Contagion and Interaction Structure: An Experimental Study*

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Abstract

Does the network structure in which economic agents interact affect their ability to coordinate on high payoff investments in environments with multiple equilibria? We conduct experiments with paid human subjects in an effort to resolve this important question. Our experiment tests whether two different exogenously imposed interaction structures, the local interaction structure of Ellison (1993) and the uniform matching structure of Kandoori, Mailath, and Rob (1993) or Young (1993), affects the ability of human subjects to coordinate on a payoff dominant Nash equilibrium in a simple coordination game where the unique payoff dominant equilibrium initially coincides with and later differs from the risk dominant Nash equilibrium. The preliminary experimental findings provide insight on how certain payoff dominated strategies may spread through an economy - our definition of a contagion. These findings are also used to construct the appropriate model of individual learning behavior that gives rise to a contagion within the coordination game environment that we study.

1. Introduction

The frequently cited goals of a financial system are efficiency and stability. Recent experience with the Asian financial crisis has highlighted the issue of contagion. There are numerous models of banking where contagion has played a role (e.g. Allen and Gale (1998), Diamond and Dybvig (1983), Lagunoff and Schreft (1998)). In each of these papers, assumptions about payoffs fall within the class of coordination games and restrictions on patterns of interaction are critical for issues of existence, multiplicity, and stability of equilibria.

In this paper, we try to shed light on how informational restrictions implied by interaction patterns may affect financial market equilibria by studying data from more general experimental coordination games.

*Preliminary and incomplete version. We wish to thank Jack Ochs for helpful comments.

2. Environment

2.1. Payoffs

The basic model is of a repeated game played in periods $t = 1, 2, 3, ..., T$. There is a finite set of players $\mathcal{N} = \{1, 2, ..., N\}$. In each period, all players are endowed with one unit of indivisible capital. Before an agent interacts with some subset of the population (according to a protocol to be described below), he must make an investment decision that involves choosing between one of two possible actions. The action chosen will then be implemented in each of this players' interactions with other players. He may invest in a productive technology that pays out a gross return of $R > 2$ only when another player with whom he interacts has also invested her capital good. In that event, the two partners divide the return equally. If a player's partner does not invest her capital, the player who invests receives a "scrap value" $1 > s > 0$. The scrap value, s, is less than the amount of capital invested as it is assumed that there is a cost to liquidating an investment project once a commitment has been made to that project. Alternatively, the player may choose to eat his own capital in which case her payoff is 1, independent of what her partner does thus assuring himself an autarkic outcome. Hence, before being matched in period, player i chooses one of two possible actions $a_i \in A = \{Invest,\ Do\ Not\ Invest\}$. We summarize the payoffs associated with interaction between agents i and j by the 2×2 coordination game:[1]

(i, j)	*Invest*	*Do Not Invest*
Invest	$\frac{R}{2}, \frac{R}{2}$	$s, 1$
Do Not Invest	$1, s$	$1, 1$

(2.1)

Note that if $1 - s < \frac{R}{2} - 1$, then $(Invest, Invest)$ is both the payoff– and the risk–dominant equilibrium. However, if $1 - s > \frac{R}{2} - 1$, then $(Invest,\ Invest)$ remains the payoff–dominant equilibrium, but $(Do\ Not\ Invest,\ Do\ Not\ Invest)$ becomes the risk–dominant equilibrium.

2.2. Matching technology

Restrictions on interactions are embodied by the choice of $\pi_{ij}(g)$, which assigns a weight of agent i meeting agent j in network g. Borrowing terminology from Morris (1997), we assume that the interactions are *bounded* (i.e. that the weights add up to one and are not degenerate). To define interaction structures or networks we borrow terminology from Jackson and Wolinsky (1996). The complete graph, denoted g^N, is the set of all subsets of $\mathcal{N}$ of size 2. The set of all possible graphs on $\mathcal{N}$ is $\{g | g \subset g^N\}$. Let ij denote the subset of $\mathcal{N}$ containing i and j. We shall refer to this subset as the *link* ij. Let $g + ij = g \cup \{ij\}$ denote the graph obtained by adding link ij to the existing graph g and $g - ij = g \backslash \{ij\}$ denote the graph obtained by deleting link ij from the existing graph g. Let $N(g) = \{i | \exists j \text{ s.t. } ij \in g\}$ be the set of players involved in at least one link and $N_i(g) = \{j | \forall j \neq i$ s.t. $ij \in g\}$ be the set of players with whom agent i is directly linked. Let $n(g)$ and $n_i(g)$ be the cardinality of $N(g)$ and $N_i(g)$. Finally, let there be the possibility of costs associated with forming links. These may be interpreted as the costs of searching for production partners. More specifically, let $c_{ij}(g) \geq 0$ denote the cost to agent i of adding link ij to graph g.

[1] This coordination game has payoffs similar to that in Diamond and Dybvig (1983).

The literature that we study is related to the class of bounded interaction games. Examples include the uniform matching rule (UM) of Kandori, Mailath, and Rob (1993) or Young (1993) and the local interaction rule (LI) of Ellison (1993). In this case, $N-1 \geq n_i(g) \geq 2$. Another strand of literature, which Morris terms *deterministic* local interaction, assumes that matches can include degenerate links (e.g. monogamous marriages (one link) or polygamous marriages (a star)). Recent examples of this literature, which also examines endogenous interaction, include Jackson and Wolinksy (1996), Mailath, Samuelson, and Shaked (1997), and Jackson and Watts (1999). We hope to extend our experimental analysis to these networks in the future.

To illustrate the types of interaction structures we study, let $N = 4$.We emphasize here that $N = 4$ was chosen for illustrative purposes only because it admits both UM and LI as special cases. Our experiments consider values of $N = 10$. The feasible graphs are shown in Figure 1. In each

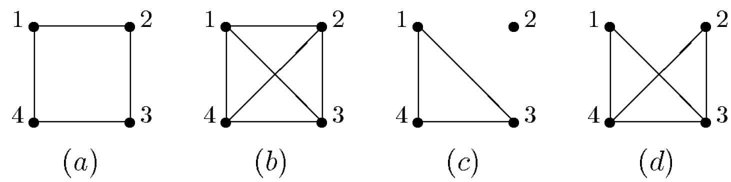

Figure 2.1: Illustration of all possible graphs when $N = 4$

graph, the interaction weights are given by

$$\pi_{ij}(g) = \begin{cases} \frac{1}{n_i(g)} & \text{if } j \in N_i(g), \\ 0 & \text{otherwise.} \end{cases}$$

The first graph (1.a), which we denote by g_{LI}, is the 4–agent version of a local interaction model.[2] In this case, each agent has $n_i(g_{LI}) = 2$ direct links (and 2 indirect links) to every agent in the economy. The second graph (1.b), which we denote g_{UM}, is a 4 agent version of the uniform matching model. In this case, each agent has $n_i(g_{UM}) = 3$ direct links to all other agents in the economy.

