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Tacit Cooperation, Strategic Uncertainty, and Coordination Failure: Evidence from Repeated Dominance Solvable Games[1]

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This paper reports an experiment designed to discover how the prospect of future interaction influences people's ability to tacitly cooperate in repeated dominance solvable games. The experiment varies two treatment variables: whether the constituent game is solvable by strict or iterated dominance and whether prospective interaction is finitely or randomly terminated. Specifically, we introduce a special repeated matching protocol consisting of an initial phase terminated randomly and a terminal phase of T periods. We call this protocol T-death. The T-death protocol allows us to observe a pair's behavior in both a sequence of infinite continuation games and a sequence of finite continuation games. *Journal of Economic Literature* Classification Numbers: C720, C920, 1120, 1400. © 2002 Elsevier Science

Key Words: cooperation; coordination; dominance; repeated games; prisoners' dilemma; duopoly; public goods; experiment.

I. INTRODUCTION

Reciprocity among patient players is often used to explain why an apparent incentive problem when analyzed in a static game does not prevent tacit cooperation in a repeated game. For example, it is often argued that oligopolists will be able to tacitly collude on the monopoly solution since they interact repeatedly. However, almost "anything" is an equilibrium of a repeated game if players are sufficiently "patient." So in applying repeated game theory, economists typically select an equilibrium that is efficient and symmetric.[3]

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[3] See Fudenberg and Tirole (1991, p. 160).

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Using field data to investigate the psychological salience of deductive selection principles, like efficiency and symmetry, is difficult. An alternative approach is to use the experimental method. Van Huyck *et al*. (1990, 1991) present evidence that security can undermine the salience of efficiency in repeated coordination games.[4] Van Huyck *et al*. (1995) present evidence that security can undermine the salience of symmetry in repeated bargaining games. Except in simple settings, subjects are unlikely to deduce a mutually consistent strategy combination from a complete information description of the game. Nevertheless, with experience behavior does frequently converge to a mutual best response outcome. It appears that past instances of the present situation allow subjects to learn to coordinate on a specific equilibrium strategy combination. Historical accident and dynamic process influence the origin of mutually consistent behavior in repeated bargaining and coordination game experiments.[5]

The relevance of these discoveries for repeated cooperation problems is an open question. Repeated game theory suggests that the prospect of future interaction among patient players converts a cooperation problem into a coordination problem. However, the resulting strategy coordination problem is more difficult than those arising in repeated bargaining and coordination games. Not only are there multiple equilibria in repeated cooperation games, but the equilibria with desirable strategic properties, like efficiency, are constructed using history contingent strategies. Consequently, history must be used not only to focus expectations on an equilibrium assignment, but also to monitor compliance with the equilibrium assignment.

Since history contingent strategies are not observable by other players in the game, one wonders if observing the history of play would allow players to solve the strategy coordination problem in the continuation game. Surprising play by other strategically rational players may be due either to a sincere disagreement about the equilibrium assignment or to an opportunistic defection from a commonly understood equilibrium assignment. In the first case one should try to teach the assignment, and in the second case one should try to enforce the assignment. This dual use of history does not arise in repeated bargaining and coordination games.

In this paper, we report evidence on how the prospect of future interaction influences the ability of people to tacitly cooperate. The experiment uses repeated dominance solvable games that vary two treatment variables: whether the constituent game was solvable by strict dominance or iterated dominance and whether prospective interaction is finitely or randomly terminated. Specifically, we introduce a special repeated

[4] See also Cachon and Camerer (1996), Cooper *et al*. (1996), and Straub (1995).

[5] See also Binmore *et al*. (1993), Roth and Schoumaker (1983), and Van Huyck *et al*. (1997).

matching protocol consisting of an initial phase terminated randomly and a terminal phase of T periods. We call this matching protocol T-death. The T-death matching protocol allows us to observe a pair's behavior in both a sequence of infinite continuation games and a sequence of finite continuation games.

Our main finding is that efficiency and symmetry need not be salient principles used by patient players to coordinate in the repeated dominance solvable games considered. In fact, it turns out to be quite difficult for subjects to learn to coordinate on the symmetric payoff-dominant play path under the T-death protocol, but it does occur in some cases.

II. LITERATURE REVIEW

There is a large experimental literature on repeated dominance solvable games, which can be divided into matrix game experiments, oligopoly experiments, and public goods experiments. Our review of this literature focuses on the influence of prospective interaction in promoting tacit cooperation. There is also a smaller evolutionary tournaments (strategy method) literature, which is of interest here due to its use of explicit strategies.

Rapoport *et al*. (1976) survey the early 2×2 game experiments. This literature emphasized the relatively high levels of cooperation observed in finitely repeated games for which the theory of the day predicted none. Under complete information, game theory predicts backwards unraveling in the finitely repeated Prisoners' Dilemma. Kreps *et al*. (1982) explained these early results for the Prisoners' Dilemma by analyzing incomplete information in finitely repeated games. Their analysis bounds the number of periods of backwards unraveling when one player may be a tit-for-tat automaton.

Selten and Stoecker (1986) report an experiment in which 35 subjects participated in 25 repeated Prisoners' Dilemma contests of 10 periods each against randomly and anonymously assigned opponents. The typical behavior of experienced subjects involves cooperation until shortly before the end of the contest. They conclude that this behavior is inconsistent with the Kreps *et al*. model because "subjects first have to learn cooperation and only afterwards do they discover the end effect" (p. 48). They conclude that it is not clear whether this decay would have continued in a much longer sequence of contests.

