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AN EXPERIMENTAL STUDY OF COMMUNICATION AND COOPERATION IN NONCOOPERATIVE GAMES†

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Abstract

This paper reports the results of an experiment designed to test the usefulness of alternative solution concepts to explain players' behavior in noncooperative games with preplay communication. In the experiment subjects communicate by *plain conversation* prior to playing a simple game. In this setting, we find that the presumption of *individualistic* and *independent* behavior underlying the concept of Nash equilibrium is inappropriate. Instead, we observe behavior to be *cooperative* and *correlated*. Statistical tests reject Nash equilibrium as an explanation of observed play. The coalition proof equilibrium of the game, however, explains the data when the possibility of errors by players is introduced.

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1 Introduction

The solution concept used in most applications of noncooperative game theory is *Nash equilibrium*. A mixed strategy profile is a Nash equilibrium if no player can increase his payoff by unilaterally changing his strategy. Thus, Nash equilibrium presumes that players choose their actions *independently* (i.e., they use "mixed" rather than "correlated" strategies), and also that the players' behavior is *individualistic* (i.e., only "individual" rather than "coordinated" deviations are considered).

This paper reports the results of an experiment designed to test whether these presumptions are appropriate when, as it is often the case in situations modelled as noncooperative games, preplay communication is possible, but binding agreements cannot be made. (In a Cournot oligopoly, for example, competitors may be unable to enforceably contract output levels due to antitrust regulation, although they may be able to freely discuss the outputs they intend to choose.) In the experiment subjects communicate by *plain conversation* prior to playing a simple game. In this setting, we find that the presumption of *individualistic* and *independent* behavior underlying the concept of Nash equilibrium is inappropriate. Instead, we observe behavior to be *cooperative* and *correlated.*[1] Statistical tests reject Nash equilibrium as an explanation of observed play. The coalition proof equilibrium of the game, however, explains the data when the possibility of errors by players is introduced.

Our experimental results show that preplay communication introduces possibilities for cooperation that may alter the outcome of a game in a fundamental way, and therefore that there is a need for solution concepts which account for them. Recently a number of such solution concepts have been developed. These concepts presume that players behave cooperatively rather than individualistically, although cooperation is limited by the inability of players to commit. Among these, the concepts of *strong Nash equilibrium* (SNE) introduced by Aumann [1], and *coalition-proof Nash equilibrium* ($CPNE$) developed by Bernheim, Peleg and Whinston [5] are perhaps

[1]Cooperation may seem paradoxical in noncooperative games. The label "noncooperative," however, should not be taken to imply that "cooperative" behavior is ruled out, but rather that cooperation is limited by the fact that players cannot make binding commitments, even if they can freely discuss their strategies (see Aumann [4]).

best known.

A strategy profile is a SNE if no coalition of players by changing their strategies can make its members better off. Hence a SNE is invulnerable to any deviation by any coalition. The concept of strong Nash equilibrium may be too strong as it requires that an equilibrium be invulnerable even to deviations which are themselves vulnerable to further deviations.[2] This problem with SNE was recognized by Bernheim, Peleg and Whinston [5], who proposed the notion of $CPNE$: A strategy profile is a $CPNE$ if no coalition has a *self-enforcing* deviation which makes its members better off. A deviation is self-enforcing if no proper subcoalition of the deviating coalition has a further self-enforcing deviation which makes its members better off.

These solution concepts maintain the presumption that players choose their actions independently. When players can communicate, however, this presumption may not be appropriate. In the following game, which we refer to as the *Three Player Matching Pennies Game* (TPMPG), cooperative behavior may give rise to correlated play.

> Three players each simultaneously choose heads or tails. If all three faces match, then players 1 and 2 each win a penny while player 3 loses two pennies. Otherwise, player 3 wins two pennies while players 1 and 2 each lose a penny.

The matrix representation of the game is given in Figure 1 below, where players 1, 2, and 3 choose, respectively, the row, the column, and the matrix.

H	H	T
H	1,1,-2	-1,-1,2
T	-1,-1,2	-1,-1,2

T	H	T
H	-1,-1,2	-1,-1,2
T	-1,-1,2	1,1,-2

Figure 1: the TPMPG

In this game, players 1 and 2 have completely common interests (either they both win a penny or they both lose a penny), and their interests are completely opposed

[2] Indeed, in many games (e.g., the prisoners' dilemma) a SNE does not exist.

to those of player 3 (when they win, player 3 loses two pennies, and when they lose, player 3 wins two pennies). If players 1 and 2 can communicate, one would expect that they will coordinate their actions (i.e., they will both choose heads or both choose tails) as they lose whenever their actions do not match. When players 1 and 2 act as a "team," the game effectively becomes the usual (two player) matching pennies game, which has a unique Nash (and unique *correlated*) equilibrium where each "team" chooses heads or tails with equal probability; i.e., with probability $\frac{1}{2}$ players 1 and 2 both choose heads and with probability $\frac{1}{2}$ both choose tails, while player 3 chooses heads or tails with equal probability. The resulting probability distribution over action profiles (i.e., *correlated strategy*) is given in Figure 2.

$$\begin{array}{c} H \\ \begin{array}{c|c|c|} & H & T \\ \hline H & \frac{1}{4} & 0 \\ \hline T & 0 & \frac{1}{4} \\ \hline \end{array} \end{array} \qquad \begin{array}{c} T \\ \begin{array}{c|c|c|} & H & T \\ \hline H & \frac{1}{4} & 0 \\ \hline T & 0 & \frac{1}{4} \\ \hline \end{array} \end{array}$$

Figure 2: the $CPCE$ of the TPMPG

As this probability distribution is not the product of its marginals, it cannot be generated by any mixed strategy profile. Thus, if players can communicate prior to play, one should not expect the players to choose their actions independently in this game.

Einy and Peleg [6] (E&P) and Moreno and Wooders [7] (M&W) develop notions of *coalition-proof correlated equilibrium* ($CPCE$) which not only presume that players behave cooperatively, but also allow the possibility that cooperation may give rise to correlated play. A $CPCE$ is a correlated strategy from which no coalition has a self-enforcing deviation which makes its members better off.[3] The notion of self-enforcingness used is the same as the one implicit in $CPNE$. Introducing the

[3]Since deviations by a single player are always self enforcing, a $CPCE$ must be a *correlated equilibrium* (see Aumann [2],[3]). A correlated strategy is a correlated equilibrium if for every action profile which is selected with positive probability, no player, knowing the action he is to play, can increase his expected payoff by taking a different action. The notion of correlated equilibrium admits the possibility of correlated play, although it maintains the presumption of individualistic behavior.

possibility of correlated play, however, makes it difficult to determine which deviations are feasible, and what is the appropriate criterion to use in deciding which deviations are improving. E&P and M&W take different approaches to resolving these difficulties, thereby obtaining different equilibrium notions. For the TPMPG, however, both equilibrium notions identify the correlated strategy in Figure 2 as the game's unique $CPCE$.