The remaining graphs in Figure 1 are variants of the more familiar LI and UM environments. The third graph (1.c), which we denote g_O, is a version of local interaction where agent 2 is ostracized (O) but the remaining agents each have only 2 direct links. The fourth graph (1.d), which we denote g_M, is a mixture of the LI and UM networks. That is, two agents are playing LI and two agents are playing UM.

2.3. Information

Since each agent interacts with every other agent in his neighborhood, $N_i(g)$, we assume that in any round $t > 1$, agents know the strategies that have been played by their neighbors in all previous rounds, through $t-1$. This information is summarized by the frequency with which a player's neighbors have chosen to invest. Consistent with the decentralized nature of agent interaction, we

[2] In Figure 1, there are many other graphs that are isomorphic to the ones we present. For instance, in (1.a) we choose only to illustrate the "square" rather than the "bowtie" or "hourglass" version of $g_{LI(4)}$.

assume that players do not know the strategies that have been played by players with whom they are not directly matched.

3. Some Equilibrium Predictions

It is best to start with a simple heuristic to gain some intuition for our results. Let us assume that $1 - s > \frac{R}{2} - 1$ which corresponds to the case where the payoff dominant equilibrium is $\{Invest, Invest\}$,while the risk dominant equilibrium is $(Do\ Not\ Invest, Do\ Not\ Invest)$.There is also a mixed strategy equilibrium for the coordination game in (2.1) which puts probability $q^* = \frac{1-s}{\frac{R}{2}-s} < 1$ on action *Invest*.

Consider the possibility of "contagion" defined as a shift from coordination on one pure strategy equilibrium to another. [3] Suppose that there is a "noise trader," denoted by agent $\eta \in \mathcal{N}$, who plays *Do Not Invest* with probability $1 \geq \mu \geq 0$. Suppose further that there is a history where all other agents $(\mathcal{N}\backslash\eta)$ play *Invest* in each period. Then the strategy of continuing to invest in the presence of a noise trader remains a deterministic best response to historical frequencies for player i where $\eta \in N_i(g)$, provided that

$$1 - \frac{\mu}{n_i(g)} \geq q^* \tag{3.1}$$

Notice that the left hand side of (3.1) is increasing in $n_i(g)$ and the right hand side is independent of $n_i(g)$. Thus, with a large enough number of links, the single noise trader cannot deter the other agents from continuing to invest in every round and remaining at the payoff dominant equilibrium. Furthermore, it is easy to see that the left hand side of (3.1) is continuous and strictly decreasing in μ and the right hand side is independent of μ. Also, the inequality is strictly satisfied for $\mu = 0$, as well as for g_{UM} at $\mu = 1$ for many admissable values of R, but is violated for g_{LI} at $\mu = 1$.[4] Thus, by continuity, there exists $\mu^* \in (0, 1)$ such that for $\mu > \mu^*$ it is not a best response for player i to choose *Invest* in LI. Therefore, in a UM network the payoff dominant equilibrium remains *stochastically stable* and no contagion occurs for any μ or s under our parametric assumptions. On the other hand, we need either μ low or s high in order for the LI network to remain at the payoff dominant equilibrium (to avoid contagion to the risk dominant equilibrium).This suggests the well known result from Ellison, that UM is more stable than LI. In our first set of experiments we address this prediction about contagion.

The above heuristic result obviously depends on how agents learn. Rather than simply consider naive best response (as in Ellison or Kandoori, Mailath, and Rob) we consider the case of *stochastic fictitious play*. Before doing so, however, we need to introduce some notation. Let $\alpha_i^t \equiv (a_i^t, a_j^t, \forall j \in N_i(g))$ denote agent $i's$ period- t neighborhood action profile. Furthermore, let $h_i^t = (\alpha_i^1, \alpha_i^2, ..., \alpha_i^{t-1})$ denote an information partition of history for agent i and let H_i^t denote the set of all period-t histories in agent $i's$ information partition. A strategy for agent i will be defined over this set. In particular, a pure strategy for player i is a sequence of maps $\{s_i^t\}_{t=1}^T$, where $s_i^t : H_i^t \to A$, with $s_i^t(h_i^t) \in A$, $\forall h_i^t \in H_i^t$. Let S_i^t denote the space of all such s_i^t. It should be understood that s_{-i}^t denotes the strategies played by neighbors $j \in N_i(g)$ other than i at time t. Denote agent $i's$ mixed strategy by $\sigma_i^t \in \Sigma_{-i}^t \equiv \Delta(S_i^t)$, where $\Delta(\cdot)$ is the space of probability distributions. Let $\varsigma_i^t \equiv (\sigma_i^t, \sigma_j^t, \forall j \in N_i(g))$ denote agent $i's$ period- t neighborhood mixed strategy profile.

[3] Morris (1998) provides an extensive analysis with general interaction structions.

[4] One such value is $R = 3$, which we use in the payoff matrix in the experimental section.

Assume that players assign *belief weights* to the strategies in their neighbors' strategy set. Let $\kappa_i^t(s_{-i})$ be the weight assigned by player i to his neighbors $j \in N_i(g)$ playing action $s_{-i} \in S_{-i}$. Given initial weights $\kappa_i^0 : S_{-i} \to R_+$ and the uniformity of the interaction weights, player i's belief weights for period t are updated as follows:

$$\kappa_i^t(s_{-i}) = (1-\delta)\kappa_i^{t-1}(s_{-i}) + \sum_{j \in N_i(g)} \iota_j$$

where the indicator function is defined as:

$$\iota_j = \begin{cases} 1 & \text{if } s_j^{t-1} = s_{-i} \\ 0 & \text{if } s_j^{t-1} \neq s_{-i} \end{cases}$$

Here, $\delta \in [0,1]$ can be thought of as the depreciation of history. In standard fictitious play $\delta = 0$, while for naive best reponse play $\delta = 1$. The probability that player i assigns to his neighbors playing action s_{-i} in period t is:

$$\gamma_i^t(s_{-i}) = \frac{\kappa_i^t(s_{-i})}{\sum_{\tilde{s}_{-i} \in S_{-i}} \kappa_i^t(\tilde{s}_{-i})}.$$

Thus belief probabilities are approximately the observed historical relative frequencies of actions played by opponents. For instance, if there are two other agents in $i = 2's$ neighborhood, say agents 1 and 3 then we have

$$\gamma_2^t(s_1, s_3) = \int_{\Sigma_{-i}} \sigma_1(s_1)\sigma_3(s_3)\mu_2^t[d(\sigma_1, \sigma_3)]$$

where μ_i denotes beliefs over $\Delta(S_{-i})$.