The backwards unraveling argument in the finitely repeated Prisoners' Dilemma breaks down when the repeated game is terminated randomly. Roth and Murnighan (1978) report an experiment using a randomly terminated repeated Prisoners' Dilemma, where the probability the game continues varied over 0.105, 0.5, and 0.895. Tacit cooperation is consistent with many equilibrium strategy combinations for continuation probabilities 0.5 and 0.895, but not 0.105. They find that the continuation probability has a statistically significant effect on the incidence of cooperation observed in the first period. Given that subjects were playing against the tit-for-tat automaton, it is interesting to note how little cooperation actually emerges overall: 31% for 0.5 and 41% for 0.895.

Their results illustrate the importance of allowing subjects to acquire experience in the repeated game. Surely, cooperation rates would have been much higher had subjects learned they were playing against the tit-for-tat automaton in Roth and Murnighan. In retrospect the puzzle about this early literature is not why there is so much cooperation, but rather why so little cooperation is observed in repeated dominance solvable games.[6]

Cooper *et al*. (1996) conduct what is probably the strongest test to date of the decision theoretic prescription—don't use strictly dominated strategies—in that subjects were allowed to acquire experience in a "one-shot" Prisoners' Dilemma but were prevented from interacting with the same player more than once. In fact, their matching protocol even prevents a subject from interacting with anyone who has interacted with someone that a subject has already met, which rules out contagion equilibria in the evolutionary game. With 19 periods of experience, only about 12% of the subjects played the symmetric efficient, but strictly dominated, action; that is, only 12% cooperate.

They also report sessions in which subjects participate in 2 repeated Prisoners' Dilemma games of 10 periods each. For the second repeated game, they observe cooperation rates less than 75% even in the early periods of the repeated game, which violates the Kreps *et al*. (1982) bound for plausible amounts of incomplete information. A comparison of the "one-shot" and repeated pairing treatments does suggest that repeated interaction promotes cooperation, but, like the results reported by Roth and Murnighan, the observed cooperation rates are well below the theoretical prediction suggesting a lot of confusion and the need for more experience.

The once-repeated Prisoners' Dilemma is special in that it can be solved by a single deletion of strictly dominated strategies. Duopoly experiments provide an interesting contrast in that the stage game is usually solvable by

[6] Rapoport *et al*. (1976, p. 234) do report that "the 'average pair' playing a long sequence of Prisoner's Dilemma eventually learns to cooperate," which is what the theory of repeated games predicts when combined with the selection principles of efficiency and symmetry. Of course, the view that there is more cooperation than game theory predicts persists to the current day; see, for example, Dawes and Thaler (1988).

iterated dominance. Unlike the deletion of strictly dominated strategies, iterated dominance requires a player to actually think about the behavior of his opponent. Hence, one would expect games solvable by iterated dominance to be more confusing to inexperienced subjects.

Fouraker and Siegel (1963) report sessions with both a price setting and quantity setting duopolists under "complete information." The price setting duopoly session allowed subjects to choose from 10 actions and the resulting matrix game is solvable by iterated dominance in 7 iterations. The quantity setting duopoly session allowed 24 actions and could be solved in 2 iterations. One problem with fitting these sessions into a repeated versus random matching classification is that, while the experimental design called for a finite number of periods (14 and 24 periods, respectively), subjects did not know this. The symmetric efficient outcome was achieved by 11% of the pairs in the terminal period of the repeated price setting duopoly session and by 12% of the pairs in the terminal period of the repeated quantity setting duopoly sessions. In comparison to the finitely repeated Prisoners' Dilemma, these are low rates of tacit cooperation.

Holt (1985) reports a quantity setting duopoly experiment with 18 actions resulting in a payoff matrix solvable by iterated dominance in 4 iterations. Holt carefully distinguishes between random and repeated matching protocols. The repeated pairings lasted for at least 7 periods. After 7 periods, the pairing continued into the next period with probability 5/6th. The random pairings consisted of 12 subjects randomly repaired in each of 10 periods. In the terminal period of the repeated pairing session, 25% of the pairs achieved the symmetric efficient outcome (collusion). In the terminal period of the random pairing sessions, none of the pairs achieved the symmetric efficient outcome. While the repeated pairing treatment significantly increased observed cooperation, the reported level of cooperation is still well below the level predicted by the theory of repeated games when combined with the selection principles of efficiency and symmetry.

Since repeated game strategies are not observed, it is hard to know if the experimental literature is reporting equilibrium or disequilibrium behavior. An alternative approach is to have subjects actually write programs, which are then run against each other and scored; see Axelrod (1984) and Selten *et al*. (1997). These tournaments tend to select strategies that have robust disequilibrium properties. For example, Axelrod (1984) concludes that the tit-for-tat automaton does well in his repeated Prisoners' Dilemma tournaments, because it is nice, provocable, forgiving, and clear.

The tit-for-tat automaton is nice in that it will coordinate on the efficient symmetric play path if matched with another nice automaton. It is provocable and, hence, willing to "punish" deviations from the efficient symmetric play path, which can make cooperate until the terminal period a best response to tit-for-tat if the incentive to defect from the cooperative assignment is not too large. It is forgiving and clear, which allows it to teach cooperation. Note that all these characteristics, except provocability, concern the strategy coordination problem rather than the enforcement problem.[7]

III. ANALYTICAL FRAMEWORK

Let $\Gamma(\delta, T)$ denote the stage game Γ played repeatedly with an initial phase that continues with probability δ and a terminal phase of T periods. When δ equals 0, there is no initial phase. $\Gamma(\delta, T)$ describes a repeated game in which a given cohort of players can be observed not only in an infinite game, but also in a finitely repeated continuation game. An experiment based on $\Gamma(\delta, T)$ allows own subject control in respect to an essential treatment variable: the length of prospective interaction.