The paper is organized as follows. In Section 2 we discuss the experimental game and study its equilibria. Section 3 discusses the experimental design. Section 4 describes the experimental results and performs some preliminary tests of alternative hypotheses about player behavior. Section 5 studies the implications of introducing errors into the TPMPG. Section 6 is devoted to testing for correlated and cooperative behavior and testing whether observed play can be explained by any of the solutions concepts discussed when players make errors. Section 7 concludes.

2 Equilibria of the TPMPG

Our experimental game is the TPMPG. This game is simple enough that equilibrium theory will have a good chance of succeeding in an experimental setting, yet cooperation and correlation both play an important role. In this section we describe the equilibria of the TPMPG. We establish that the game does not have a $CPNE$. We also establish that although the set of correlated equilibria is large, there is a unique $CPCE$.

Nash Equilibria and Coalition-Proof Nash Equilibria

The pure strategy profiles (H, H, T) and (T, T, H), and the mixed strategy profile where each player chooses heads or tails with equal probability are the only Nash equilibria of the TPMPG. In each of the pure Nash equilibria players 1, 2 each lose a penny, while player 3 wins two pennies. In the mixed strategy Nash equilibrium players 1 and 2 each obtain a expected payoff of $-\frac{1}{2}$, while player 3's expected payoff is 1.

The TPMPG, however, does not have a $CPNE$. Note that since any deviation by a single player is self-enforcing, then a $CPNE$ must be a Nash equilibrium. None of the Nash equilibria is a $CPNE$: In each of the pure strategy Nash equilibria, the coalition of players 1 and 2 by jointly deviating in order to "match" player 3's action–i.e., both choosing T in the equilibrium (H, H, T), and both choosing H in the equilibrium (T, T, H)–can each win a penny. Both these deviations are self-enforcing as neither player 1 nor player 2 can gain by deviating further. Hence neither (H, H, T) nor (T, T, H) is a $CPNE$. Nor is the mixed Nash equilibrium a $CPNE$, as the deviation in which players 1 and 2 both choose T is also improving (players 1 and 2 obtain a payoff of 0) and self-enforcing. Therefore the TPMPG has no $CPNE$.[4]

Coalition-Proof Correlated Equilibria

We establish now that the correlated strategy in Figure 2, denoted by p^*, is the unique $CPCE$ of the TPMPG. This is established by first showing that self-enforcing deviations by either player 3 or by the coalition of players 1 and 2 rule out any other correlated strategy as a possible $CPCE$: only the correlated strategy p^* is immune to these deviations. It is then shown that this strategy is indeed a $CPCE$.

Let p be an arbitrary correlated strategy, and write p_{ijk} for the probability of action profile $(i, j, k) \in \{H, T\}^3$. Since p is a probability distribution, it satisfies

$$p_{HHH} + p_{HTH} + p_{THH} + p_{TTH} + p_{HHT} + p_{HTT} + p_{THT} + p_{TTT} = 1, \qquad (1)$$

and $p_{ijk} \geq 0$ for each $(i, j, k) \in \{H, T\}^3$. Let $U_i(p)$ denote the expected payoff of player i when action profiles are selected according to the correlated strategy p. We have

$$U_1(p) = U_2(p) = -\frac{U_3(p)}{2} = p_{HHH} - p_{HTH} - p_{THH} - p_{TTH} - p_{HHT} - p_{HTT} - p_{THT} + p_{TTT}. \qquad (2)$$

Assume that p is a $CPCE$ of the TPMPG. Consider the deviation by player 3 in which he chooses H. When players 1 and 2 continue to choose their actions according to p, then the probability that they both choose H is $p_{HHH} + p_{HHT}$; in this case player

[4] A SNE is always a $CPNE$ since a SNE is invulnerable to improving deviations, self-enforcing or otherwise, by any coalition of players. Therefore, the TPMPG does not have a SNE either.

3 loses two pennies. For every other pair of actions chosen by players 1 and 2, player 3 wins two pennies. Thus, by deviating to H player 3 obtains

$$2(-p_{HHH} - p_{HHT} + p_{HTH} + p_{THH} + p_{TTH} + p_{HTT} + p_{THT} + p_{TTT}).$$

Since this deviation by player 3 cannot be improving, p must satisfy

$$2(-p_{HHH} - p_{HHT} + p_{HTH} + p_{THH} + p_{TTH} + p_{HTT} + p_{THT} + p_{TTT}) \leq U_3(p). \quad (3)$$

Also, since a deviation by player 3 to T cannot be improving either, p must satisfy

$$2(-p_{TTT} - p_{TTH} + p_{HHH} + p_{HTH} + p_{THH} + p_{HHT} + p_{HTT} + p_{THT}) \leq U_3(p). \quad (4)$$

We now study the constraints imposed on p by the possibility of deviations by the coalition of players 1 and 2. Note that in the TPMPG players 1 and 2 only win when they both choose the same face; thus, any deviation by the coalition of both players is self-enforcing so long as it prescribes that both players choose the same action, as in this case no player can benefit by deviating further. Consider the (self-enforcing) deviation by the coalition of players 1 and 2 in which they both choose H with probability one. When player 3 continues to choose his action according to p, then the probability that he chooses H is $p_{HHH} + p_{HTH} + p_{THH} + p_{TTH}$; in this case players 1 and 2 each win a penny. In any other case (i.e., when player 3 chooses T) players 1 and 2 each lose a penny. Thus, if players 1 and 2 deviate to both choosing H, each obtains

$$p_{HHH} + p_{HTH} + p_{THH} + p_{TTH} - p_{HHT} - p_{HTT} - p_{THT} - p_{TTT}.$$

Since this deviation cannot be improving, p must satisfy

$$p_{HHH} + p_{HTH} + p_{THH} + p_{TTH} - p_{HHT} - p_{HTT} - p_{THT} - p_{TTT} \leq U_1(p) = U_2(p). \quad (5)$$

As the deviation in which players 1 and 2 both choose T with probability one cannot be improving either, p must satisfy also

$$p_{HHT} + p_{HTT} + p_{THT} + p_{TTT} - p_{HHH} - p_{HTH} - p_{THH} - p_{TTH} \leq U_1(p) = U_2(p). \quad (6)$$

It is straightforward to check that p^* is the unique correlated strategy satisfying conditions (1) through (6); i.e., "incentive compatibility constraints" rule out every correlated strategy but p^*. Thus, if p^* is a $CPCE$, then it is the unique $CPCE$ of the TPMPG.