Finally, following Fudenberg and Levine (1995) let player $i's$ payoff be given by

$$\sum_{s_{-i}^t} u_i^t(s_i^t, s_{-i}^t)\gamma_i^t(s_{-i}^t) - \lambda \sum_{s_i^t} \sigma^t(s_i^t) \log \sigma_i^t(s_i^t)$$

The best response function in this case is given by the logistic function

$$BR_i^t(\sigma_{-i}^t)[s_{-i}^t] = \frac{\exp((1/\lambda)u_i^t(s_i^t, \sigma_{-i}^t))}{\sum_{\tilde{s}_i} \exp((1/\lambda)u_i^t(\tilde{s}_i^t, \sigma_{-i}^t)}$$

where the probability that any strategy is not a best response is played goes to zero as $\lambda \to 0$.

In light of the experimental evidence that will be presented in the next section, we conducted a series of monte carlo simulations in order to see how an economy with $N = 10$ agents might play in different interaction structures. We consider two polar cases: a LI structure where an agent plays with his two immediate neighbors and a UM structure where each agent plays with every other agent. We used a payoff matrix that is a scaled up version of (2.1); in particular, we let $R = 3$,$s = \frac{1}{5}$ and then scale the payoff matrix by 50 (see Game 2 below). We consider different levels of the stochastic experimentation parameter $\lambda = 0.1$ and $\lambda = 0.2$, as well as different levels of the depreciation of history $\delta = 1$ (a stochastic version of naive best response) and $\delta = 0$ (the standard case). We endow all agents with priors that their neighbors will play *Invest* with probability one. We consider an "experiment" to be T rounds, which is simulated 1000 times. Our actual experiments (see Section 4.2.1) set $T = 20$. We also report some simulations below with $T = 50$ for comparison.

We report the average (over all agents, rounds, and runs) frequency of cooperation, frequency of coordination, and payoffs in Table 3.1 and Figures 3.1 through 3.4 (the figures simply consider the case where $T = 50$). The frequency of cooperation refers to the frequency with which the $N = 10$ agents chose the Invest action, and the frequency of coordination refers to the frequency with which the 10 agents were coordinated on a pure strategy Nash equilibrium with all of their neighbors.

What is evident from these simulations is the important effects of learning on contagion (captured by the depreciation of memory and the amount of experimentation). In particular, contagion in LI structures is much more likely with full depreciation (i.e. the stochastic equivalent of naive best response ($\delta = 1$)) than when there is no depreciation ($\delta = 0$). There is also some effect on the speed of contagion due to changes in the λ parameter, which represents the extent to which best responses are stochastic. However, this effect is only secondary to the effect of variations in the δ parameter. By continuity, the results in Table 3.1 suggest that learning need not be completely naive for there to be important effects of interaction structure on the spread of payoff dominated strategies.

Table 3.1

parameters	freq. cooperation (LI,UM)	freq. coordination (LI,UM)	av. payoffs (LI,UM)
$\delta = 1, \lambda = 0.1, T = 20$	$0.7892, 0.9911$	$0.6756, 0.9220$	$0.7696, 0.9884$
$\delta = 1, \lambda = 0.1, T = 50$	$0.5468, 0.9864$	$0.5848, 0.9188$	$0.6275, 0.9861$
$\delta = 1, \lambda = 0.2, T = 20$	$0.3358, 0.3978$	$0.5905, 0.4774$	$0.5893, 0.6802$
$\delta = 0, \lambda = 0.1, T = 20$	$0.9919, 0.9924$	$0.9762, 0.9263$	$0.9890, 0.9895$
$\delta = 0, \lambda = 0.1, T = 50$	$0.9911, 0.9925$	$0.9759, 0.9274$	$0.9886, 0.9897$
$\delta = 0, \lambda = 0.2, T = 20$	$0.8029, 0.7979$	$0.5825, 0.1991$	$0.7860, 0.7838$

4. Experimental Evidence

4.1. Overview and relationship to previous research

The first phase of this project involves an experiment in which the interaction structure is exogenously imposed on subjects. In a later, second phase of this project we plan to allow subjects to choose the structure in which they interact with other agents. For now, we limit our discussion to the exogenous interaction experiment.

In this experiment, the treatment variable is the exogenously imposed interaction structure. The population size of individual subjects, N, is held constant across the two treatments. In the first treatment, individuals repeatedly play a coordination game with their two immediate neighbors (left and right), which we referred to earlier as the "local interaction" (LI) treatment, and in the second treatment individuals repeatedly play a coordination game with all $N - 1$ subjects which we refer to as the "uniform matching" (UM) treatment.

We are aware of only one prior experimental test of coordination in an exogenously imposed local interaction setting as reported in Keser et al. (1998). These authors studied a three player, "minimum effort" game – a rather severe coordination game first studied by Van Huyck et al. (1990, 1991) in which payoffs are an increasing function of the minimum effort level simultaneously chosen by each of three players. This game was played repeatedly, either in groups of 3 players by themselves or in a larger group of 8 players where the players were positioned on a circle and each player interacted only with the player to her left and right (e.g. local interaction). Keser et al. (1998) essentially obtained results similar to those found by Van Huyck et al. (1990) in a non–local interaction setting; nearly all of the 3–player groups coordinated on the payoff dominant equilibrium of the game, while all of the 8–player groups positioned on a circle coordinated on the risk dominant equilibrium by the end of 20 rounds of repeated play.

Our experimental design differs from Keser et al. (1998) in a number of important respects as will become clear in the discussion that follows. In particular, we study standard coordination games (e.g. without order statistics, so there are no strategic complementarities to confound our findings. Furthermore, we maintain constant group sizes across experimental treatments, so there is no group size effect to confound our findings. We also make some effort to coordinate subjects' prior beliefs by having them play a sequence of two games as discussed below. Finally, unlike Keser et al. (1998), we are interested in testing the predictions of the various learning models described in section 3 within the context of the coordination games we study. We view this exercise as a first step in the process of building a microfoundation model of contagion.