The second treatment variable is whether the stage game Γ is solvable by the deletion of strictly dominated actions or by iterated (strict) dominance. Consider the stage game I, which is inspired by the price setting duopoly games studied in Fouraker and Siegel (1963); see Fig. 1. Game I is symmetric and dominance solvable. It consists of five actions and is solvable by iterated dominance in four iterations.[8] The dominance solvable equilibrium (DSE) is (a_5, a_5).

A player's best response in Game I is always one larger than his opponent's action if possible. Game S is constructed from Game I by making action a_5 the best response to any action by a player's opponent. Game S is solvable by strict dominance. Like Game I, the DSE for Game S is (a_5, a_5), which results in a payoff of 3 for each player.

The payoffs have been chosen so that the set of feasible payoffs and the DSE payoff are the same for both Game I and S. The convex hull of the set of feasible payoffs is graphed in Fig. 2. Like the Prisoners' Dilemma,

[7] Axelrod (1984) also has some wonderful anecdotal evidence on the influence of prospective interaction on cooperation, including the observation that "a visiting professor is likely to receive poor treatment by other faculty members compared to the way these same people treat their regular colleagues" (p. 60) and Caesar's explanation of why Pompey's allies stopped cooperating with him: "They regarded his [Pompey's] prospects as hopeless and acted according to the common rule by which a man's friends become his enemies in adversity" (p. 59).

[8] The mixed strategy $\{0, 0.7, 0.1, 0.1, 0.1\}$ strictly dominates a_1; $\{0, 0, 0.7, 0.15, 0.15\}$ strictly dominates a_2 once a_1 has been deleted; $\{0, 0, 0, 0.7, 0.3\}$ strictly dominates a_3 once a_1, a_2 have been deleted; a_5 strictly dominates a_4 once a_1, a_2, a_3 have been deleted.

	a_1	a_2	a_3	a_4	a_5
a_1	7,7	0,11	0,0	0,0	0,0
a_2	11,0	6,6	0,10	0,0	0,0
a_3	0,0	10,0	5,5	0,9	0,0
a_4	0,0	0,0	9,0	4,4	0,8
a_5	0,0	0,0	0,0	8,0	3,3

Game *I*

	a_1	a_2	a_3	a_4	a_5
a_1	7,7	0,0	0,0	0,0	0,11
a_2	0,0	6,6	0,0	0,0	0,10
a_3	0,0	0,0	5,5	0,0	0,9
a_4	0,0	0,0	0,0	4,4	0,8
a_5	11,0	10,0	9,0	8,0	3,3

Game *S*

FIG. 1. Payoff tables.

price or quantity setting duopolies, and the voluntary contribution mechanism for the provision of public goods, the DSE payoff is not contained in the set of efficient outcomes in Games I and S.

Both games have the same DSE (a_5, a_5) and the same set of feasible payoffs. However, the security level of the two games differs. The secure action in Game S is a_5, which guarantees a payoff of 3, but security fails to select a unique action in Game I as all actions guarantee a payoff of 0. For Game S, the maximin strategy is the secure action a_5. For game I, the maximin strategy is mixed and assigns probabilities $\{0, 9/55, 9/110, 17/110, 3/5\}$ to actions $\{a_1, a_2, a_3, a_4, a_5\}$, respectively. The maximin strategy ensures an expected payoff of 1.8.

A. *Finitely Repeated Play*: $\Gamma(0, T)$

There are some subtle differences in the set of equilibrium payoffs when the game is repeated arising from the different security levels of I and S. The usual backwards unraveling argument leads to the conclusion that the only Nash equilibrium in $S(0, T)$ is repeated play of (a_5, a_5). This is

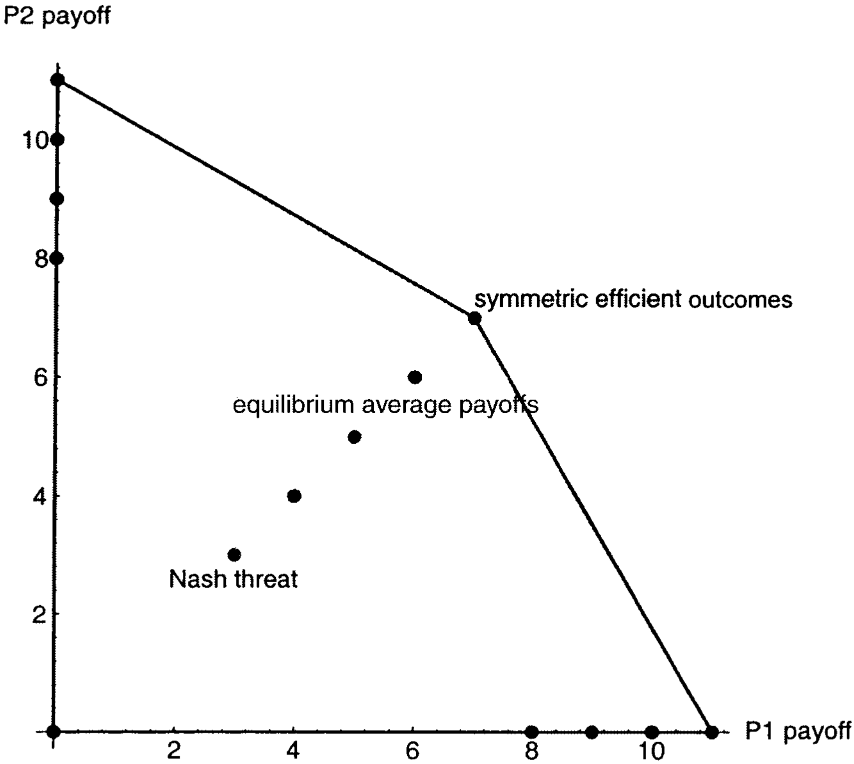

FIG. 2. Convex hull of feasible payoffs in games I and S.

because in the terminal period, which is now a once-repeated game, the only mutually consistent strategy combination is (a_5, a_5). Hence, in the penultimate period a player cannot threaten to drive his opponent's payoff below the (a_5, a_5) payoff of 3 in the terminal period in order to establish cooperation now and so forth.