It is established that p^* is a $CPCE$ by showing that no coalition of players has an improving deviation. Clearly, neither player 1 nor player 2 can improve by unilaterally deviating as they both lose whenever they choose different actions. Because p^* satisfies the inequalities (3) and (4), player 3 cannot improve either by unilaterally deviating. (Hence p^* is a correlated equilibrium.) Moreover, as player 3's interests are completely opposed to those of player 1 and player 2, no coalition of more than one player which includes player 3 has a deviation which is improving for all its members. Further, when player 3's action is selected according to p^* he chooses heads or tails with equal probability; hence players 2 and 3 obtain at most a payoff of zero from any deviation. Since they already obtain a payoff of zero when action profiles are selected according to p^*, the coalition of players 1 and 2 does not have an improving deviation either. Thus, p^* is the unique $CPCE$ of the TPMPG.[5]

3 Experimental Design

In the version of the TPMPG played in the experiment, each player chose either circle or square. We adopted these labels for the strategies as the labels "Heads" and "Tails" are suggestive of randomization. A subject's role in the game was indicated by one of the colors "Blue," "Red," or "White." The game was described to the subjects as follows: If all three players choose the same figure (that is, if all three choose circle or all three choose square), then the Blue and the Red player each earn \$7.50 and the White player earns \$0. In any other case, the Blue and the Red player each earn \$0 and the White player earns \$15.00. Subjects played the game only once.

Subjects were recruited in groups of twelve for sessions lasting one hour.[6] None of the subjects had previously participated in the experiment. Prior to the subjects entering the lab, twelve computers were "linked" by software to form four groups of

[5]It is worth noting that this strategy is in fact a "strong correlated equilibrium," as it is immune to any deviation (self-enforcing or otherwise) by any coalition.

[6]In 7 sessions only 9 subjects participated due to "no shows."

three computers. Each subject was seated at one of these computers. The game was played anonymously as subjects did not know which computers where in the same group.

In order to provide the subjects with the rich communication opportunities presumed by the notions of coalition-proofness we discuss, each subject was able to communicate both publicly and privately with the other members of his group. Subjects used their computers to communicate for 15 minutes before choosing their actions. To facilitate this communication, each subject's computer screen was divided into three windows. A label at the top of each window indicated which players could send messages to that window and which players could see that window's messages.

A Blue player, for example, had windows labelled "Blue-Red," "Blue-White," and "Blue-Red-White." A Blue player could communicate privately with the Red (White) player in his group by exchanging messages in the "Blue-Red" ("Blue-White") window. A Blue player communicated publicly through the "Blue-Red-White" window.[7] The screen of a Blue player, before any messages have been exchanged, is displayed in Figure 3.

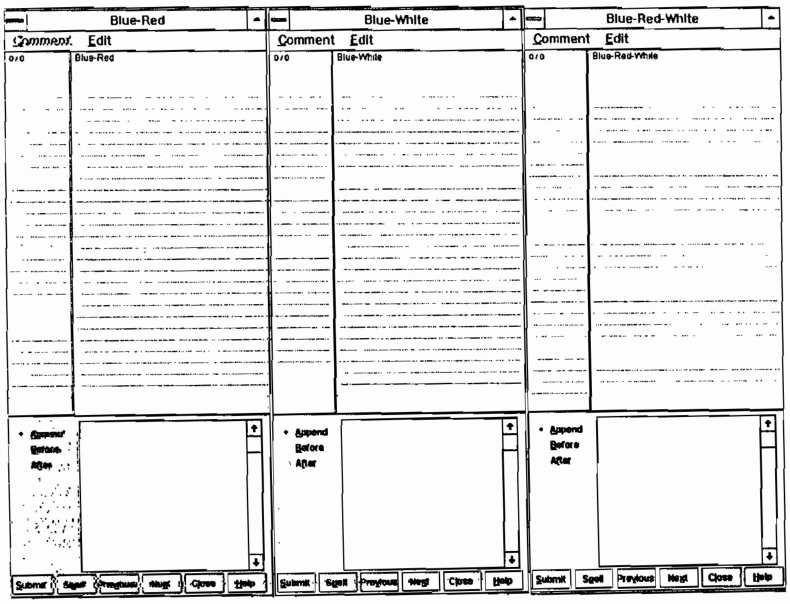

Figure 3: A Blue player's screen

[7]A Red player had windows labelled "Blue-Red," "Red-White," and "Blue-Red-White," while a White player had windows labelled "Blue-White," "Red-White," and "Blue-Red-White."

The mechanics of exchanging messages were simple. To send a message to a particular window, a subject activated it by using his mouse to point and click on it. The subject then composed his message, which was displayed in the lower box of the window as it was typed. The message was sent when the subject used his mouse to point and click on the Submit button at the bottom of the window. A message sent to a window was then displayed on the screens of all the players listed in the window's label. A message sent to the "Blue-Red" window, for example, was displayed in the "Blue-Red" window of the screens of both the Blue and the Red player. Whenever a player sent a message, a tag was automatically attached which identified his color. The tag also indicated the hour and minute that the message was sent. (A transcript of players' dialog in one of the sessions is given in Appendix B. In this transcript, the first message in the Blue-Red, Red-White, and Blue-Red-White windows were practice messages. The time spent exchanging these messages was not included in the 15 minutes of the communication phase.)

ANONYMITY

The solution concepts we discuss apply to situations where the players of the game cannot make binding agreements. Therefore, preserving the anonymity of subjects throughout the experiment was an essential feature of the experimental design. Had subjects not been anonymous, reneging on agreements would be costly and, in that case, agreements are no longer entirely non-binding. Anonymity also had the important role of eliminating the possibility of credible promises of side payments. In order to preserve anonymity, subjects were instructed that they were not to send messages in which they identified themselves. They were also told that their messages would be monitored to insure that they did not identify themselves. No other constraints were placed on the content of messages.

EXPECTED UTILITY AND EXPECTED MONETARY PAYOFF

The TPMPG has only two outcomes; either the figures of all three players are the same (a "win" for the Blue and the Red player and a "loss" for the White player), or they are not all the same (a win for the White player and a loss for the Blue and

Red player). Therefore, provided that each player prefers the outcome where he wins (and obtains a higher monetary payoff in this case), and provided that each player's preferences over lotteries can be represented by a von Neumann-Morgenstern utility function, we can take monetary payoffs to be utility payoffs. Since payoffs in the experimental game can be obtained by positive affine transformations of the payoffs of the version of the TPMPG presented in the Introduction, the equilibria of these games are the same.