4.2. Experimental Design

The exogenous interaction experiment involves a 2×2 experimental design where the treatment variables are 1) the two–player game matrix, either Game 1 or Game 2 as illustrated below and 2) the exogenously imposed matching technology, either local, 2–neighbor matching (LI) where each player plays the game against his two neighbors or uniform matching (UM), where each player plays the game against his $N-1$ neighbors, where $N > 3$ is the number of players in each group (graph).[5]

Game1

	A	B
A	75, 75	40, 50
B	50, 40	50, 50

Game 2

	A	B
A	75, 75	10, 50
B	50, 10	50, 50

In both Games 1 and 2, action A corresponds to the *Invest* strategy while action B corresponds to the *Do Not Invest* strategy. In the experiment, of course, we avoid reference to such language as "Invest" or "Do Not Invest." The only difference between the two games lies in the "scrap value" of an investment: in Game 1, the scrap value is 40 "points" whereas in Game 2 it is 10 points. Both games have two pure strategy Nash equilibria with the same payoffs, (A,A) and (B,B), and one mixed strategy equilibrium. In Game 1, the mixed strategy equilibrium involves play of action A with probability .286, and the mixed strategy equilibrium of Game 2 involves play of action A with probability .615. Note further that in Game 1, (A,A) is both payoff and risk dominant while in Game 2, (A,A) is payoff dominant but (B,B) is risk dominant.

We are in the process of conducting a number of experimental sessions with paid human subjects as part of our exogenous interaction experiment. In each of these sessions, a group of $N = 10$ subjects begins by playing several rounds of Game 1 followed by several rounds of Game 2 under a single, exogenously imposed interaction structure, either local or uniform matching. The matching

[5] Notice that the payoff matrices are just scalar (50) multiples of the payoff matrix used in section 2.1 with $R = 3$ and $s = 4/5$ for Game 1 and $s = 1/5$ for Game 2.

protocol used is carefully explained to subjects and will remain constant throughout a session.[6] In each round, subjects first choose an action to play against all of their neighbors, either their 2 neighbors in the local interaction treatment or their 9 ($N-1$) neighbors in the uniform matching treatment, according to the matching protocol that has been chosen for the session. After all players have made their decisions, subjects are informed of 1) their payoffs for the round which will consist of a equal–weighted point total they have earned from playing their chosen strategy against all of their neighbors, and 2) the strategy played by all of their neighbors in the last round, as well as the overall frequency with which their neighbors have played each strategy. This second piece of information serves to reinforce to subjects the exogenously imposed matching technology that determines their payoffs, i.e. either local (2–neighbor) or uniform matching.

In further work, we also plan to introduce a single, robot, (i.e. automated) "noise trader" in place of one of the 10 human subject players, as discused in section 3. The purpose of adding this noise trader is to provide us with greater control over the experimental environment and to test the predictions that arise from the various learning models when the presence of a controlled noise trader player (or confederate) are taken into account. To avoid deceiving subjects, we will inform them of the presence (though not the location within the group) of this robot player, and we will further inform them that this robot player plays action B with probability μ and action A with probability $1-\mu$ throughout the session, i.e. regardless of the game that is being played. The environment without the automated noise trader can be viewed as one in which extraneous or subjective uncertainty among the 10–member human subject population may give rise to a contagion, while the environment in which the noise trader is present can be viewed as one in which intrinsic or objective uncertainty also plays a role in triggering contagion. Thus, we will be able to assess the marginal contributions of both types of uncertainty to the possibility of a contagion. As we have not yet conducted experimental sessions in which a noise trader is present, we limit our discussion here to environments in which the noise trader is absent and all 10 players are inexperienced human subjects.

The exogenous interaction experiment described above currently being conducted in our computer laboratory using networked personal computers. Implementation of the uniform matching algorithm is straightforward. Each subject chooses one strategy to play against all 9 ($N-1$) neighbors. The computer program then determined the payoffs from playing that strategy against the strategy played by all of the other 9 players and calculated an equal–weighted point total for that subject for the round. The local (2–neighbor) matching algorithm was implemented using the unique ID number, $i = 1, 2, ..., 10$, assigned to each player. Players were aligned on a circle, so that player i's two neighbors were those with ID numbers $i-1$ and $i+1$. The player with ID number 1 had the players with ID numbers 10 and 2 as neighbors, and, similarly, the player with ID number 10 had the players with ID numbers 9 and 1 as neighbors. Each player's set of two neighbors remained constant throughout a session. In each round, each player chose a strategy to play against both neighbors. As in the uniform matching treatment, the computer program then determined the payoffs from playing that strategy against both neighbors and calculated an equal–weighted point total for each subject at the end of each round.

The number of points subjects earn in each round represents their probability of winning a \$1 prize, e.g. 50 points corresponds to a 50% chance of winning a dollar.[7] After subjects had

[6] We may consider reversing the order of the games played to determine whether there is any "order effect" on subject behavior.

[7] Weighted point totals were rounded to the nearest integer in determining probabilities.

recorded their point totals in each round we randomly drew an integer from the interval $[1, 100]$. If a subject's point total was greater than or equal to this randomly chosen number they earned \$1 for that round; otherwise they earned 0 for that round.[8]

An example of the instructions used in a "local interaction" experimental session are provided in the Appendix.

C.4.3 Hypotheses

We hypothesize that by the last few rounds of Game 1, most subjects will be choosing to play action A, regardless of the matching protocol (LI or UM) as the (A,A) equilibrium in Game 1 is both payoff and risk dominant.[9] Playing action A in Game 1 is a best response provided that the frequency with which a player's neighbors plays action A is greater than the mixed strategy probability, .286. Thus it is possible to achieve (and sustain) the (A,A) equilibrium even in the local interaction environment provided that one–half of a players' neighbors begin by playing action A. Previous experimental studies of games similar to Game 1 suggest that this prior condition is not unreasonable and is likely to be satisfied in Game 1.[10]

By contrast, in Game 2, we hypothesize that behavior will be different under the two different matching protocols. In Game 2, a player's best response is to play action A so long as the frequency with which his neighbors play action A is greater than .615. In the local interaction treatment, if one of a player's two neighbors begins by playing action B, this inequality cannot be satisfied, so the player's (naive) best response will be to choose action B. Of course if this player plays action B, then eventually his neighbor, player j, may do the same and so on around the circle. We recognize that subjects may be slow to learn to play best responses to the changing frequencies with which their neighbors play action A (B), so that the contagion from the payoff–dominant to the risk dominant equilibrium in Game 2 may take more time than is possible in a laboratory setting. Therefore, as an alternative hypothesis, we predict a much lower frequency of the play of action A in Game 2 relative to Game 1 in our exogenous interaction treatment.