This is not so in $I(0, T)$. The security level is 1.8, which is below 3. The minimax strategy for I is $\{3/25, 2/25, 1/5, 0, 3/5\}$. The threat to minimax a player if they do not conform can enforce symmetric efficient play up to the last 4 periods.[9] Hence, for T greater than 4 the set of Nash equilibria for $I(0, T)$ and for $S(0, T)$ differs. Of course, if one restricts attention to subgame perfect equilibria and complete information, then the equilibrium

[9] The benefit to defecting is 4 and the maximal punishment is 1.2, which is the difference between the payoff from (a_5, a_5) and the security level. Hence, one should not defect if $1.2t > 4$, where t is the number of punishment periods.

sets for both games are identical, because minimaxing a player who defects from the conjectured equilibrium assignment is not self-enforcing in the subgame.

B. Randomly Repeated Play: $\Gamma(\delta, 0)$

Consider an infinitely repeated game with discounting constructed from I or S by letting the probability that the game is repeated be $\delta \in (0, 1)$. The Nash threats folk theorem implies that for sufficiently large δ, any payoff combination greater than or equal to the stage game equilibrium payoff combination is in the set of subgame perfect average payoffs.

For example, let the strategy assignment for each player be play a_1 in period 0; and in every period so long as one's opponent has played a_1; if one's opponent plays something else, then play a_5 forever after. For a strategy combination consisting of this "unforgiving" strategy to be an equilibrium assignment the payoff to conforming, $\pi_{conform}$, must be greater than the payoff to defecting, π_{defect},

$$\pi_{conform} = 7 + \frac{\delta}{1-\delta}7$$
$$\pi_{defect} = 11 + \frac{\delta}{1-\delta}3.$$

Notice that these equations hold for both I and S. The only difference is that I *defect* implicitly means play a_2, while S *defect* means play a_5. For $\delta = 5/6$, $\pi_{conform} = 42$ which is greater than $\pi_{defect} = 26$. Hence, play of a_1 in the infinitely repeated game is consistent with a subgame perfect equilibrium of $\Gamma(5/6, 0)$. A similar argument rationalizes play of a_2, a_3, and a_4. Of course, repeated play of the stage game equilibrium (a_5, a_5) is also a subgame perfect equilibrium of the repeated game.

For Games I and S, the Nash threats folk theorem implies that for δ sufficiently close to 1 the set of equilibrium average payoffs is everything in the convex hull of feasible payoffs with a payoff greater than or equal to 3; see the shaded region of Fig. 2. Hence, appealing to individual rationality and mutual consistency leaves a theorist or a player with a difficult equilibrium selection problem. One must invoke additional assumptions, such as efficiency and symmetry, to obtain a unique solution to the game or to even have an inkling of what to do.[10]

[10] Allowing for "minimax threats" rather than "Nash threats" would not change the analysis of game S but would result in a larger set of equilibrium average payoffs for game I than the shaded region of Fig. 1. The polygon's southwest corner would extend to (1.8, 1.8).

Efficiency requires an outcome on the northeast frontier of the convex hull of feasible payoffs in Fig. 2. Symmetry selects the points along the diagonal from the origin to $(7, 7)$. Combining efficiency and symmetry selects the average payoff $(7, 7)$ from the set of feasible outcomes. Of course, there exist many strategy combinations that result in this outcome.

C. Randomly Repeated Play and T-Death: $\Gamma(\delta, T)$

Finally, consider an infinitely repeated game constructed from I or S by letting the probability that the repeated game enters a T-period finite continuation game be $(1 - \delta) \in (0, 1)$. Even if players find efficiency and symmetry salient selection principles—and, hence, coordinate on repeated play of (a_1, a_1) each period of the random-endpoint phase—a strategic analysis predicts that once the finite-endpoint phase has been entered play will collapse to repeated play of (a_5, a_5) if T is not too large. We call this the symmetric payoff-dominant play path.

Let t be a random variable with probability distribution $\delta^{t-1}(1 - \delta)$ and let T denote the number of periods in the finite-endpoint phase. For both $I(\delta, T)$ and $S(\delta, T)$, the symmetric payoff-dominant play path is a_1 through period t and then a_5 through period $t + T$. Figure 3 graphs the

