Entry," *Rand Journal of Economics*, Spring 1987, *18*, 34–39.

Harrison, Glenn W. and Hirshleifer, Jack, "An Experimental Evaluation of Weakest Link/Best Shot Models of Public Goods," *Journal of Political Economy*, February 1989, *97*, 201–225.

Harsanyi, John C. and Selten, Reinhard, *A General Theory of Equilibrium Selection in Games*, Cambridge: MIT Press, 1988.

Heller, Walter, "Coordination Failure under Complete Markets with Applications to Effective Demand," in *Equilibrium Analysis, Essays in Honor of Kenneth J. Arrow, Volume II*, Walter Heller, Ross Starr, and David Starrett, eds., Cambridge: Cambridge University Press, 1986.

Katz, Michael and Shapiro, Carl, "Network Externalities, Competition and Compatibility," *American Economic Review*, June 1985, *75*, 424–40.

Kendall, Maurice and Stuart, Alan, *The Advanced Theory of Statistics, Vol. 2*, New York: Macmillan, 1979.

Kiyotaki, Nobuhiro, "Implications of Multiple Expectations Equilibria Under Monopolistic Competition," *Quarterly Journal of Economics*, November 1988, *103*, 695–714.

Kohlberg, Elon and Mertens, Jean-Francois, "On the Strategic Stability of Equilibria," *Econometrica*, September 1986, *54*, 1003–38.

Kreps, David et al., "Rational Cooperation in the Finitely Repeated Prisoners' Dilemma," *Journal of Economic Theory*, August 1982, *17*, 245–52.

Luce, R. Duncan and Raiffa, Howard, *Games and Decisions*, New York: Wiley & Sons, 1957.

Myerson, Roger, "Refinements of the Nash Equilibrium Concept," *International Journal of Game Theory*, 1978, *7*, 73–80.

Palfrey, Thomas and Rosenthal, Howard, "Private Incentives and Social Dilemmas: The Effects of Incomplete Information and Altruism," mimeo., 1987; forthcoming, *Journal of Public Economics*.

Rapoport, Anatol and Chammah, Albert M., *Prisoner's Dilemma*, Ann Arbor: University of Michigan Press, 1965.

Roth, Alvin E. and Malouf, Michael W. K., "Game-Theoretic Models and the Role of Bargaining," *Psychological Review*, 1979, *86*, 574–94.

Schelling, Thomas, *The Strategy of Conflict*, Cambridge: Harvard University Press, 1960.

______, *Micromotives and Macrobehavior*, New York: Norton & Company, 1978.

Selten, Reinhard, "A Reexamination of the Perfectness Concept for Equilibrium Points in Extensive Games," *International Journal of Game Theory*, 1974, *4*, 25–55.

Van Huyck, John B. et al., "Coordination Failure, Strategic Uncertainty, and Convergent Expectations," mimeo., Department of Economics, Texas A&M University, July 1987.

______, "Asset Markets as an Equilibrium Selection Mechanism: Coordination Failure, Game Form Auctions, and Forward Induction," Texas A&M University Working Paper No. 88-40, February 1989.