The prediction in Game 1, under both matching protocols, that players coordinate on the (A,A) equilibrium is based on an *equilibrium selection* argument; (A,A) is both payoff– and risk–dominant. If players are indeed coordinated on the (A,A) equilibrium by the last round of Game 1, then the switch from Game 1 to Game 2 midway through a session provides us with a test of the *stability* of the payoff dominant equilibrium under the two different matching protocols.

In the uniform matching treatment, if the aggregate frequency with which all players play action A in by the end of Game 1 turns out to be greater than .615, then we would expect little change in the frequency of play of action A when the game is switched to Game 2, i.e. we expect the payoff dominant equilibrium to remain stochastically stable. By contrast, in the local interaction treatment, we instead predict that play will dramatically change when the game is switched from Game 1 to Game 2; in particular we hypothesize that the frequency with which action B is played in Game 2 of the local interaction treatment is significantly greater than in Game 1. Essentially

[8] This binary lottery procedure for controlling risk aversion (inducing risk neutral behavior) is due to Roth and Malouf (1979).

[9] The presence of a 'robot' player who played action B with probability μ would complicate, but need not alter this prediction.

[10] Our expectations are based on the results of many prior experimental studies of coordination games similar to (though not precisely the same as) our Games 1 and 2. See, e.g. the work of Cooper et al. (1990, 1992) and Van Huyck et al. (1990, 1991). Cooper (1999) and Ochs (1995) provide surveys of experimental coordination game results.

what we are testing for is whether there is any kind of "contagion" effect. Such a test is possible because the (A,A) equilibrium yields the same expected payoffs in both games, as does the (B,B) equilibrium, and we hypothesize that players will be largely coordinated on the (A,A) equilibrium in Game 1, under both the uniform and the 2–neighbor matching protocols.

If we do observe significant differences in behavior between the 2–neighbor and uniform matching treatments, we may seek to find, via further experiments, the threshold at which behavior changes. We can do this by considering local interaction environments where individuals have more than 2, but less than $N-1$ neighbors. For instance, in our computer laboratory, we can easily consider two–dimensional lattice network structures, embedded on a torus, in which each agent has 4 or 8 neighbors.

We also plan to explore whether simple belief–based learning models, e.g. the variations on fictitious play discussed in section 3, can track the behavior of the experimental data both quantitatively and qualitatively. We can initialize beliefs in these learning models using the initial frequencies with which actions are played in the experiment. If these belief–based learning models provide a good fit to the experimental data over the short horizon of the experiment, we will allow the learning model simulations to continue over a much longer time horizon. The purpose of this exercise will be to determine whether the results we observe in the experiment are robust to the longer spans of time that may be required for coordination on an equilibrium.

4.2.1. Preliminary findings

Thus far we have conducted a single experimental session involving the local interaction matching protocol. We are in the process of conducting further sessions of this treatment as well as sessions involving the uniform matching protocol. The preliminary findings from our single experimental session are very encouraging, and we now turn to a brief description of these results.

A group of 10 subjects with no prior experience was recruited to participate in a one–hour session. The instructions (provided in the appendix) were read aloud and subjects' questions about the experimental design were answered. Subjects did not know the identity of their neighbors but were informed that they would interact with the same two neighbors over the course of the session. They were further informed of how subjects in the room were connected to one another (i.e. the assignment of neighbors around the circle).

Subjects began by playing 10 rounds of Game 1 followed by 20 rounds of Game 2. They were informed of the payoff matrix for both games in advance and were told they would play both games but they did not know in advance how many rounds of each game they would play.

Subjects were paid a \$5 show–up fee and had the opportunity to earn \$1 for every round of the game they played (up to a maximum of \$30) as described in the experimental design. Average subject earnings were \$29 for the one–hour session.

Figure 4.1 reveals the aggregate frequency with which all 10 players chose action A (chose to "cooperate") over the 10 rounds of Game 1 and over the subsequent 20 rounds of Game 2. We see that there is a very striking difference in the evolution of the aggregate frequency of cooperation between the two games. In Game 1 we see that, by round 7, all 10 subjects (100%) had coordinated on the payoff dominant equilibrium. By contrast, we see that in Game 2, the frequency of the choice of the cooperative action A started high at 90% and declined over the course of the 20 rounds played of Game 2 in the direction of coordination on the risk dominant equilibrium. While a full contagion to the risk dominant equilibrium did not occur within the time allowed by our experiment, the different trajectories for the frequencies of cooperative play are in line with our hypotheses.

Figure 4.2 sheds further light on our experimental findings by revealing the frequency with which each player (ID numbers 1 through 10) played action A (cooperated) against his two neighbors. We see that the 90% frequency of cooperation observed in the first 6 rounds of Game 1 was not due to the action choices of any single player, but rather was due to action choices (of action B) by three different players with ID numbers 5, 6 and 8. In Game 2, we see that player number 5 never chose to play the cooperative action, instead choosing Action B in all 20 rounds. His two neighbors, players 4 and 6, responded in kind by choosing action B more frequently than they chose action A. However, the neighbors of players 4 and 6 appear to have been little affected by the actions of players 4 and 6; player number 3 chose to play action B only one time (in round 16).

To sum up, while a full contagion did not occur within the 20 rounds allotted for Game 2, the observed behavior appears to lie in between the predictions of the stochastic fictitious play model where $\delta = 0$ and the stochastic naive best response model where $\delta = 1$. Of course, further experiments are necessary to determine the robustness of this finding. However, these preliminary results do suggest that intrinsic uncertainty alone may be sufficient to trigger a contagion.

Appendix: Instructions used in the Experiment

Overview

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 that will be paid to you in cash at the end of the session. If you have a question at any time, please feel free to ask the experimenter. We ask that you not talk with one another during the experiment.

In this experimental session we will play two different games. Each game consists of a number of rounds.

In each round you will choose between one of two possible actions. Your "score" in each round of a game depends on your action choice and the action choice of your two "neighbors." Your two neighbors will not change over the course of a session. You will not be informed of the names of your two neighbors, even after the end of the session.

Your neighbors

In this experiment there are a total of N players. Each player has an ID number, $i = 1,2,...,N-1,N$. If you have player ID number i, your two neighbors will be the players with ID numbers $i-1$ and $i+1$. For example, if your ID number is 4, your two neighbors – your "neighborhood" – consists of the players with ID numbers 3 and 5. If you have ID number 1, your neighbors are the players with ID numbers N and 2. Similarly, if you have ID number N, your neighbors are the players with ID numbers $N-1$ and 1. Your neighbors are not necessarily the players who are located to your left and right in the physical layout of the computer laboratory. Your two neighbors will remain the same throughout today's session. Note that each of your two neighbors also has you as one of their neighbors, but each of your two neighbors also has another neighbor (player) who is not a member of your "neighborhood."