4 The Experimental Data

In the game, each player had two actions, circle (C) or square (S). An action profile is a triple (i, j, k) in the set $\{C, S\}^3$ of possible action profiles, where i, j, and k denote, respectively, the action of the Blue (row), Red (column), and White (matrix) player. Table 1 presents the empirical frequency of each action profile after 69 plays of the TPMPG.[8] The number in parentheses below each frequency is the number of times that profile was observed.

TABLE I

Empirical Frequency Distribution

	C		S	
	C	S	C	S
C	.261 (18)	.072 (5)	.217 (15)	.029 (2)
S	.014 (1)	.188 (13)	.029 (2)	.188 (13)

Blue and Red players won in 31 of 69 plays, a win frequency which is not significantly different from one half, the win frequency implied by the $CPCE$ of the game. In the mixed Nash equilibrium this win frequency is only 25%, and in either of the pure

[8] The frequencies do not add up to one due to rounding.

Nash equilibria it is 0%. The hypothesis that this win frequency is 25% is rejected for degrees of significance as small as 0.005. Of course, the hypothesis that this win frequency is 0% is rejected at any level of significance. Blue players chose circle in 40 of the plays, while Red and White players chose circle in 36 and 37 plays, respectively. Each player's frequency of circle is not, however, statistically significantly different from one half.

Next we investigate whether our data is consistent with the presumption of independent behavior underlying the concepts of Nash equilibrium, $CPNE$, and SNE. Throughout we conduct hypothesis tests using the "likelihood ratio test." Our data can be regarded as a sequence of independent realizations of a multinomial random variable whose values are the set of possible action profiles. For each action profile $(i,j,k) \in \{C,S\}^3$, denote by p_{ijk} its probability. A sample can be represented by a vector $n = (n_{ijk})_{ijk\in\{C,S\}^3}$, where each n_{ijk} is the number of times action profile (i,j,k) was observed. Also denote by N the number of observations in a sample (i.e., $N = \sum_{ijk\in\{C,S\}^3} n_{ijk}$). The likelihood that a given sample n has been generated by the multinomial $p = (p_{ijk})_{ijk\in\{C,S\}^3}$ is given by

$$L(p) = a \prod_{ijk\in\{C,S\}^3} p_{ijk}^{n_{ijk}},$$

where $a = \frac{N!}{\prod_{ijk\in\{C,S\}^3} n_{ijk}!}$. The log of the likelihood function is therefore given by

$$l(p) = \ln a + \sum_{ijk\in\{C,S\}^3} n_{ijk} \ln p_{ijk}. \tag{7}$$

We first consider the null hypothesis that all three players chose their actions independently against the alternative hypothesis that they did not (i.e., that the sample has been generated by an arbitrary multinomial distribution). Under the null, the maximum likelihood estimator of p_{ijk} is

$$\hat{p}^0_{ijk} = \frac{n_{i..}n_{.j.}n_{..k}}{N^3},$$

where $n_{i..}$, $n_{.j.}$, and $n_{..k}$ are the number of times that Blue players chose action i, Red players chose action j, and White players chose action k, respectively; i.e., $n_{i..} = \sum_{jk\in\{C,S\}^2} n_{ijk}$, $n_{.j.} = \sum_{ik\in\{C,S\}^2} n_{ijk}$, and $n_{..k} = \sum_{ij\in\{C,S\}^2} n_{ijk}$. The maximum likelihood estimator of p_{ijk} under the alternative hypothesis that the data has been generated by an arbitrary multinomial distribution is

$$\hat{p}^1_{ijk} = \frac{n_{ijk}}{N}.$$

The likelihood ratio, given by

$$-2\left(l\left(\hat{p}^0_{ijk}\right) - l\left(\hat{p}^1_{ijk}\right)\right),$$

is asymptotically distributed as chi-square with 4 degrees of freedom. The degrees of freedom is the difference between the dimension of the parameter space under the alternative hypothesis (7 in this case) and under the null hypothesis (3 in this case). For a given degree of significance α, we can calculate a value such that with probability $1 - \alpha$ a chi-square with 4 degrees of freedom is less than or equal this value. We reject the null hypothesis whenever the likelihood ratio is greater than this value. Tests of pairwise independence are constructed in a similar fashion.

The results of likelihood ratio tests of independence of players' actions are given in Table 2 below. (The column $\chi^2_{0.05}$ provides a value such that if the likelihood ratio exceeds this value, then the null hypothesis is rejected at the 0.05 significance level; the number in parentheses indicates the degrees of freedom of the chi square.)

TABLE 2

Likelihood Ratio Tests of Independence

Null: Independence of Players' Actions	$\chi^2_{0.05}$	Likelihood Ratio
Blue-Red-White	9.49 (4)	40.71
Blue-White	3.84 (1)	0.58
Red-White	3.84 (1)	0.02
Blue-Red	3.84 (1)	339.70

The hypothesis that the actions of all three players are independent is rejected at the 0.05 significance level. In fact, it is rejected for significance levels as small as 0.005. The source of this rejection is the apparent correlation in the actions of Blue and Red players; the hypothesis that the Blue and Red players choose their actions independently is rejected at significance levels as small as 0.005. The hypotheses of pairwise independence between Blue and White and between Red and White are not rejected at the 0.05 level of significance.

Although these results are inconsistent with the presumption of independence implicit in the concept of Nash equilibrium, one cannot conclude that play is inconsistent with the predictions of Nash equilibrium on the basis of these tests alone. Different Nash equilibria in different plays of the game could lead to the appearance of correlation, even if actions in any given play were independent. In Section 6 we test this hypothesis. The results of the tests of independence, however, are consistent with the prediction of coalition-proof correlated equilibrium that Blue and Red players correlate their actions, and that the actions of Blue and Red players are uncorrelated with the actions of White players.

In the TPMPG, when players choose their actions cooperatively rather than individualistically, then Blue and Red players always coordinate their actions. Indeed, in 59 plays the Blue and the Red player chose the same figure. Nonetheless, Blue and Red players failed to coordinate in 10 plays, which is inconsistent with $CPCE$ unless players make errors. In the next section we present a model of play in the TPMPG which admits this possibility.