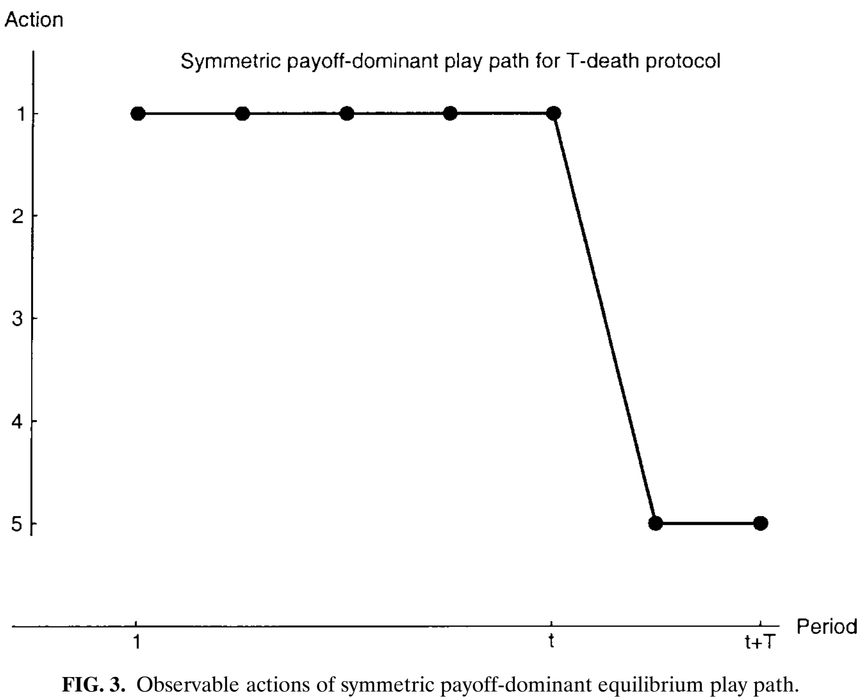

FIG. 3. Observable actions of symmetric payoff-dominant equilibrium play path.

observable actions produced by the symmetric payoff-dominant equilibrium play path.

D. *Adaptive Learning*

Both formal analysis and extant experiments suggest that subjects will need to acquire experience before behavior will be mutually consistent in repeated dominance solvable games. Milgrom and Roberts (1991) provide a general theory of adaptive learning, which includes Cournot dynamics, fictitious play, stochastic learning processes based on learning to optimize, like genetic algorithms, and stochastic learning processes based on experimentation, like reinforcement learning. A sequence of strategies is "consistent with adaptive learning if player n eventually chooses only strategies that are nearly best responses to some probability distribution over his competitors' joint strategies, where near zero probability is assigned to strategies that have not been played for a sufficiently long time" (p. 85). Milgrom and Roberts prove that if behavior is consistent with adaptive learning then it will converge to the set of iteratively undominated strategies.

Since both I and S are dominance solvable, all behavior consistent with adaptive learning will converge to the DSE, that is, eventually the players will play $\{a_5, a_5\}$ almost always. Adaptive learning models applied to the stage game predict that cooperation will decay over time.

IV. EXPERIMENTAL DESIGN

The treatment variables in our experiment were the length of prospective interaction and the payoff table: either I or S. The entries in the payoff tables I and S denoted dimes. Four sessions were conducted for each cell of the 2×2 design matrix making a total of 16 sessions; see Fig. 4.

Ten subjects participated in each session. Subjects were randomly and repeatedly paired to play $\Gamma(\delta, T)$: either $\Gamma(5/6, 2)$ or $\Gamma(0, 1)$. Hence, the subjects were in an evolutionary repeated game with one population of size ten.

	I	S
$\Gamma(5/6,2)$	3,4,5,8	1,2,6,7
$\Gamma(0,1)$	9,12,13,15	10,11,14,16

FIG. 4. Design matrix.

For $\Gamma(5/6, 2)$, we explained the probabilistic mechanism to the subjects using the heuristic of a bowl with five white chips and one red chip. The finite-endpoint phase began when a red chip was reported. While we actually drew chips in a previous experiment, these sessions used a script file based on one of those sequences.[11] The subjects were randomly paired 8 times in the $\Gamma(5/6, 2)$ sessions and 55 times in the $\Gamma(0, 1)$ sessions to give them a chance to learn to cooperate.

The period game was described to the subjects using a computer assisted graphical user interface available in the TAMU economic research laboratory. The instructions were read aloud to ensure that the description of the game was common information. The instructions text file used by the graphical user interface is available on the web at http://erl.tamu.edu. After reading the instructions, but before the session began, the subjects filled out a questionnaire to determine that they understood how to compute payoffs for themselves and their opponents. If any subject made a mistake on the questionnaire, the relevant section of the instructions was read again.

No pre-play negotiation was allowed. After each repetition of the period game, the subjects calculated their earnings for that period. Subjects only observed the actions taken in their own sequence of period games.

The subjects were undergraduate students in economics and business classes at Texas A & M University in the 1992 and 1993 fall semesters. A total of 160 subjects participated in the 16 sessions reported below. The sessions took about one and one-half hours to conduct. Consequently, subjects could earn significantly more than the minimum wage. For example, if subjects always play the symmetric efficient outcome, then each subject would earn \$38.50.

V. EXPERIMENTAL RESULTS

The results are reported in three subsections. First, we report the $\Gamma(0, 1)$ treatments. Second, we report the $\Gamma(5/6, 2)$ treatments. Finally, we report average payoffs and compare the outcomes to predictions based on efficiency and symmetry.

[11] The sequence for t was $\{3, 7, 14, 1, 3, 5, 3, 3\}$. The Kolmogorov T-statistic for the geometric distribution is 0.205. $\text{Prob}(T < 0.358) > 0.8$ for a sample size of 8; see Conover (1980, p. 462). Hence, one fails to reject the hypothesis that the sequence was drawn from the geometric distribution using the Kolmogorov statistic and conventional significance levels.

A. Sessions with Contest $\Gamma(0, 1)$

Figure 5 reports the median action for sessions with contest $I(0, 1)$ and $S(0, 1)$. The difference between the two series is striking. The median subject in treatment $S(0, 1)$ always chooses the strictly dominant action a_5. The median subject in treatment $I(0, 1)$ initially chooses a_3, which corresponds to only two rounds of iterated dominance.

This behavior is unstable. It slowly decays much like adaptive learning theories predict. After period 39, the median subject chooses the iteratively dominant action a_5 in $I(0, 1)$.

Figures 6a and 6b report the frequency distribution of actions by period observed in treatments $I(0, 1)$ and $S(0, 1)$, respectively. As the figures show, the median is representative. However, there is a second striking difference between the two treatments. The frequency distribution for treatment $I(0, 1)$ is single peaked at a_3; while the frequency distribution for treatment $S(0, 1)$ is double peaked with peaks at a_1 and a_5.

The $S(0, 1)$ sessions reveal some innately cooperative behavior in the sense that subjects are not making uniformly distributed errors. Initially, some subjects are focused on the cooperative action a_1. This behavior is extinguished by experience with the $S(0, 1)$ contest.

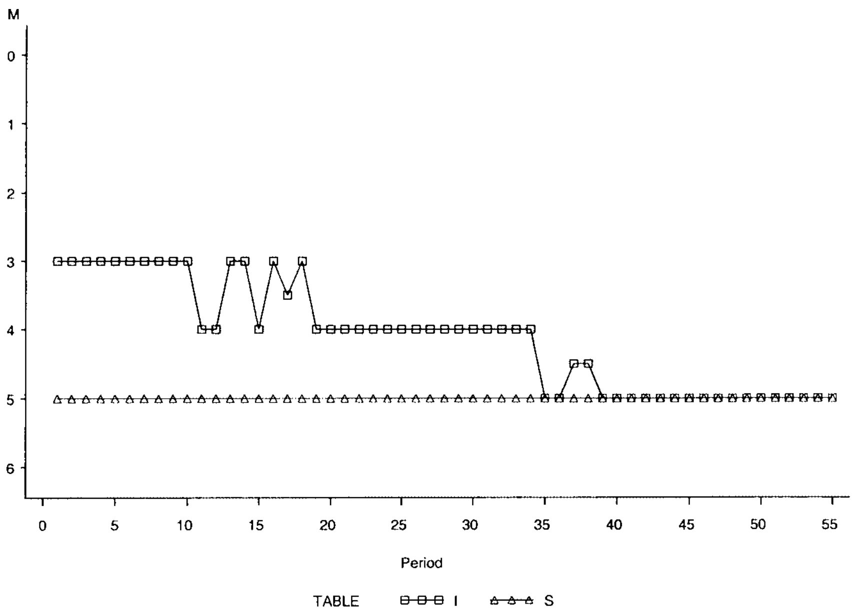

FIG. 5. Median actions for $I(0, 1)$, □, and $S(0, 1)$, △, sessions.

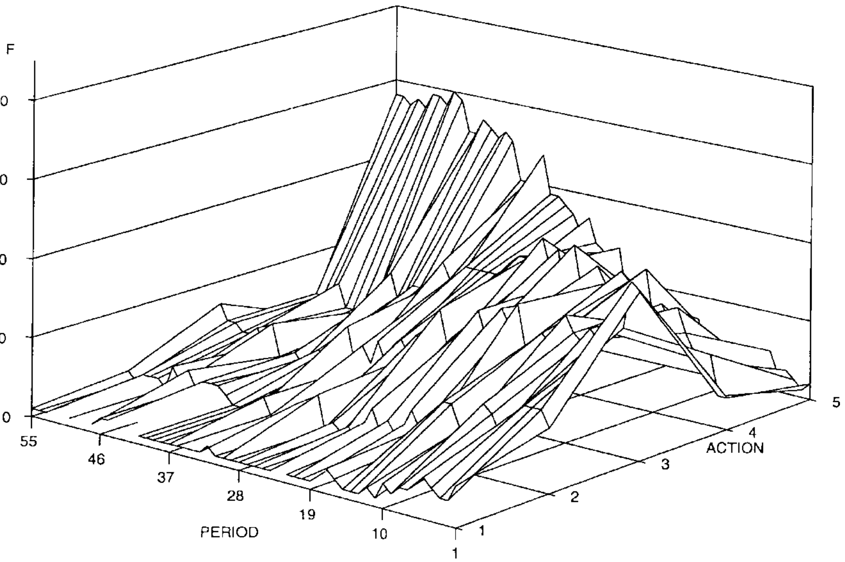

FIG. 6a. Frequency distribution of actions observed in $I(0, 1)$ by period.

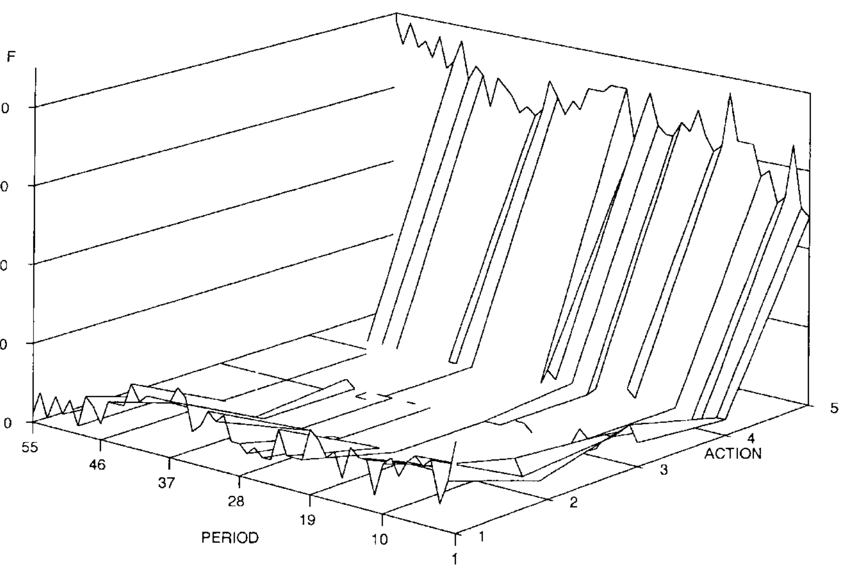

FIG. 6b. Frequency distribution of actions observed in $S(0, 1)$ by period.

Reporting cooperation rates is a conventional way to report the results of repeated cooperation games. By the end of the $\Gamma(0,1)$ treatments the cooperation rates are not high. Only one subject chooses the "cooperative" action, a_1, in period 55 of either $\Gamma(0,1)$ treatment. Conversely, 70% of the subjects choose the "noncooperative" action a_5 in treatment $I(0,1)$ and more than 97% of the subjects choose a_5 in treatment $S(0,1)$.

In the initial periods, Smirnov tests reject the null hypothesis that the sample distribution for $I(0,1)$ and $S(0,1)$ was drawn from the same population distribution at conventional levels of significance. This confirms what is already apparent in Figs. 5 and 6: behavior is influenced by the difference between iterative dominance and strict dominance.

Even though it appears that the two distributions have converged to a_5 by the terminal period, this observation is only weakly consistent with the Smirnov test. In the terminal period, the Smirnov statistic is 0.275, which exceeds the critical value of 0.25 at the 10% level of statistical significance (Conover, 1980, Table A20). So even after 54 periods the difference between iterative and strict dominance has not disappeared entirely.

It is also interesting to compare the sample distributions to the DSE prediction. The Kolmogorov test fails to reject the hypothesis that behavior in treatment $S(0,1)$ has converged to the DSE prediction, but it does reject the hypothesis for treatment $I(0,1)$ at the 1% level (Conover, 1980, Table A14). Nevertheless, behavior appears to be converging to the DSE much as one would expect if human behavior were consistent with adaptive learning. It takes longer for behavior to converge to the DSE when the solution requires iterative dominance rather than strict dominance.

B. Sessions with Contest $\Gamma(5/6,2)$

Figure 7 reports the median action for treatment $I(5/6,2)$ and $S(5/6,2)$. The dashed vertical lines mark the start of a terminal phase and the solid vertical lines mark the start of a new contest. In the first two contests, the length of prospective interaction seems to play no role. This is true both when comparing the initial and terminal phases of the $\Gamma(5/6,2)$ contests or when comparing the $\Gamma(5/6,2)$ contests with the $\Gamma(0,1)$ contests. Hence, if one only studied the first (or second) contest, as is typical, one would conclude that prospective interaction, whether randomly or finitely repeated, didn't influence behavior.

However, the third contest lasts 16 periods and it permanently alters behavior in treatment $S(5/6,2)$. Median behavior in 3 out of the last 5 contests *exactly* matches the predicted symmetric payoff-dominant play path. The two exceptions, the sixth and eighth contest, only differ from predicted play in that there is more cooperation in the first period of the terminal phase than predicted.

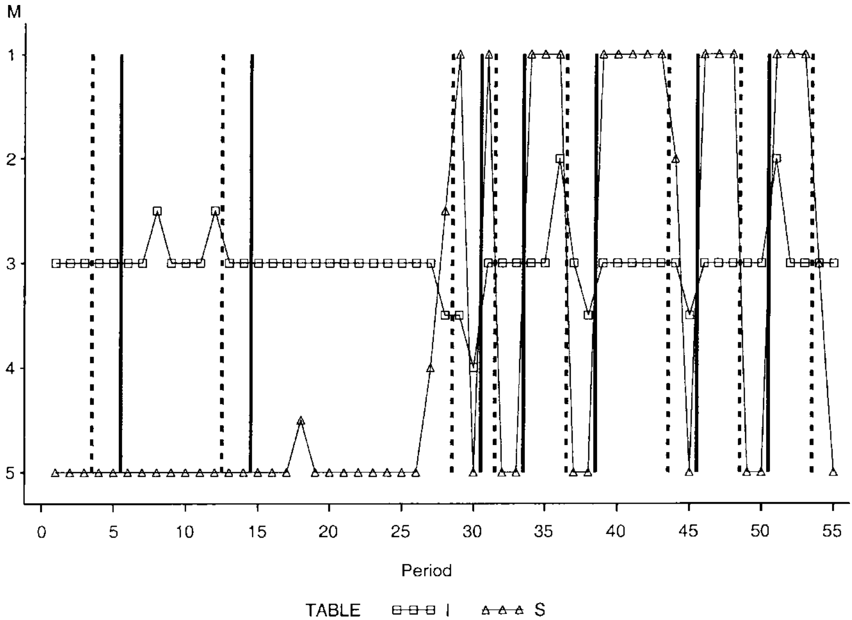

FIG. 7. Median action in $I(5/6, 2)$, □, and $S(5/6, 2)$, △. Dotted vertical line denotes transition to terminal phase and solid vertical line denotes rematching.

Neither the DSE of the stage game nor the symmetric payoff-dominant play path emerge as a convention in treatment $I(5/6, 2)$. Instead, the median action remains fixed at a_3 and appears invariant to the length of prospective interaction. Cooperation does not decay as it did in treatment $I(0, 1)$.