At the top of your record sheet, write down your ID number in the space indicated. Also write down the ID numbers of your two neighbors.

The play of the games

The payoff table for each of the two games you play will be shown on your computer screen and will also be drawn on the chalkboard. We will begin by playing the first game for a number of rounds. We will then play the second game for a number of rounds.

In every round of a game each player has a choice between two possible actions, which are labeled "A" and "B." You simply type in your choice at the prompt, a or b. You must then confirm your choice by typing y for yes at the confirm prompt. If you want to change your choice, type n for no at the confirm prompt. You will then have the opportunity to submit a new choice of action.

Your action choice together with the actions chosen by each of your two neighbors determines the number of points you get for that round. The payoff table on your screen indicates the number of points that are possible from your choice of action in combination with the choices of your two neighbors. In each box of the payoff table, the first number represents the number of points you receive, and the second number represents the number of points your neighbors receive.

How payoff scores are determined

The number of points you receive depends on your action choice and the choices of both your neighbors, and will be referred to as your payoff score. The calculation of these payoff scores will also depend on the game played.

Game 1

The payoff table for Game 1 will appear on you computer screens and looks like this:

		Neighbor's Choice	
		A	B
Your	A	75, 75	40, 50
Choice	B	50, 40	50, 50

Recall that the first number in each of the four boxes of this table represents the number of points you receive and the second number represents the number of points your neighbors receive.

Your payoff score from playing action A or B in Game 1 is determined as the *weighted average* number of points from your choice of action and the choices of your two neighbors. The complete set of possible payoff score outcomes for Game 1 is given in Table 1 below.

Table 1: Determination of Payoff Score in Game 1

Your choice of action	Fraction of Your 2 Neighbors Choosing A	Fraction of Your 2 Neighbors Choosing B	Your Payoff Score
A	0/2	2/2	40
A	1/2	1/2	57.5
A	2/2	0/2	75
B	0/2	2/2	50
B	1/2	1/2	50
B	2/2	0/2	50

The calculation of your payoff score involves the payoff table values and the fractions of your neighbors who choose to play actions A and B. For example, if you choose to play action A and 1 of your 2 neighbors (1/2) plays action A, while the other 1 of your 2 neighbors (1/2) plays action B, your payoff score is determined as the weighted average: $1/2 \times 75 + 1/2 \times 40 = 57.5$ points. As a second example, suppose you choose to play action B and both of your neighbors (2/2) play action A (so that 0/2 play B), your payoff score is determined as the weighted average: $2/2 \times 50 + 0/2 \times 50 = 50$ points.

Are there any questions about how payoff scores are determined?

Game 2

The payoff table for Game 2 will appear on your computer screens and looks like this:

		Neighbor's Choice A	Neighbor's Choice B
Your Choice	A	75, 75	10, 50
	B	50, 10	50, 50

As in Game 1, your payoff score from playing action A or B in Game 2 is determined as the weighted average number of points from your choice of action and the choices of your two neighbors. The complete set of possible payoff outcomes for Game 2 is given in the Table 2 below.

Table 2: Determination of Payoff Score in Game 2

Your choice of action	Fraction of Your 2 Neighbors Choosing A	Fraction of Your 2 Neighbors Choosing B	Your Payoff Score
A	0/2	2/2	10
A	1/2	1/2	42.5
A	2/2	0/2	75
B	0/2	2/2	50
B	1/2	1/2	50
B	2/2	0/2	50

The Outcome of a Round

After all players have made their action choices, the results of the round will be revealed to you on your computer screens. You will see your action choice and payoff score for the last round along with the fraction of your neighbors who chose actions A or B in the last round. Please record your action choice, your payoff score, the fraction of your neighbors playing action A (%A), and the fraction playing B (%B) on your record sheet. Following the first round, the results from your previous rounds of play will be reported at the bottom of your computer screen for ease of reference.

Earnings in Each Round

Your payoff score in a round is a number between 0 and 100. This is your percent chance of earning $1.00 in that round. After everyone has recorded their payoff score for the round, a random number between 1 and 100 will be chosen and announced. Record the random number that is announced on your record sheet under the heading "Lottery Number." If your payoff score is greater than or equal to the announced number (the lottery number), you earn one dollar ($1) for that round. If your score is less than the randomly chosen number, you earn zero for that round. Record your earnings for each round (either \$1 or 0) in the last column of your record sheet under the heading "Earnings." Notice that the more points you earn in a round the greater is your probability of winning the \$1 prize.

Payments

At the end of the session we will ask you to total up your earnings from all rounds played of both games and record the sum at the bottom of your record sheet. All earnings will be paid in cash at the end of the session.

ARE THERE ANY QUESTIONS BEFORE WE BEGIN?