5 The TPMPG with Errors

In experimental settings there are a number of elements that might lead a player to choose an action different from the one he intended: a player may misunderstand the rules of the experimental game, or he may simply make an error. In our experiment, there is also the possibility that a player's choice of an action may be based on a "miscommunication" (i.e., a message may be misinterpreted, the source of a message may be confused, or a message may be sent to a player different from the one intended). A theory which ignores the possibility of errors might be rejected, even though it correctly predicts "intended behavior."

We introduce the possibility of errors into the TPMPG by assuming that when a player selects a figure, with probability $1-\epsilon$ he chooses the figure he intended, but with probability ϵ he chooses a figure randomly (i.e., he chooses "square" or "circle" with equal probability). We assume that all players make errors with the same probability, that the errors of players are independent, and that the error structure is common knowledge.

The TPMPG combined with errors by players yields a new game which we denote by TPMPG(ϵ). In this new game, a pure strategy for a player is interpreted as the action he intends to play. The payoff of each player for each profile of intended actions is given in Figure 4 below, where $w = 7.5\rho_w(\epsilon)$, and $l = 7.5\rho_l(\epsilon)$. The term $\rho_w(\epsilon) = 1 - \frac{3}{2}\epsilon + \frac{3}{4}\epsilon^2$ is the probability that all the players choose the same figure when all the players intend to choose the same figure, and $\rho_l(\epsilon) = \frac{1}{2}\epsilon - \frac{1}{4}\epsilon^2$ is this probability when one of the players intends to choose a figure different from the figure of another player.

C

	C	S
C	$w, w, (15-2w)$	$l, l, (15-2l)$
S	$l, l, (15-2l)$	$l, l, (15-2l)$

S

	C	S
C	$l, l, (15-2l)$	$l, l, (15-2l)$
S	$l, l, (15-2l)$	$w, w, (15-2w)$

Figure 4: the TPMPG(ϵ)

For error rates ϵ less than one, the payoffs in the TPMPG(ϵ) can be obtained by positive affine transformations of the payoffs in the original TPMPG, and therefore the equilibria of these games are the same.

In the TPMPG(ϵ), however, it is necessary to make a distinction between intended actions and actual actions (i.e. the actions that are observed). The probability distribution over intended actions is generally different from the probability distribution over actual actions, the latter distribution depending on the error rate. Thus, although the equilibria of the TPMPG and TPMPG(ϵ) are the same, the probability distributions over profiles of actual actions corresponding to these equilibria are generally different. (An exception is the mixed Nash equilibrium.)

Nash Equilibria of the TPMPG with errors

Each of the Nash equilibria gives rise to a probability distribution over actual action profiles of the form given in Figure 5 below.[9] The probabilities ρ_k differ for each of the equilibria: when the players intend to play the pure strategy Nash equilibrium (S, S, C), then $\rho_k = (\frac{\epsilon}{2})^k(1 - \frac{\epsilon}{2})^{3-k}$; when they intend to play the pure strategy Nash equilibrium (C, C, S), then $\rho_k = (\frac{\epsilon}{2})^{3-k}(1 - \frac{\epsilon}{2})^k$; finally, if the players intend to play the mixed strategy Nash equilibrium, then $\rho_k = \frac{1}{8}$.

C

	C	S
C	ρ_2	ρ_1
S	ρ_1	ρ_0

S

	C	S
C	ρ_3	ρ_2
S	ρ_2	ρ_1

Figure 5: Nash equilibria in the TPMPG (ϵ)

CPCE OF THE TPMPG WITH ERRORS

In the *CPCE* of the TPMPG(ϵ), with probability $\frac{1}{2}$ the Blue and the Red player both intend to choose square and with probability $\frac{1}{2}$ they both intend to choose circle, while the White player intends to choose each figure with equal probability. The probability distribution over actual action profiles is given in Figure 6, where $\delta = \epsilon\left(1 - \frac{\epsilon}{2}\right)$ is the probability that the Blue and the Red players fail to coordinate their actions.

C

	C	S
C	$\frac{1-\delta}{4}$	$\frac{\delta}{4}$
S	$\frac{\delta}{4}$	$\frac{1-\delta}{4}$

S

	C	S
C	$\frac{1-\delta}{4}$	$\frac{\delta}{4}$
S	$\frac{\delta}{4}$	$\frac{1-\delta}{4}$

Figure 6: *CPCE* in the TPMPG

Unlike the probability distribution over intended action profiles (see Figure 2), the probability distribution over actual action profiles gives each outcome a positive probability. Hence when players make errors, the likelihood of any finite sample is positive under the hypothesis that players play the *CPCE* of the game. Thus, we can no longer automatically reject this hypothesis if there is a coordination failure.

[9]The labels C and S in this table now represent actual (i.e., observed) actions, whereas in Figure 4 they represented intended actions.

6 Tests of Hypotheses in the TPMPG with errors

In this section we analyze the experimental data in the context of the TPMPG(ϵ). We test the underlying assumptions of the alternative solution concepts (i.e., independent versus correlated behavior, and individualistic versus cooperative behavior), and also we test alternative equilibrium theories. Our hypothesis tests are based on the likelihood ratio test. We begin by deriving the likelihood function for each of the hypothesis of interest. Henceforth denote by $\theta_k = (\frac{\epsilon}{2})^k(1-\frac{\epsilon}{2})^{3-k}$, the probability that exactly k players choose an action different from the one intended.

INDEPENDENT BEHAVIOR

In section 4 we reported the results of tests of independence of the players' (actual) actions. The presumption of independence in the TPMPG(ϵ) pertains to players intended actions rather than to their actual play. It is easy to check, however, that since players make errors independently, whenever players intend to choose their actions independently, then actual actions are also independent. Hence incorporating the possibility that players make errors does not increase the maximum likelihood under the hypothesis of independence, and the results of tests of independence for the TPMPG(ϵ) are the same as those reported in Section 4 for the TPMPG.

COOPERATIVE BEHAVIOR

As we discussed in Section 4, cooperative behavior in the TPMPG results in Blue and Red players always choosing the same action. Thus, under the null hypothesis of cooperative behavior, intended actions are selected according to a multinomial distribution $p = (p_{ijk})_{ijk\in\{C,S\}^3}$ satisfying

$$p_{CCC} + p_{CCS} + p_{SSC} + p_{SSS} = 1.$$

In this case, actual actions are selected according to the multinomial $\bar{p}$ given by

$$\bar{p}_{ijk} = p_{ijk}\theta_0 + (p_{\neg ijk} + p_{i\neg jk} + p_{ij\neg k})\,\theta_1 + (p_{\neg i\neg jk} + p_{\neg ij\neg k} + p_{i\neg j\neg k})\,\theta_2 + p_{\neg i\neg j\neg k}\theta_3,$$

where $\neg r = S$ if $r = C$, and $\neg r = C$ if $r = S$.