Table I reports frequency counts and empirical distribution functions for the first and last contests of the $I(5/6, 2)$ and $S(5/6, 2)$ treatments. If we look at the last period of the last contest, the cooperation rates, the frequency of a_1, are only 5% for $I(5/6, 2)$ and 7.5% for $S(5/6, 2)$. However, if we look at the last period of the initial phase of the last contest, the cooperation rates are 30% for $I(5/6, 2)$ and 65% for $S(5/6, 2)$. These rates are not only significantly higher than the cooperation rates of the last period of the terminal phase of the last contest, but also significantly higher than the cooperation rates of the last period of the initial phase of the first contest, which are 10 and 17.5% respectively; see repetition 3 of Table I. However, the high cooperation rates in the initial phase of the last contest are still well below that predicted by selection theories based on symmetry and efficiency.

TABLE I
Frequency Counts and Empirical Distribution Functions for the First and Last Match of the $I(5/6, 2)$ and $S(5/6, 2)$ Treatments

		$I(5/6,2)$				$S(5/6,2)$			
Match period	Act	First match		Last match		First match		Last match	
	a_1	8	20.0	12	30.0	10	25.0	26	65.0
	a_2	8	20.0	9	22.5	2	5.0	0	0.0
1	a_3	16	40.0	9	22.5	3	7.5	0	0.0
	a_4	7	17.5	9	22.5	0	0.0	0	0.0
	a_5	1	2.5	1	2.5	25	62.5	14	35.0
	a_1	4	10.0	11	27.5	10	25.0	23	57.5
	a_2	15	37.5	5	12.5	3	7.5	1	2.5
2	a_3	14	35.0	15	37.5	1	2.5	1	2.5
	a_4	5	12.5	6	15.0	2	5.0	0	0.0
	a_5	2	5.0	3	7.5	24	60.0	15	37.5
	a_1	4	10.0	12	30.0	7	17.5	26	65.0
	a_2	5	12.5	2	5.0	1	2.5	0	0.0
3	a_3	16	40.0	10	25.0	2	5.0	0	0.0
	a_4	9	22.5	8	20.0	2	5.0	0	0.0
	a_5	6	15.0	8	20.0	28	70.0	14	35.0
	a_1	5	12.5	9	22.5	7	17.5	20	50.0
	a_2	14	35.0	8	20.0	0	0.0	0	0.0
4	a_3	12	30.0	6	15.0	0	0.0	0	0.0
	a_4	4	10.0	4	10.0	0	0.0	0	0.0
	a_5	5	12.5	13	32.5	33	82.5	20	50.0
	a_1	0	0.0	2	5.0	4	10.0	3	7.5
	a_2	13	32.5	5	12.5	0	0.0	0	0.0
5	a_3	18	45.0	14	35.0	0	0.0	0	0.0
	a_4	4	10.0	9	22.5	4	10.0	0	0.0
	a_5	5	12.5	10	25.0	32	80.0	37	92.5

Note. Act denotes action.

For treatment $I(5/6, 2)$, Smirnov tests fail to reject the hypothesis that the sample distribution of actions in the first contest and the last contest was drawn from the same population distribution for any match period in the contest.[12] Experience had little influence on behavior in treatment $I(5/6, 2)$. For treatment $S(5/6, 2)$, things are different. Smirnov tests do reject the hypothesis for all but the last repetition at the 5% significance

[12] The probability values are 0.91, 0.57, 0.40, 0.40, 0.16, respectively.

level.[13] Experience had a statistically significant influence on behavior in treatment $S(5/6, 2)$.

Holding experience constant, Smirnov tests reveal that there is also a statistically significant difference between behavior in treatment $I(5/6, 2)$ and $S(5/6, 2)$.[14] The basic difference remains the single peaked distributions of the iterative dominance treatments and the double peaked distributions of the strict dominance treatments. Subjects don't play actions a_2, a_3, or a_4 in $S(5/6, 2)$.

VI. CONCLUSIONS

The experiment varied two treatment variables: whether the constituent game was solvable by strict dominance or iterated dominance and whether prospective interaction was finitely or randomly terminated. Both treatments had an economically significant influence on behavior.

The difference between strict and iterated dominance had a large influence on behavior initially. Our results suggest a low order of reasoning about the reasoning of others; see also Nagel (1995) and Stahl and Wilson (1995). Nevertheless, with experience behavior does appear to be converging to the dominance solvable equilibrium, which is the same for both payoff tables, under a once-repeated random matching protocol, $\Gamma(0, 1)$, as predicted by adaptive learning theories.

While reciprocity among patient players explains why an apparent incentive problem when analyzed in a static game does not prevent tacit cooperation in theory, our results suggest that the resulting strategy coordination problem is difficult and should not be assumed away in practice. Our subjects were not able to coordinate on the symmetric payoff-dominant equilibrium play path initially. In fact, if one only studied the first (or second) match, as is typical, one would conclude that prospective interaction, whether randomly or finitely repeated, didn't influence behavior.

The use of an evolutionary repeated game protocol allows subjects to learn to discriminate between the randomly terminated initial phase and the finite terminal phase of the T-death matching protocol in the $S(5/6, 2)$ treatment, but not in $I(5/6, 2)$. Again, we attribute this to the difference between the depth of reasoning needed to solve the stage games. In

[13] The probability values are 0.00, 0.03, 0.00, 0.03, 0.91, respectively.

[14] The probability values for the null hypothesis of no difference are 0.00, 0.00, 0.00, 0.00, 0.00, respectively, in the first contest and 0.01, 0.05, 0.01, 0.09, 0.00, respectively, in the last contest.

$S(5/6, 2)$, there are only two salient actions and this clarity allows subjects to learn to coordinate on the symmetric payoff-dominant equilibrium play path.

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