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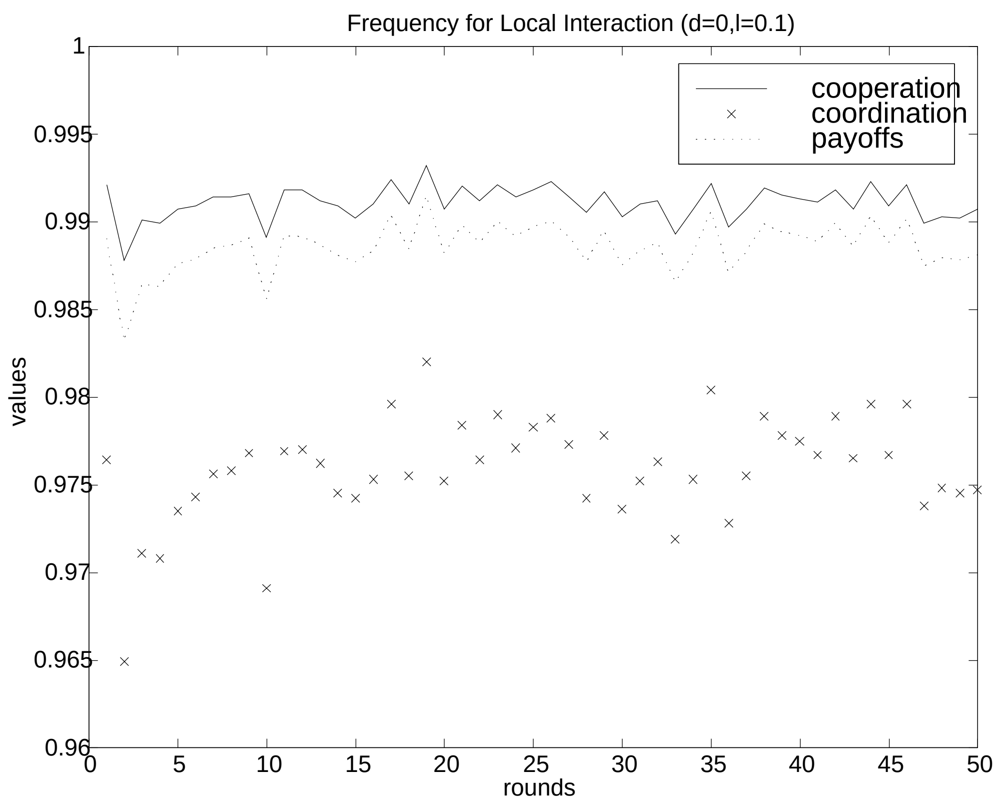
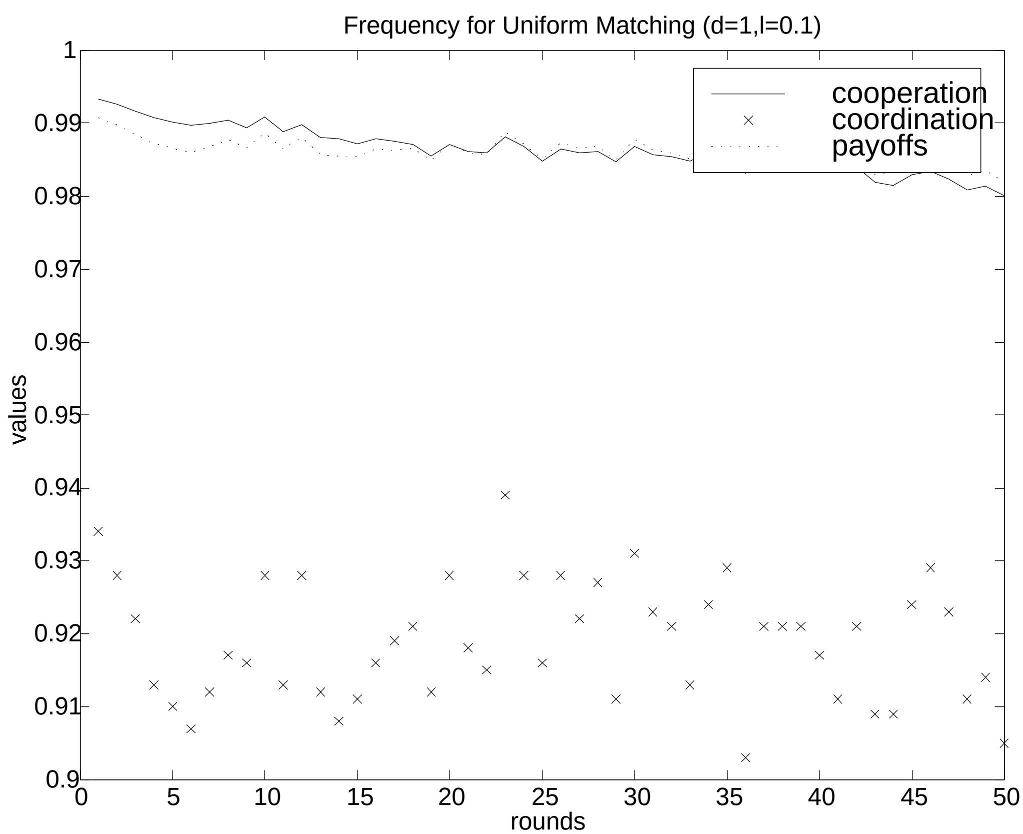

Frequency for Local Interaction (d=0,l=0.1)
cooperation
coordination
payoffs
values
rounds
1
0.995
0.99
0.985
0.98
0.975
0.97
0.965
0.96
0
5
10
15
20
25
30
35
40
45
50

Figure 4.1: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cooperation
coordination
payoffs
values
rounds
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0.98
0.97
0.96
0.95
0.94
0.93
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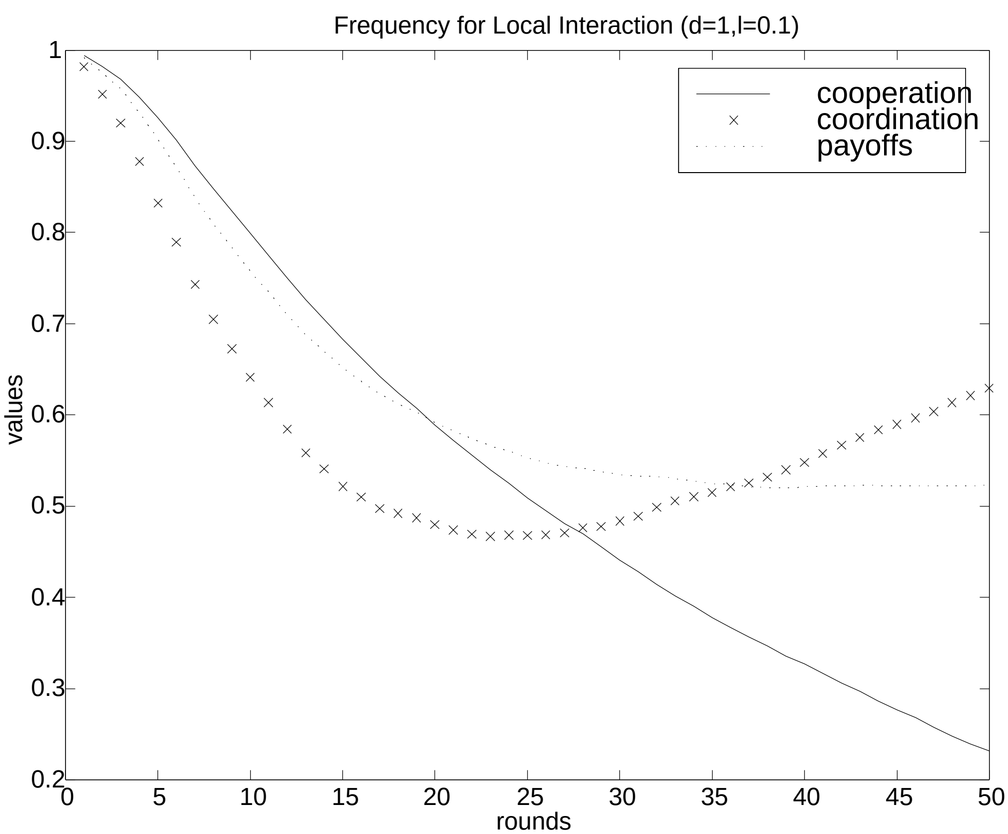
5
10
15
20
25
30
35
40
45
50