The likelihood of our data under the hypothesis of cooperative behavior is obtained by replacing these probabilities in equation (7).

NASH EQUILIBRIUM

As the TPMPG has multiple Nash equilibria, an appropriate test for whether our data has been generated by Nash equilibrium play must allow the possibility that observed play is the result of a "mixture" of Nash equilibria. When the pure strategy Nash equilibria (S,S,C) and (C,C,S) have generated a proportion λ_1 and λ_2 of the observed plays, respectively, and the mixed Nash equilibrium has generated the remaining observed plays, the probability distribution over actual actions is of the form in Figure 5, where

$$\rho_k = \lambda_1\theta_k + \lambda_2\theta_{3-k} + (1 - \lambda_1 - \lambda_2)\frac{1}{8}.$$

¿From this multinomial distribution one can calculate the log likelihood function using equation (7). For our data this function is

$$l^{NE}(\lambda_1, \lambda_2, \epsilon) = \ln a + 13\ln\rho_0 + 19\ln\rho_1 + 22\ln\rho_2 + 15\ln\rho_3.$$

COALITION-PROOF CORRELATED EQUILIBRIUM

The probability distribution over actual action profiles that results when players choose their actions according to the coalition-proof correlated equilibrium of the TPMPG(ϵ) is described in Figure 6. Given a sample n, denote by N_F the number of observations where the Blue and the Red players fail to coordinate their actions (i.e., $N_F = n_{CSC} + n_{SCC} + n_{SCS} + n_{CSS}$). Using equation (7), one can calculate the log likelihood that the observed data has been generated by the $CPCE$ of the game as

$$l^{CPCE}(\epsilon) = \ln a + N_F \ln\frac{\delta}{4} + (N - N_F)\ln\frac{1-\delta}{4}.$$

Thus, under the null hypothesis that our data has been generated by the $CPCE$, the likelihood of a sample depends only on the error rate, the sample size, and the number of coordination failures by Blue and Red players. For our sample, the likelihood function is

$$l^{CPCE}(\epsilon) = \ln a + 10\ln\frac{\delta}{4} + 59\ln\frac{1-\delta}{4}.$$

Results

The results of our tests are presented in Table 3 below. (As before, the column $\chi^2_{0.05}$ gives a value such that if the likelihood ratio exceeds this value, then the null hypothesis is rejected at the 0.05 significance level; the number in parentheses indicates the degrees of freedom.) The first row contains the maximum likelihood estimate of the error rate and the value of the likelihood ratio under the null hypothesis of cooperative behavior. At the 0.05 significance level we fail to reject this null hypothesis. Thus, the presence of coordination failures in our data can be explained as the result of players' errors.

TABLE 3

Tests of Hypotheses in the TPMPG(ϵ)

Null Hypothesis	$\chi^2_{0.05}$	$\hat{\epsilon}$	Likelihood Ratio
Cooperative Behavior[10]	7.82 (3)	0.155	3.118
Mixture of NE[11]	9.49 (4)	0.5404	34.60
CPCE	12.59 (6)	0.1573	4.42

The second row contains the maximum likelihood estimate of the error rate and the value of the likelihood ratio under the null hypothesis that the data has been generated by a mixture of the three Nash equilibria, against the alternative that the data has been generated by some arbitrary multinomial distribution. According to the likelihood ratio test, this null hypothesis is rejected at the 0.05 level of significance; in fact, it is rejected for levels of significance as small as 0.005. Although we do not report the tests here, each of the null hypotheses that the data has been generated by the mixed or either of the pure Nash equilibria of the game is also rejected.

[10]The maximum likelihood estimates of $p_{CCC}, p_{CCS}, p_{CCS}$, and p_{SSC} are, respectively, 0.32, 0.23, 0.24, and 0.21. These estimates were obtained by a grid search over the parameter space.

[11]The maximum likelihood estimates of the other parameters are $\hat{\lambda}_1 = 0.55$, and $\hat{\lambda}_2 = 0.44$. The estimated weight on the mixed Nash equilibrium is zero ($\hat{\lambda}_1$ and $\hat{\lambda}_2$ do not sum to 1 due to rounding). These estimates were obtained by a grid search over the parameter space.

The third row of Table 3 shows the results of the maximum likelihood estimation of the error rate, and the value of the likelihood ratio under the null hypothesis that the data was generated by the $CPCE$ of the TPMPG(ϵ). The maximum likelihood estimator of the error rate is

$$\hat{\epsilon} = 1 - \sqrt{1 - 2\left(\frac{N_F}{N}\right)}.$$

(The second order condition for a maximum is that $N_F < \frac{N}{2}$, a condition which is satisfied by our data.) According to the likelihood ratio test we fail to reject this hypothesis at the 0.05 significance level. In fact, we fail to reject this hypothesis for significance levels as large as 0.5.

The failure to reject the null hypothesis that the data has been generated by the $CPCE$ of the TPMPG(ϵ) against the alternative that it has been generated by an arbitrary multinomial distribution is very robust with respect to the error rate. The curve in Figure 7 below shows the value of the likelihood ratio as a function of the error rate.

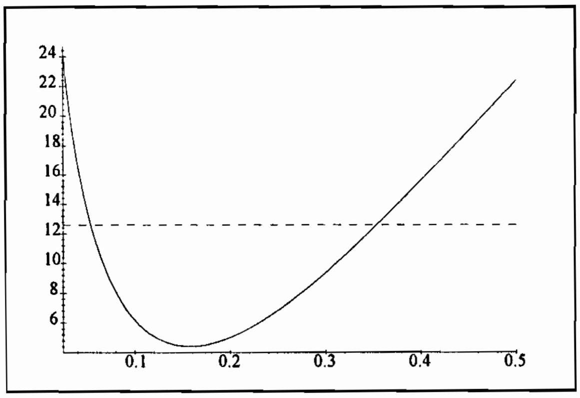

Figure 7: Likelihood Ratio for $CPCE$ as a function of ϵ

A horizontal line has been drawn at the value 12.59 (A chi-square with 6 degrees of freedom is less than 12.59 with probability 0.95). At a 0.05 significance level, we fail to reject the null hypothesis that the data has been generated by the $CPCE$ of the $TPMPG(\epsilon)$ for a large range of error rates (any rate in the interval [0.054,0.353]).

Although we do not report these tests, one cannot reject the null hypothesis that the data has been generated by the $CPCE$ of the game against the alternative hypothesis that it has been generated by an arbitrary correlated equilibrium. (This alternative is more restrictive than the previously considered alternative that the data was generated by an arbitrary multinomial distribution.) We continue to reject the null hypothesis that the data has been generated by a mixture of the Nash equilibria even with this more restrictive alternative.

In summary, our experimental data provides support to the hypothesis of cooperative behavior, and it strongly rejects the presumption of independent behavior. Moreover, it supports the hypothesis that the data has been generated by play of the coalition-proof correlated equilibrium of the game, while it clearly rejects the hypothesis of Nash equilibrium play. We should note also that although the experiment does not allow one to test the predictive power of the notions of coalition-proof Nash equilibrium or strong Nash equilibrium (neither type of equilibria exists for the TPMPG), it provides some evidence against these theories as both fail to identify a coalition-proof equilibrium even though there is an intuitively compelling one, the $CPCE$ of the game, which is supported by the data.

7 Conclusions

The results of our experiment stress the importance of accounting for cooperation in noncooperative games with preplay communication. Moreover, the experiment strongly suggests that cooperative behavior naturally leads to correlated play. Indeed, in many applications of noncooperative games the situations under study are ones where the players have rich opportunities to communicate prior to play. In these applications, the use of Nash equilibrium as "the" solution concept may not be appropriate.[12] Instead, one should investigate the behavior predicted by solution concepts that account for the cooperation possibilities there might be.

An alternative approach to dealing with preplay communication is to transform the game, introducing explicitly any opportunities to communicate the players might have. There are two potential difficulties with this approach: First, it might simply be infeasible when opportunities to communicate are very rich and unstructured.

[12]Except for dominance solvable games, for which Nash, $CPNE$, correlated, and $CPCE$ coincide (see Moreno and Wooders [8]).

(With "plain conversation", for example, there is no prespecified order in which messages may be sent and no restriction on the content of messages.) Second, even when communication opportunities are limited and structured, and therefore they can be modelled explicitly, taking the Nash equilibria of the transformed game as the prediction of play ignores any cooperation possibilities that communication might bring about. Moreover, this approach leads to very weak predictions: For any Nash equilibrium of the original game there is a Nash equilibrium of the transformed game where the players choose their messages arbitrarily and then, ignoring all messages, choose actions according to a Nash equilibrium of the original game.

A feasible and perhaps more practical approach is to devise solution concepts which account for communication opportunities implicitly. Moreover, this approach might lead to stronger predictions. (In the TPMPG, for example, there is a continuum of correlated equilibria, but only one coalition-proof correlated equilibrium.) The notions of coalition-proof equilibrium developed by Einy and Peleg [6] or Moreno and Wooders [7] predict well in simple games like the TPMPG, but in general games they are subject to criticism. It will be important to design solution concepts which are not subject to these criticisms.

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Appendix A: Instructions

To control for the possiblity that the order of the presentation of the examples may introduce bias in the play, we used two sets of instructions which differed in the order the examples were presented, but did not differ in any other respect. We could not reject the hypothesis that the data generated using different sets of instructions came from the same probability distribution.

Instructions

If at any time you have a question as I go through these instruction, please raise your hand. During this experiment, you may not speak to other participants.

In this experiment, you and the other participants have been divided into groups of three players. You will play a simple game with the other two members of your group. In every group there is one "Blue," one "Red," and one "White" player. (Please turn over the envelop at your station. The color of the sticker on the envelope at your station tells you which type of player you are.) Your monetary earnings from playing the game are determined by your color and the choices made by the players in your group.

You will play the game only once!

COMMUNICATION

Before making your choice, you will have the opportunity to communicate with the other members of your group. You communicate by using your computer to send and receive messages. To help you do this, the screen in front of you is divided into three windows. You can send messages to any of these windows. The label at the top of a window tells you which players in your group can see that window's messages. In order to show you how you can send messages, you will send a practice message.

Instructions for BLUE PLAYERS

If you are a Blue player, your screen displays the three windows shown on the overhead. These windows are labelled "Blue-Red," "Blue-White" and "Blue-Red-White." (If you are a Blue player and your screen does not show these windows, please raise your hand.)

You can send messages to any window on your screen. Only you and the Red player in your group can see messages in the Blue-Red window. Only you and the White player in your group can see messages in the Blue-White window. All three players in your group can see messages in the Blue-Red-White window.

You will now send a practice message to the Red player (but not the White player) in your group. If you are a Blue player, please do the following.

(1) Use your mouse to point and click on the lower box in the Blue-Red window;

(2) type "`Hi,this is a message to Red.`"

(3) Use your mouse to point and click on the <u>S</u>ubmit button at the bottom of the Blue-Red window.

Your screen now appears as displayed on the overhead. The message you just typed is displayed in your Blue-Red window.

You can send messages to White (but not to Red) from the Blue-White window, and you can send messages to both Red and White from the Blue-Red-White window.

Instructions to RED PLAYERS

If you are a Red player, your screen displays windows labelled "Blue-Red," "Red-White" and "Blue-Red-White," as shown in the overhead. (If you are a Red player and your screen does not show these windows, please raise your hand.)

Notice that the message just typed by the Blue player appears in your Blue-Red window. At the end of the message is a label which identifies Blue as the sender of the message.

You will now send a practice message to the White player (but not the Blue player) in your group. If you are a Red player, please do the following.

(1) Use your mouse to point and click on the lower box in the Red-White window;

(2) type "`Hi, this is a message to White.`"

(3) Use your mouse to point and click on the <u>S</u>ubmit button in the Red-White window.

Your screen now appears as displayed on the overhead. Your message to White is displayed in your Red-White window.

You can send messages to Blue (but not to White) from the Blue-Red window, and you can send messages to both Blue and White from the Blue-Red-White window.

Instructions to WHITE PLAYERS

If you are a White player, your screen should display the three windows shown in the overhead. The windows are labelled "Blue-White," "Red-White," and "Blue-Red-White." (If you are a White player and your screen does not show these windows, please raise your hand.)

Notice that the message just typed by the Red player appears in your Red-White window.

You will now send a practice message to both the Blue and the Red player in your group. If you are a White player, please do the following.

(1) Use your mouse to point and click on the lower box in the Blue-Red-White window

(2) type "`Hi, this is a message to both the other players.`"

(3) Use your mouse to point and click on the Submit button in the Blue-Red-White window.

Your screen now appears as displayed on the overhead. Your message appears in your Blue-Red-White window. Your message also is displayed in the Blue-Red-White window of the Blue and the Red player in your group.

You can send messages to Blue (but not to Red) from the Blue-White window, and you can send messages to Red (but not to Blue) from the Red-White window.

In this experiment you will remain anonymous. As preserving anonymity is important, **you may not send messages that in any way identify yourself.** You may not, for example, send a message which gives your name or your phone number. The messages you send will be monitored in order to insure that you do not identify yourself.

The Game: Choices and Earnings

If you have a question as I read through the remaining instructions, please raise you hand and a monitor will approach you to answer your question.

Please open the envelope at your station. Inside you will find a sheet of paper. On the side labelled "Record Sheet," please copy the number on your bingo ball in the space for "Subject ID." Keep the ball as it is the only way in which we can identify you.

I will now describe the game that you play with the other members of your group. In the game, each player chooses either "circle" or "square." Your earnings are determined according to the following rules:

- If all three players in your group choose the same figure (that is, if all three choose "circle" or all three choose "square"), then
  - Blue earns $7.50.
  - Red earns $7.50
  - White earns $0.
- If any player in your group chooses a figure different from another player, then
  - Blue earns $0.
  - Red earns $0.
  - White earns $15.

These rules are summarized by the following table. (A copy of this table is on the other side of your record sheet.)

Choices				Earnings		
Blue	Red	White	Same Figures?	Blue	Red	White
○	○	○	Yes	$7.50	$7.50	$0
○	○	□	No	$0	$0	$15
□	□	○	No	$0	$0	$15
□	□	□	Yes	$7.50	$7.50	$0
○	□	○	No	$0	$0	$15
○	□	□	No	$0	$0	$15
□	○	○	No	$0	$0	$15
□	○	□	No	$0	$0	$15

If all the players in your group choose "circle," then all have chosen the same figure. The first row of the table shows that, in this case, Blue earns $7.50, Red earns $7.50, and White earns $0. If Blue chooses "square," Red chooses "circle," and White chooses "square" then all three players have not chosen the same figure. The last row shows that, in this case, Blue and Red each earn $0 and White earns $15.

If you have any questions regarding how your earnings are determined, please raise your hand now.

The experiment proceeds as follows.

- Before making your choice, you will have 15 minutes to communicate with the other members of your group.

- After 15 minutes, you will make your choice.

- Once earnings are computed you will be called by your subject ID, one person at a time, to collect your earnings. At that time you will be told the choices of the other players in your group.

- You will then immediately exit the lab.

REMEMBER: You will play the game only once and you may not send messages which identify yourself.

If you have any questions, please raise your hand now.

[Subjects communicated for fifteen minutes.]

The communication phase is now over. Please turn off your monitor.

- Please make your choice by checking either the circle or the square on your record sheet.

- Put your record sheet back into the envelop.

[Record sheets were collected.]

While we determine your earnings, we ask you to take a short quiz to test whether you understand how your earnings are determined.

- Write your subject ID on the quiz where indicated.

- For the given choices, write the earnings of each player. Your answers to the quiz will not affect your earnings.

[Quizzes were collected.]

Please wait at your station until your subject ID is called.

- When you are called, take your bingo ball to the back of the room to collect your earnings.

- After you are paid, please exit the laboratory.

Apendix B: Transcript

Players Actions (C,S,S)

Blue-Red

Hi, this is a messageto Red. {5/23/95, 2:16 PM, Blue}

We have to choose the same one and convince White to also {5/23/95, 2:27 PM, Blue}

How do we do that {5/23/95, 2:28 PM, Red}

Tell white that we are picking a circle so he will probably pick a circle thinking that we are tricking him. {5/23/95, 2:29 PM, Red}

Won't he think that is reverse psychology anyway? {5/23/95, 2:30 PM, Blue}

Maybe it will work {5/23/95, 2:30 PM, Blue}

Should I tell him we're picking circle? {5/23/95, 2:31 PM, Blue}

If we tell him we are picking a circle he will think we are picking a square and pick the circle so we should pick the circle {5/23/95, 2:32 PM, Red}

Ok I'll do it on the open channel {5/23/95, 2:32 PM, Blue}

Now what do you think he'll think {5/23/95, 2:33 PM, Blue}

He is probably trying to figure out what we

Blue-White

What do you think we should do? {5/23/95, 2:27 PM, White}

I really have no idea, you have the best chance to win {5/23/95, 2:28 PM, Blue}

How are you doing? {5/23/95, 2:39 PM, Blue}

I'm doing great {5/23/95, 2:39 PM, White}

Red-White

"Hi this is a message to white" {5/23/95, 2:18 PM, Red}

What do you think we should do? {5/23/95, 2:28 PM, White}

What are you going to pick {5/23/95, 2:33 PM, Red}

Blue-Red-White

"Hi, this is a message to both the other players" {5/23/95, 2:19 PM, White}

We're going to pick circle {5/23/95, 2:33 PM, Blue}

If both of you try to put the same thing you have a 50/50 chance of winning $7.50 each considering that I put the opposite. However, if I just put whatever I want, I can win 15$ {5/23/95, 2:34 PM, White}

My best chance of winning is to choose circle or square without letting you know, so I think that's what I'm going to do. Good Luck with your guess of what I'm going to pick. If you have anything to say just write back. {5/23/95, 2:39 PM, White}

Thank goodness we don't know anyone else in the group, huh? {5/23/95, 2:40 PM, Blue}

Yes, because I would be mad at you for not picking what we pick. {5/23/95, 2:41 PM, Red}

I think I got lucky today by sitting in this chair. I hope it sticks with me after you two choose your circles, or was it squares? {5/23/95, 2:42 PM, White} are really picking {5/23/95, 2:34 PM, Red}

So we're definitly picking circle, right? {5/23/95, 2:34 PM, Blue}

right there is 50/50 chance, basically he doesn't know what we're picking what if he thinks we are really picking the circle- he doesn't know about reverse psychology {5/23/95, 2:36 PM, Red}

Maybe not! Now we have to figure out what he thinks. Should we change our minds to him for a bit of confusion and still pick circle? {5/23/95, 2:37 PM, Blue}

Maybe we should pick the square, i can't decide now {5/23/95, 2:37 PM, Red}

Why don't we pass messages back and forth on the open and directly to him for part of the rest of the time and still pick the same one, but with all our messages there's still a 50/50 chance {5/23/95, 2:38 PM, Blue}

If we type on the open screen he'll know what we are trying to do. we should just decide what we want to pick and hope its the same as him. {5/23/95, 2:40 PM, Red}

Let's do it privately then on the direct to white channel {5/23/95, 2:41 PM, Blue}

So do w pick square? {5/23/95, 2:41 PM, Blue}

What do you mean, let's pick the circle. {5/23/95, 2:42 PM, Red}

Ok {5/23/95, 2:42 PM, Blue}