Figure 4.2:


Frequency for Local Interaction (d=1,l=0.1)
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coordination
payoffs
values
rounds
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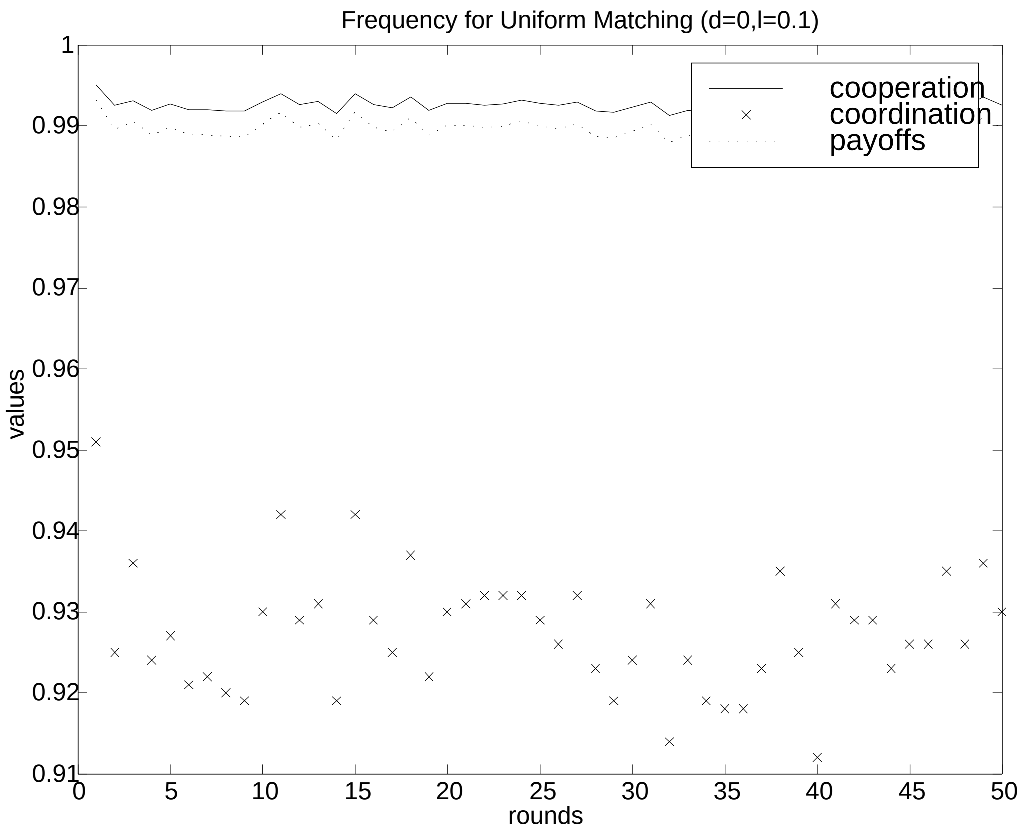
5
10
15
20
25
30
35
40
45
50

Figure 4.3:


Frequency for Uniform Matching (d=0,l=0.1)
cooperation
coordination
payoffs
values
rounds
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0.98
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0.95
0.94
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Figure 4.4:

Figure 4.1: Aggregate Frequency of Cooperation in Games 1 & 2

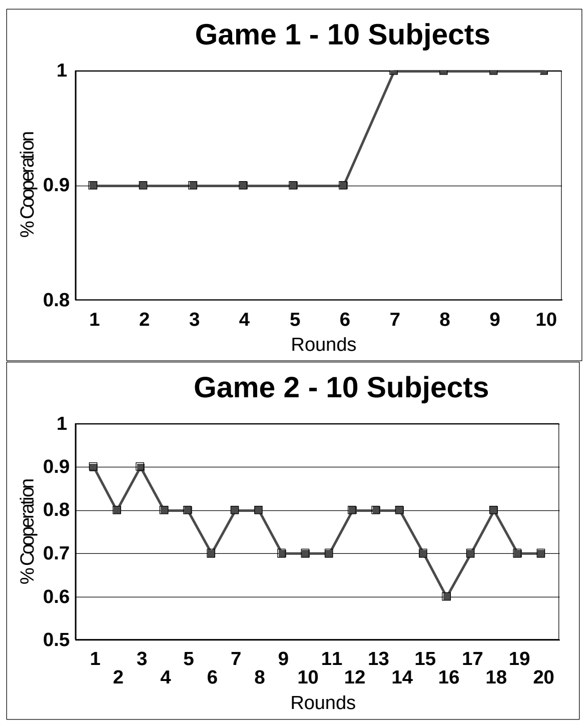

Figure 4.5:

Figure 4.2: Individual Frequency of Cooperation in Games 1 & 2

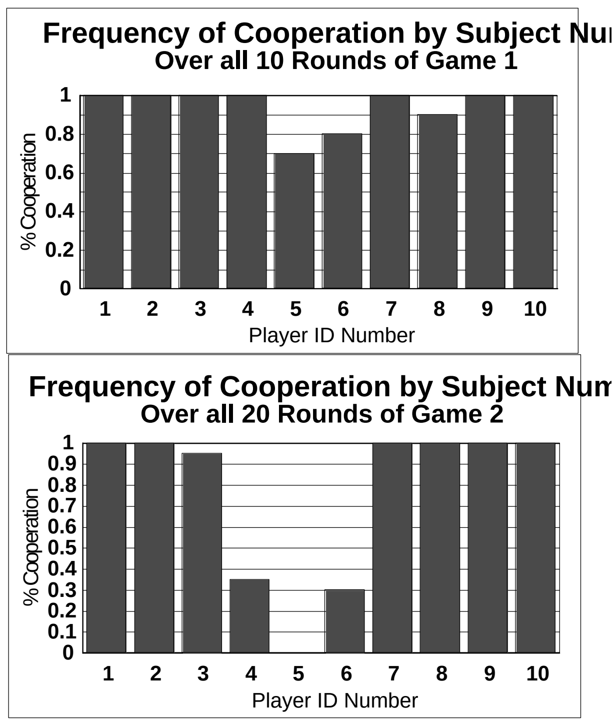

Figure 4.6: