Secure Implementation Experiments:
Do Strategy-proof Mechanisms Really Work?[†]

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November, 2003; revised July 22, 2005

[†] We thank anonymous referees and an associate editor for their useful comments. Research was partially supported by the Grant in Aid for Scientific Research 15310023 of the Ministry of Education, Science and Culture in Japan, a Tokyo Center for Economic Research Grant, a Japan Economic Research Foundation Grant, and a University Faculty Scholar award at Purdue University.

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ABSTRACT

Strategy-proofness, requiring that truth-telling is a dominant strategy, is a standard concept used in social choice theory. Saijo et al. (2003) argue that this concept has serious drawbacks. In particular, many strategy-proof mechanisms have a continuum of Nash equilibria, including equilibria other than dominant strategy equilibria. For only a subset of strategy-proof mechanisms do the set of Nash equilibria and the set of dominant strategy equilibria coincide. For example, this double coincidence occurs in the Groves mechanism when preferences are single-peaked. We report experiments using two strategy-proof mechanisms. One of them has a large number of Nash equilibria, but the other has a unique Nash equilibrium. We found clear differences in the rate of dominant strategy play between the two.

Journal of Economic Literature Classification Number: C92, D71, D78, and H41.

Keywords: Experiment, Laboratory, Secure Implementation, Groves-Clarke, Pivotal, Learning

1. Introduction

Strategy-proofness, requiring that truth-telling is a dominant strategy, is a standard concept that has been used in the design of a variety of mechanisms for social choice as well as for eliciting values for non-market goods. Its main appeal is that it relies on what would seem to be one of the most basic game-theoretic notions and apparently innocuous assumptions for behavior: that players adopt dominant strategies. Theorists often fail to recognize, however, that laboratory evidence calls into question the descriptive relevance of this assumption. For example, Attiyeh, Franciosi, and Isaac (2000) and Kawagoe and Mori (2001) report pivotal mechanism experiments in which subjects adopt dominant strategies less than half the time, and Kagel, Harstad, and Levin (1987), Kagel and Levin (1993) and Harstad (2000) report second price auction experiments in which most bids do not reveal true value. Attiyeh, Franciosi, and Isaac (2000) conclude pessimistically (p. 112) "we do not believe that the pivot mechanism warrants further practical consideration…This is due to the fundamental failure of the mechanism, in our laboratory experiments, to induce truthful value revelation".

Experimentalists sometimes argue that players who use weakly dominated strategies must suffer from confusion due to the complexity of the mechanism and the non-transparency of the dominant strategy. But in fact, neither "epistemic" (deductive) nor "evolutive" (dynamic) models provide unambiguous support for the elimination of weakly dominated strategies. According to the epistemic model, if each player is perfectly rational and can deduce what strategies the opponent will use, then the outcome of the game must be a Nash equilibrium (Aumann and Brandenburger, 1995), but there is nothing that forces a player to eliminate weakly dominated strategies. However, the epistemic model seems almost irrelevant when interpreting behavior in experiments, because very few subjects appear to consciously compute equilibria. (Consequently, behavior in the first round of play is often far from equilibrium.) The dynamic perspective may be more relevant because it considers the changing behavior of boundedly rational players who play many times.[1] The dynamic models do not assume that the players deduce the opponent's action from complete information about payoff functions. Convergence to Nash equilibrium is solely based on players reacting to each other's previous actions. Consequently, even if the payoff functions are privately known, the long-run outcome may approximate a Nash equilibrium of the corresponding *complete information* game (see Hurwicz, 1972, and Smith, 2002). But while the rest points of dynamic processes such as fictitious play must be Nash equilibria, there is no guarantee that weakly dominated strategies will be eliminated. Intuitively, the feedback the players receive may be very weak because the use of a weakly dominated strategy may not cause any loss in payoff. Binmore, Gale and Samuelson (1995) and Kagel and Levin (1993) argue that this weak feedback effect can explain some experimental results, and Cabrales and Ponti (2000) discuss the implications for mechanism design. Of course, epistemic and evolutive models do provide clear-cut support for the elimination of *strictly* dominated strategies. The problem is that very few social choice rules are implementable in strictly dominant strategies.

Motivated by this problem, Saijo, Sjöström and Yamato (2003) developed a new concept called *secure* implementation. A social choice function is securely implementable if there exists a mechanism (game form) that implements it in dominant strategy equilibria, and the set of dominant strategy equilibrium outcomes and the set of Nash equilibrium outcomes coincide. That is, all Nash equilibrium outcomes must be socially optimal in a secure mechanism. The current paper takes a first step towards establishing the empirical significance of these ideas. We report a new experiment comparing the rate of dominant strategy adoption for the pivotal mechanism (where implementation is not secure) and for the Groves-Clarke mechanism when

[1] Hurwicz (1972), Muench and Walker (1983), Cabrales and Ponti (2000) and others have looked at mechanism design from a dynamic perspective.

preferences are single-peaked (where implementation is secure). Our results indicate that subjects play dominant strategies significantly more often in the secure Groves-Clarke mechanism than in the non-secure pivotal mechanism, even though we have simplified both mechanisms with context-free payoff tables. Our findings suggest that the highly pessimistic conclusion of Attiyeh, Franciosi, and Isaac (2000) should be modified to allow the possibility that a Groves-Clarke mechanism can perform satisfactorily in environments where implementation is secure.

Recently, Chen (2005) argued that mechanisms used for Nash implementation might perform better if they induce supermodular games, because supermodularity guarantees convergence of standard learning processes. On the other hand, supermodularity is not a necessary condition for convergence of these learning processes. In contrast, we study dominant strategy mechanisms. In this context, for any learning dynamics with the property that all Nash equilibria are rest points, secure implementation is necessary for global convergence to a desirable outcome. In the environment we study in this paper, it is sufficient as well.

The practical relevance of secure mechanisms is enhanced by the fact that for any common prior over the set of possible valuation functions, all Bayesian Nash equilibria will produce the socially optimal outcome. Thus, secure mechanisms will perform well if the agents are Bayesian expected utility maximizers with a common prior, but the social planner does not know what this prior is. The importance of this type of consideration will increase as more mechanisms are implemented in the field. Auctions provide an important example. The English (ascending price) auction is an important mechanism that has been used since at least 500 B.C. in Babylon (Cassady, 1967). Theorists have noted the strategic equivalence between English and second price auctions since Vickrey (1961), but for some information conditions the second price auction is strategy-proof but not securely implementable. Until recently the second price auction has not been adopted in the field, although this is likely to change as online auctions grow in importance. Bidders in online auctions at eBay and Amazon can submit a reservation price (called a proxy bid) early in the auction, and if this bid is highest then this bidder wins the auction and pays only the minimum bid increment above the second-highest submitted price. This institution shares a number of incentive features of theoretical second price auctions, although as currently implemented submitting one's reservation price is generally not a dominant strategy (Roth and Ockenfels, 2002). But the adoption of true sealed-bid second price auctions may grow over time, particularly for intermediate goods and in procurement ("business-to-business") transactions. As we illustrate in Section 3, however, under some information conditions the second price auction for a single indivisible good has "bad" Nash equilibrium outcomes in the sense that the agent with the highest value does not receive the good. This suggests that proponents of second price auctions may want to be more cautious when proposing them for online markets or to elicit valuations for non-market goods.

The remainder of the paper is organized as follows. Section 2 presents a brief review of the laboratory evidence on strategy-proof mechanisms. Section 3 gives examples of two well-known strategy-proof mechanisms that have a continuum of Nash equilibria, including equilibria other than the dominant strategy equilibrium that theorists usually focus on. We characterize secure implementability in Section 4 for the case of two agents and quasi-linear preferences that is relevant for our experiment (Saijo et al. (2003) presents results for more general conditions). Section 5 describes the experimental environment and Section 6 contains the experimental results. Section 7 provides concluding remarks.

2. Experimental Results on Strategy-Proof Mechanisms

Until recently, most of the experimental studies of strategy-proof mechanisms have considered the second price auction (Vickrey, 1961). For example, Coppinger, Smith and Titus (1980) studied the relationship between Dutch, English, first price sealed-bid and second price sealed-bid auctions. Bidders in both the English and the second price auction have a dominant strategy to fully reveal their resale value in their bid (or reveal their value in their "drop-out price" in the case of the English auction). Bidders in Coppinger et al.'s (oral) English auctions typically dropped out of the bidding when predicted, so prices corresponded to the equilibrium prediction—the second-highest bidders' resale value. Similarly, Kagel, Harstad and Levin (1987) show that bidders in English (clock) auctions lock on to the dominant strategy of bidding equal to value after a few periods of initially overbidding.

Bidders in Coppinger et al.'s second price auctions were prohibited from bidding above their resale value. Kagel and Levin (1993) find, however, that 58 to 67 percent of second price auction bids are greater than resale value, which they attribute to (1) the equilibrium bidding strategy being less transparent than in the English auction and (2) learning feedback to discourage overbidding is weak under sealed-bid procedures because typically the overbidding is not "punished" with losses. Harstad (2000) also documents rather severe overbidding in second price auctions that does not decline over time but that may be less pronounced when subjects first obtain experience in English auctions. Garratt, Walker and Wooders (2002) show that bidders who are highly experienced in online auctions are no more likely to overbid than to underbid, but as with inexperienced bidders only very few (roughly 20 percent) of bids are approximately equal to value. Most bids in the Garratt et al. study vary considerably from the bidders' true values, and consequently less than one half of the auctions result in efficient allocations. Overall the data clearly indicate that subjects do not play their dominant strategy, and in all cases the evidence suggests that bidding equal to value is significantly more common in English than in second price auctions.

While the transparency, experience and feedback explanations for the lower frequency of dominant strategy play in the second price auction are all plausible, we propose a complementary explanation. In English auctions with a stage-game structure, the (sub-game perfect) Nash equilibrium outcome coincides with the dominant strategy equilibrium outcome in which bids fully reveal values. But in second price sealed-bid auctions with a one-shot game structure, Nash equilibria that do not coincide with the dominant strategy equilibrium exist and involve overbidding and underbidding. For example, suppose bidder 1 has a value of $555 and bidder 2 has a value of $550, and that these values are common knowledge. It is a Nash equilibrium for bidder 1 to bid $540 and bidder 2 to bid $560, resulting in the inefficient allocation of the object to bidder 2. Kagel and Levin (1993) and others have noted that overbidding is not discouraged because bidders can bid above values and not lose money. It is precisely this feature of the second price auction institution that causes "bad" Nash equilibria to exist.

More recent experiments have studied the pivotal mechanism, which is a strategy-proof social choice mechanism that is strategically equivalent to the second price auction.[2,3] In this mechanism an agent pays the amount needed to implement his preferred outcome only if his report is pivotal and changes the chosen outcome. These studies have also documented that subjects frequently do not play dominant strategies. Attiyeh, Franciosi and Isaac (2000) find that

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[2] Another truth-telling mechanism that has been widely employed in experiments is the Becker-DeGroot-Marshak (BDM) mechanism. In this mechanism the subject states a maximum buying price or minimum selling price, but the actual buying or selling price is determined by a randomizing device and the transaction is carried out if it is acceptable giving the subject's reported maximum or minimum. This mechanism is not a game so it is not directly relevant for our study.

[3] We do not review here other social choice mechanism experiments like the serial cost sharing mechanism because the researchers have implemented those mechanisms in environments where the Nash equilibria are not in dominant strategies (e.g., Chen, 2003; Dorsey and Razzolini, 1999).

less than 10 percent of the bids reveal the subjects' true value for the public good, in a setting where the experimenter explained the mapping of bids to outcomes (and required taxes for the pivotal players) for five- and ten-person groups. Part of the poor performance of this mechanism might be due to subject confusion and the complexity of the pivotal mechanism. Kawagoe and Mori (2001) provide support for this interpretation, using a controlled experiment that manipulates the complexity across treatments. They also find that only a small number of bids (less than 20 percent) reveal true values when the context and complexity of the pivotal mechanism is part of the experiment; but when the mechanism is simplified and represented by (detailed) payoff tables then nearly half of the subjects play the dominant strategy.[4] In the present experiment we also study the pivotal mechanism with detailed payoff tables to help simplify the decision environment and promote equilibrium bids. Although confusion and complexity may be partly responsible for the poor performance of some mechanisms, we will try to go beyond this explanation. We will argue that the existence of multiple Nash equilibria allows us to predict *how* behavior will deviate from the dominant strategy equilibrium. That is, we will identify systematic rather than random deviations from the dominant strategy equilibrium in non-secure mechanisms.

3. Why do Strategy-Proof Mechanisms Not Work Well?

Many of the strategy-proof mechanisms that have been studied in the literature have Nash equilibrium outcomes that do not coincide with the dominant strategy equilibrium

[4] Charness, Frechette and Kagel (2004) also provide experimental evidence that the use of payoff tables significantly affects behavior, but in a very different economic environment that features sequential decisions and the potential for reciprocal exchanges. One interpretation they offer for this finding is that the payoff tables clarify the monetary and distributional considerations of alternative actions.

outcome. These Nash equilibrium outcomes are frequently socially undesirable. This is illustrated be the following two well-known strategy-proof mechanisms.[5]

Example 1: The pivotal mechanism (Clarke, 1971).

Consider the pivotal mechanism, which is one of the two mechanisms studied in the present experiment, for a two-agent economy with a binary non-excludable public good and quasi-linear preferences. Two agents 1 and 2 are facing a decision whether or not they should produce the public good. Agent *i*'s true net value of the public good is v_i if it is produced, and her true net value is 0 otherwise ($i = 1,2$). In the pivotal mechanism, each agent *i* reports his net value $\tilde{v}_i$ and the outcome is determined as follows:

Rule 1: if $\tilde{v}_1 + \tilde{v}_2 \geq 0,$ then the public good is produced, and if not, then it is not produced; and

Rule 2: each agent *i* must pay the pivotal tax t_i

$$
\begin{aligned}
t_i &= -\tilde{v}_j && \text{if } \tilde{v}_j < 0 \text{ and } \tilde{v}_1 + \tilde{v}_2 \geq 0 \\
&= \tilde{v}_j && \text{if } \tilde{v}_j > 0 \text{ and } \tilde{v}_1 + \tilde{v}_2 < 0 \\
&= 0 && \text{otherwise}
\end{aligned}
$$

where $j \neq i$.

That is, an agent pays the amount needed to implement his preferred outcome if his report is pivotal and changes the chosen outcome.

First, let $(v_1, v_2) = (5, -4)$ be the true net value vector. Figure 1-(a) shows that the set of Nash equilibria is approximately a half of the two dimensional area. Notice that the public good should be produced because the sum of the net values of the public good is positive. The upper-right part of the set of Nash equilibria is "good" in the sense that constructing the public good is recommended. However, the lower-left part of the set of Nash equilibria is "bad" in the sense that producing the public good is not recommended.

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[5] Other examples of strategy-proof mechanisms where "bad" Nash equilibria lead to inefficient outcomes include the Condorcet winner (median voter) scheme with single-peaked preferences, the uniform allocation rule (a fixed-price trading rule) with single-peaked preferences, and the top trading cycle rule in a market with indivisible goods.

Second, let $(v_1, v_2) = (5,5)$ be the true net value vector. In this case, both agents want to construct the public good. However, Figure 1-(b) shows the area of bad Nash equilibria is still large. Saijo et al. (2003) generalize this negative result to the case with any arbitrary finite numbers of public projects and agents.

Link to Figure 1

Example 2: The second price auction (Vickrey, 1961).

Consider a two-agent model with an indivisible good. Agent *i*'s true value of the good is $v_i \geq 0$ if she receives it, and her true value is 0 otherwise ($i = 1,2$). Let $(\tilde{v}_1, \tilde{v}_2)$ be a reported value vector. The second price auction consists of two rules:

Rule 1: if $\tilde{v}_i > \tilde{v}_j$, then agent *i* receives the good and pays $\tilde{v}_j$ ($i, j = 1,2; i \neq j$); and
Rule 2: if $\tilde{v}_1 = \tilde{v}_2$, then agent 1 receives the good and pays $\tilde{v}_2$.

Let $(v_1, v_2) = (7, 5)$ be the true value vector. Figure 2 shows that the set of Nash equilibria is quite large. Notice that agent 1 should receive the good because her value is greater than agent 2's. The lower-right part of the set of Nash equilibria is "good" in the sense that agent 1 receives the good. However, the upper-left part of the set of Nash equilibria involving overbidding is "bad" in the sense that agent 2 receives the good.

Link to Figure 2

We do not dispute the possibility that, in practice, some confused bidders may fail to recognize their dominant strategy because it is not transparent (e.g., Harstad, 2000). However, our key observation is that the Nash equilibrium areas shown in Figure 2 indicate the possibility of systematic rather than random deviations from the dominant strategy equilibrium.

4. Secure Implementation in Public Good Economies

The previous section presented two examples drawn from many strategy-proof mechanisms that may have "bad" Nash equilibria. They implement the social choice function (SCF) in dominant strategies, but not in Nash equilibria. Saijo et al. (2003) introduce a new concept of implementation, called secure implementation, which does not share this shortcoming.

We introduce notation and definitions here to describe the concept of secure implementation in the context of public good economies with two agents and quasi-linear preferences. Denote the set of feasible allocations by

$$A = \{(y, t_1, t_2) | y \in Y, t_1, t_2 \in \Re\},$$

where $Y \subseteq \Re$ is a production possibility set, $y \in Y$ is an output level of a public good, and t_i is a transfer of a private good to agent *i*. For simplicity, we assume that there is no cost involved in producing *y*. Each agent *i*'s utility function, $u_i : A \to \Re$, is selfish and quasi-linear:

$$u_i(y, t_1, t_2) = u_i(y, t_i) = v_i(y) + t_i, \quad i = 1,2.$$

The class of valuation functions, $v_i : Y \to \Re$, admissible for agent *i* is denoted by V_i. Following Holmström (1979), suppose V_i is smoothly connected. Let $v = (v_1, v_2) \in V \equiv V_1 \times V_2$ be a valuation profile.

A *social choice function* (SCF) is a function $f: V \to A$ that associates with every list of valuation functions, $v \in V$, a unique feasible allocation $f(v)$ in A. The allocation $f(v)$ is said to be *f-optimal for v.*

A *mechanism* (or *game form*) is a function g: $S_1 \times S_2 \to A$ that assigns a unique element of A to every $(s_1, s_2) \in S_1 \times S_2$, where S_i is the *strategy space of agent i.* For a strategy profile $s = (s_1, s_2) \in S_1 \times S_2$, the outcome of g for the profile s is denoted by $g(s) = (y^g(s), t^g(s))$, where $y^g(s)$ is the level of the public good and $t^g(s) = (t_1^g(s), t_2^g(s))$ is the transfer vector.

The strategy profile $s = (s_1, s_2) \in S_1 \times S_2$ is a *Nash equilibrium of g at* $v \in V$ if

$$v_1(y^g(s_1, s_2)) + t_1^g(s_1, s_2) \geq v_1(y^g(s_1', s_2)) + t_1^g(s_1', s_2) \text{ for all } s_1' \in S_1, \text{ and}$$

$$v_2(y^g(s_1,s_2)) + t_2^g(s_1,s_2) \geq v_2(y^g(s_1,s_2')) + t_2^g(s_1,s_2') \text{ for all } s_2' \in S_2.$$

Let $N_A^g(v)$ be the set of Nash equilibrium allocations of g at v, i.e., $N_A^g(v) \equiv \{((y,t_1,t_2) \in A \mid$ there exists a Nash equilibrium at v, $s \in S$, such that $g(s) = (y,t_1,t_2)\}$.

The strategy profile $s = (s_1,s_2) \in S_1 \times S_2$ is a *dominant strategy equilibrium of g at* $v \in V$ if

$$v_1(y^g(s_1,s_2')) + t_1^g(s_1,s_2') \geq v_1(y^g(s_1',s_2')) + t_1^g(s_1',s_2') \text{ for all } s_1' \in S_1 \text{ and } s_2' \in S_2; \text{ and}$$

$$v_2(y^g(s_1',s_2)) + t_2^g(s_1',s_2) \geq v_2(y^g(s_1',s_2')) + t_2^g(s_1',s_2') \text{ for all } s_1' \in S_1 \text{ and } s_2' \in S_2.$$

Let $D_A^g(v)$ be the set of dominant strategy equilibrium allocations of g at v, i.e., $D_A^g(v) \equiv \{((y,t_1,t_2) \in A \mid$ there exists a dominant strategy equilibrium at v, $s \in S$, such that $g(s) = (y,t_1,t_2)\}$.

Definition 1. The mechanism g *implements the SCF f in dominant strategy equilibria* if for all $v \in V$, $f(v) = D_A^g(v)$. f is *implementable in dominant strategy equilibria* if there exists a mechanism which implements f in dominant strategy equilibria.

Definition 2. The mechanism g *securely implements the SCF f* if for all $v \in V$, $f(v) = D_A^g(u) = N_A^g(u)$.[6] The SCF f is *securely implementable* if there exists a mechanism which securely implements f.

Dominant strategy implementation requires that for every possible preference profile, the dominant strategy equilibrium outcome coincides with the f-optimal outcome. In addition to this requirement, secure implementation demands that there be no Nash equilibrium outcome other than the dominant strategy equilibrium outcome.

Saijo et al. (2003) characterize the class of securely implementable SCF's using two conditions. The first condition is strategy-proofness. The allocation recommended by the SCF f

[6] Secure implementation is identical to *double* implementation in dominant strategy equilibria and Nash equilibria. It was Maskin (1979) who first introduced the concept of double implementation. See also Yamato (1993).

for the profile $v=(v_1,v_2)$ is denoted by $f(v)=(y^f(v),t^f(v))$, where $y^f(v)$ is the level of the public good and $t^f(v)=(t_1^f(v),t_2^f(v))$ is the transfer vector.

Definition 3. The SCF *f* is *strategy-proof* if

$v_1(y^f(v_1,\tilde{v}_2))+t_1^f(v_1,\tilde{v}_2)\geq v_1(y^f(\tilde{v}_1,\tilde{v}_2))+t_1^f(\tilde{v}_1,\tilde{v}_2)$ for all $\tilde{v}_1\in V_1$ and $\tilde{v}_2\in V_2$; and

$v_2(y^f(\tilde{v}_1,v_2))+t_2^f(\tilde{v}_1,v_2)\geq v_2(y^f(\tilde{v}_1,\tilde{v}_2))+t_2^f(\tilde{v}_1,\tilde{v}_2)$ for all $\tilde{v}_1\in V_1$ and $\tilde{v}_2\in V_2$.

By the Revelation Principle (Gibbard, 1973), strategy-proofness is necessary for dominant strategy implementation, and therefore also for secure implementation. However, the following additional condition, called the *rectangular property*, is necessary for secure implementation.

Definition 4. The SCF *f* satisfies the *rectangular property* if for all $v,\tilde{v}\in V$, if

$v_1(y^f(v_1,\tilde{v}_2))+t_1^f(v_1,\tilde{v}_2)=v_1(y^f(\tilde{v}_1,\tilde{v}_2))+t_1^f(\tilde{v}_1,\tilde{v}_2)$ and

$v_2(y^f(\tilde{v}_1,v_2))+t_1^f(\tilde{v}_1,v_2)=v_2(y^f(\tilde{v}_1,\tilde{v}_2))+t_2^f(\tilde{v}_1,\tilde{v}_2)$,

then $f(v_1,v_2)=f(\tilde{v}_1,\tilde{v}_2)$.

Saijo et al. (2003) show that the rectangular property is necessary and sufficient for sure implementation:[7]

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[7] To see why the rectangular property is necessary for secure implementation intuitively, suppose that the direct revelation mechanism $g=f$ securely implements the SCF *f*. Let $n=2$ and (v_1,v_2) be the true preference profile. Suppose $u_1(f(v_1,\tilde{v}_2))=u_1(f(\tilde{v}_1,\tilde{v}_2))$, i.e.,

(*) $v_1(y^f(v_1,\tilde{v}_2))+t_1^f(v_1,\tilde{v}_2)=v_1(y^f(\tilde{v}_1,\tilde{v}_2))+t_1^f(\tilde{v}_1,\tilde{v}_2)$.

In other words, agent 1 is indifferent between reporting the true preference v_1 and reporting another preference $\tilde{v}_1$ when agent 2's report is $\tilde{v}_2$. Since reporting v_1 is a dominant strategy by strategy-proofness, it follows from (*) that $v_1(y^f(\tilde{v}_1,\tilde{v}_2))+t_1^f(\tilde{v}_1,\tilde{v}_2)=v_1(y^f(v_1,\tilde{v}_2))+t_1^f(v_1,\tilde{v}_2)\geq v_1(y^f(v_1',\tilde{v}_2))+t_1^f(v_1',\tilde{v}_2)$ for all $v_1'\in V_1$,

that is, reporting $\tilde{v}_1$ is one of agent 1's best responses when agent 2 reports $\tilde{v}_2$.

Next suppose that $u_2(f(\tilde{v}_1,v_2))=u_2(f(\tilde{v}_1,\tilde{v}_2))$, i.e.,

(**) $v_2(y^f(\tilde{v}_1,v_2))+t_1^f(\tilde{v}_1,v_2)=v_2(y^f(\tilde{v}_1,\tilde{v}_2))+t_2^f(\tilde{v}_1,\tilde{v}_2)$.

By using an argument similar to the above, it is easy to see that $v_2(y^f(\tilde{v}_1,\tilde{v}_2))+t_2^f(\tilde{v}_1,\tilde{v}_2)=v_2(y^f(\tilde{v}_1,v_2))+t_2^f(\tilde{v}_1,v_2)$ $\geq v_2(y^f(\tilde{v}_1,v_2'))+t_1^f(\tilde{v}_1,v_2')$ for all $v_2'\in V_2$,

Theorem 1. *An SCF is securely implementable if and only if it satisfies strategy-proofness and the rectangular property.*

Let us consider an SCF *f* satisfying the efficiency condition on the public good provision:

(4.1) $y^f(v_1,v_2) \in \arg\max_{y \in Y}[v_1(y)+v_2(y)]$ for all $(v_1,v_2) \in V$.

The following result is well known:

Proposition 1 (*Clarke, 1971; Groves, 1973; Green and Laffont, 1979; Holmström, 1979*). *An SCF f satisfying* (4.1) *is implementable in dominant strategy equilibria if and only if f satisfies*

(4.2) $t_1^f(v_1,v_2) = v_2(y^f(v_1,v_2)) + h_1(v_2)$, $t_2^f(v_1,v_2) = v_1(y^f(v_1,v_2)) + h_2(v_1)$ $\forall (v_1,v_2) \in V$,

where h_i *is some arbitrary function which does not depend on* v_i.

A direct revelation mechanism satisfying (4.1) and (4.2) is called a *Groves-Clarke mechanism*. Proposition 1 says that we can focus on the class of Groves-Clarke mechanisms for implementation of an SCF satisfying (4.1) in dominant strategy equilibria. In general, Groves-Clarke mechanisms do not achieve secure implementation. However, if *V* contains only single-peaked preferences and *y* is a continuous variable, then SCF's satisfying (4.1) are securely implementable by Groves-Clarke mechanisms. Suppose that $Y = \Re$ and for $i = 1,2$,

$$V_i = \{v_i : \Re \to \Re \mid v_i(y) = -(y-r_i)^2, r_i \in \Re\},$$

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that is, reporting $\tilde{v}_2$ is one of agent 2's best responses when agent 1 reports $\tilde{v}_1$. Therefore, $f(\tilde{v}_1,\tilde{v}_2) = (y^f(\tilde{v}_1,\tilde{v}_2), t^f(\tilde{v}_1,\tilde{v}_2))$ is the Nash equilibrium outcome. Moreover, $f(v_1,v_2) = (y^f(v_1,v_2), t^f(v_1,v_2))$ is the dominant strategy outcome, and by secure implementability, the dominant strategy outcome coincides with the Nash equilibrium outcome. Accordingly we conclude that $f(v_1,v_2) = f(\tilde{v}_1,\tilde{v}_2)$ if (*) and (**) hold.

where r_i is agent i's most preferred level of the public good. We can represent these single-peaked preferences by the r_i instead of the v_i. The optimal output level of the public good satisfying (4.1) is given by $y(r_1, r_2) = (r_1+r_2)/2$. In this case any SCF f meeting (4.1) and (4.2) satisfies the rectangular property and is therefore securely implementable (Saijo et al., 2003).

Consider an example that will be used in our experimental design later, in which $h_i = 0$. Then,

$$u_1(\tilde{r}_1, \tilde{r}_2) = v_1(y(\tilde{r}_1, \tilde{r}_2)) + t_1(\tilde{r}_1, \tilde{r}_2) = -((\tilde{r}_1 + \tilde{r}_2)/2 - r_1)^2 - ((\tilde{r}_1 + \tilde{r}_2)/2 - \tilde{r}_2)^2$$
$$= -\left\{(\tilde{r}_1 - r_1)^2 + (\tilde{r}_2 - r_1)^2\right\}/2$$

where r_1 is player 1's true peak and $(\tilde{r}_1, \tilde{r}_2)$ is a vector of reported peaks. Clearly agent 1's payoff is maximized at r_1. Since the payoff function is quadratic, no other maximizers exist. Furthermore, the payoff is maximized at r_1 regardless of $\tilde{r}_2$. Figure 3 shows agent 1's payoff when $r_1 = 12$. If $\tilde{r}_2 = 4$, the maximizer is *a*, and if $\tilde{r}_2 = 12$, it is *b*. Both are maximized at $r_1 = 12$. Therefore, the best response curve is a line parallel to the $\tilde{r}_2$ axis. This indicates that truth-telling is *the* dominant strategy. In fact, it is *strictly* dominant. However, this is true only as long as the public goods level is continuously variable. In our experiment, we will discretize the public goods level and the payoff functions, and truth-telling will not be strictly dominant even though preferences are single-peaked.[8] However, with single-peaked preferences implementation will still be *secure*, because there will be a unique dominant strategy equilibrium which is also a unique Nash equilibrium (Treatment S). When preferences are not single peaked, there will be multiple Nash equilibria and implementation is not secure (Treatment P).

[8] In general, with a discrete public good, single-peaked preferences will not assure the existence of a strictly dominant strategy. However, secure implementation will be assured.

Link to Figure 3
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5. The Experiment

Our experiment studies the pivotal mechanism and a Groves-Clarke mechanism with single-peaked preferences. It consisted of four sessions with 20 subjects each (80 total subjects). We conducted two sessions in Treatment P that corresponded to the pivotal mechanism and two sessions in Treatment S that corresponded to a Groves mechanism with single-peaked preferences. All sessions employed payoff tables to simplify the presentation of the two mechanisms to subjects. As already noted above in Section 2, previous findings by Kawagoe and Mori (2001) suggest that this reduction in complexity may improve the performance of the mechanisms. We consider the secure mechanisms to be a benchmark, in the sense of having the greatest hope of successful implementation, compared to other social choice mechanisms. In order to evaluate how this benchmark performs under ideal conditions, we decided in this initial experiment to provide favorable, maximally-transparent conditions. The use of payoff tables allows for a comparison of the benchmark (secure) mechanism with the non-secure alternative, holding their degree of transparency constant.

Our experiment provides evidence that the existence of Nash equilibria in weakly dominated strategies can significantly influence the subjects' behavior. We suspect that this will be the case in many environments, including those where the complexity of the environment will lower the performance of any mechanism. This leads us to believe that secure mechanisms will perform better in many different environments. Of course, payoff tables are somewhat unrealistic for potential applications of these mechanisms in the field. We did not evaluate the secure mechanism without payoff tables, so our experiment does not prove that secure mechanisms will be successful in the field. Whether or not mechanisms fail in practical applications may depend on how well understood they are by the participants. As we discuss further in the conclusion, that issue can be addressed in future research.

5.1 Design

We conducted two sessions (one P and one S) at Tokyo Metropolitan University during June of 1998 and two sessions (one P and one S) at Purdue University during February of 2003. Each session took approximately one hour to complete.

Treatment P implements the pivotal mechanism for a two-person group. The net true value vector (v_1, v_2) is equal to $(-6,8)$ if a binary public good is produced and $(v_1, v_2) = (0,0)$ otherwise. The public good should be produced since $v_1 + v_2 \geq 0$. Let the strategy space of type 1 be the set of integers from -22 to 2, and the strategy space of type 2 be the set of integers from -4 to 20. According to the rules of the pivotal mechanism described in Section 3, we can construct the payoff matrices of types 1 and 2.

The payoff tables that we actually distributed to subjects in Treatment P were Tables 1 and 2 whose basic structures were the same as the original payoff tables, modified as follows. First, we changed the names of strategies. Type 1's strategy "-22" was renamed "1", "-21" was renamed "2", and so on. Similarly, type 2's strategy "-4" was renamed "1", "-3" was renamed "2", and so on. Second, we employed a linear transformation of the valuation functions: $14v_1 + 294$ for type 1 and $14v_2 + 182$ for type 2.

Link to Table 1 and 2

Table 3 is a payoff matrix with both players' payoffs displayed: the left-hand number is type 1's payoff and the right-hand number is type 2' payoff in each cell.[9] It also specifies the dominant strategy equilibria and the other Nash equilibria. Type 1's dominant strategies are 16 and 17, and type 2's dominant strategies are 12 and 13. The two dominant strategies are equivalent for each type in the sense that her payoffs are identical for every possible strategy played by the other type; and although payoffs of the other type could be different depending

[9] We did not provide this table to any subject. Type 1 subjects used table 1 only and type 2 subjects employed table 2 only.

on her own choices, she did not know the other's payoffs. In this sense, there is an *essentially* unique dominant strategy in Treatment P.

Let us look at the best response structure of each type given a strategy of the other type in Table 3. For example, (i) when type 2 chooses 8, the payoffs of type 1 are "high" (252) if she chooses less than or equal to 19, and her payoffs are "low" (210) otherwise; (ii) when type 2 chooses 11, the payoffs of type 1 are the same (210) for all her strategies; and (iii) when type 2 chooses 15, the payoffs of type 1 are "low" (154) if she chooses less than or equal to 12, and her payoffs are "high" (210) otherwise. That is, given each strategy of the other type, either a) the payoffs of each type are divided into just two "tiers": a "high" payoff obtained by choosing "good" strategies and a "low" payoff by "bad" strategies; or b) the payoffs are the same for all strategies. Because the best response function of each type has such a "flat" feature, there is a huge set of Nash equilibria in Table 3. The lower-right region of Nash equilibria is "good" in the sense that the public good is produced. The upper-left region of Nash equilibria is "bad" in the sense that the public good is not produced. The number of good Nash equilibria is 162, while the number of bad Nash equilibria is 165. Implementation is clearly not secure.

Link to Table 3

As is well known, the pivotal mechanism sometimes generates a surplus, i.e., the tax revenue exceeds the cost of producing the public good. (In general, no dominant strategy mechanism can both satisfy condition (4.1) and balance the budget). From the point of view of the participants, the budget surplus is wasteful. Suppose type 1 chooses either 8 or 17 and type 2 chooses either 5 or 12. Then the payoff table is given by Table 4. Notice that (17, 12) is a dominant strategy equilibrium and (8, 5) is a bad Nash equilibrium. However, the sum of the players' payoffs is greater under the bad Nash equilibrium than under the dominant strategy equilibrium (476>420). For the original case in which the strategy spaces of both types are the set of 25 integers, see Table 5. It is easy to check that 91% (=10/11) of payoffs in the region of bad Nash equilibria are not Pareto dominated by either of the dominant strategy equilibrium payoffs ((210, 196) or (210, 210)). The corresponding ratio in the region of good Nash equilibria is 92% (=150/163). Moreover, the ratio of Pareto efficient payoffs among bad Nash equilibrium payoffs is 45.5% (=5/11), while the corresponding ratio among good Nash equilibrium payoffs is 27.6% (=45/163).

Link to Tables 4 & 5

However, the pivotal mechanism was designed specifically to implement social decisions that satisfy the efficiency condition (4.1). This condition has played a central role in the literature. The experiments can shed light on whether or not the outcome will in fact be consistent with condition (4.1). If it is not, then the pivotal mechanism does not perform in the way described in the literature on efficient mechanism design, and a new theory may be needed.

Treatment S is the same as Treatment P except for the payoff tables. The payoff tables for Treatment S are based on the following model of a Groves mechanism with single-peaked preferences with two players. Suppose that the true valuation functions of agent types 1 and 2 are respectively $v_1(y) = -(y-12)^2$ and $v_2(y) = -(y-17)^2$, where $y \in \Re_+$ is the level of a public good. Each type reports his most preferred level of the public good called a peak. Given a vector of reported peaks $(\tilde{r}_1, \tilde{r}_2)$, the level of the public good, $y(\tilde{r}_1, \tilde{r}_2)$, and the transfer to type *i*, $t_i(\tilde{r}_1, \tilde{r}_2)$, are determined by a Groves mechanism: $y(\tilde{r}_1, \tilde{r}_2) = (\tilde{r}_1 + \tilde{r}_2)/2$ and $t_i(\tilde{r}_1, \tilde{r}_2) = -((\tilde{r}_1 + \tilde{r}_2)/2 - \tilde{r}_j)^2$, $i, j = 1,2; j \neq i$. The payoff functions are therefore given by

$$v_1(y(\tilde{r}_1, \tilde{r}_2)) + t_1(\tilde{r}_1, \tilde{r}_2) = -((\tilde{r}_1 + \tilde{r}_2)/2 - 12)^2 - ((\tilde{r}_1 + \tilde{r}_2)/2 - \tilde{r}_2)^2 ,$$

$$v_2(y(\tilde{r}_1, \tilde{r}_2)) + t_2(\tilde{r}_1, \tilde{r}_2) = -((\tilde{r}_1 + \tilde{r}_2)/2 - 17)^2 - ((\tilde{r}_1 + \tilde{r}_2)/2 - \tilde{r}_1)^2 .$$

Let the strategy space of each type be the set of integers from 0 to 24. According to the above payoff functions, we can construct the payoff matrices of types 1 and 2.

The payoff tables used in Treatment S were Tables 6 and 7 whose basic structures were the same as those of the original payoff tables, modified as follows. First, we changed the names of strategies: strategy "0" was renamed "1", "1" was renamed "2", and so on. Second, we employed a linear transformation of the payoff functions: $10v_i / 14 + 218.5$ for $i = 1,2$.

Link to Tables 6 and 7

There is a unique dominant strategy in Tables 6 and 7: 13 for Type 1 and 18 for Type 2. However, note that because we discretized the possible levels in the payoff tables and rounded payoffs to the nearest whole number, neither player type has a strictly dominant strategy. Therefore, Treatments S and P cannot be differentiated in terms of strictly dominant strategies. However, only Treatment S involves a secure mechanism in which there is no Nash equilibrium other than the dominant strategy equilibrium.

Let us consider the situation from an "evolutive" perspective. It is easy to check from the payoff tables that in Treatment S, any number less than 12 or greater than 14 is strictly dominated for player 1, while any number less than 17 or greater than 19 is strictly dominated for player 2. Moreover, if player 2 chooses a number between 17 and 19, then player 1's unique best response is 13, while if player 1 chooses a number between 12 and 14 then player 2's unique best response is 18. Therefore, in Treatment S, convergence towards (13, 18) should be fairly rapid. On the other hand, in Treatment P, any learning dynamics with the property that Nash equilibria are rest points can theoretically get "stuck" at a bad Nash equilibrium. In practice, convergence in Treatment P may occur but be very slow, due to the very weak pressure to adopt weakly dominant strategies.

5.2 Procedures

The sessions in Japan and in the United States involved a variety of procedural differences. They were not intended to replicate the same experimental conditions, but instead were useful to evaluate the robustness of our findings to different subject pools and procedures. Most notably, the sessions in Japan were run "by hand" with pen and paper, and the sessions in the U.S. were computerized using zTree (Fischbacher, 1999). If we had observed significant differences across experiment sites, then we would not be able to identify the source of those differences without further experimentation. Fortunately, the data do not indicate any meaningful statistically significant differences across sites within either mechanism treatment.[10]

In the Japan sessions the twenty subjects were seated at desks in a relatively large room and had identification numbers assigned randomly. These ID numbers were not publicly displayed, however, so subjects could not determine who had which number. In the U.S. sessions the twenty subjects were seated at computer stations in the Vernon Smith Experimental Economics Laboratory that were separated with visual partitions. In every period, each of the type 1 subjects was paired with one of the type 2 subjects. The pairings were determined in advance by experimenters so as not to pair the same two subjects more than once ("strangers"). Each subject received written instructions, a record sheet, a payoff table, and (in the Japan sessions only) information transmission sheets. Instructions were also given by tape recorder in Japan and were read aloud by the experimenter in the U.S.[11] Each subject chose her number from an integer between 1 and 25 by looking at her own payoff table only.[12] No subject knew the payoff table of the other type. Moreover, we provided no explanation regarding the rules of the mechanisms or how the payoff tables were constructed.

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[10] A detailed statistical analysis comparing the Japanese and American sessions results is available from the authors upon request.

[11] The experiment instructions are available from the authors upon request.

[12] We required subjects to examine their payoff table for ten minutes before we began the real periods.

After deciding which number she chose, each subject marked the number on an information transmission sheet (Japan) or typed in her number on her computer (U.S.). Experimenters collected these information transmission sheets and then redistributed them to the paired subjects in Japan. The computer network handled the message transmission in the U.S. Each period, subjects in both countries were asked to fill out the reasons why they chose these numbers. After learning the paired subject's choice, subjects calculated their payoffs from the payoff tables (Japan) or verified the computer-calculated payoffs (U.S.). Record sheets were identical (except for the language translation, of course) at the two sites. These steps were repeated for eight periods in Japan and for ten periods in the U.S. Recall that subjects were never paired together for more than one period.

In the Japan sessions the mean payoff per subject was 1677 yen in Treatment S and it was 1669 yen in Treatment P. In the U.S. sessions the mean payoff per subject was $21.04 in Treatment S and it was $20.35 in Treatment P.

Even though each subject can see only her own payoff table, the repeated play allows learning to take place. A Nash equilibrium can be interpreted as a rest point of the dynamic learning process (Hurwicz, 1972; Smith, 2002), which is one justification for our interest in secure implementation. [13]

6. Results

6.1 Treatment P

Since each period had 20 pairs of players and each session had 8 or 10 periods, we have 180 pairs of data. Denote each pair by (x_1, x_2) where x_i is a number chosen by a subject of

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[13] The theoretical prediction can be interesting even in a one-shot game. In fact, another justification for secure implementation is that, for any possible prior beliefs about types that the players could have, secure mechanisms have the property that any Bayesian Nash equilibrium outcome is socially optimal. We thank an anonymous referee for prompting us to think about these issues.

type i, i = 1, 2. Figure 4 shows the frequency distribution of all data in Treatment P. The maximum frequency pair was (16, 12) with 34 pairs, the second was (16, 13) with 27 pairs, the third was (17, 13) with 19 pairs, and the fourth was (17, 12) with 10 pairs. The total frequency of the four dominant strategy equilibria (16,12), (16,13), (17,12), and (17,13) was 90—exactly one-half of the outcomes.[14] Sixty-one other outcomes were Nash equilibria other than dominant strategy equilibria. The total frequency of Nash equilibria including dominant strategy equilibria was 151. Although nearly half (298/621) of the possible strategy pairs shown in Table 3 that are not dominant strategy equilibrium outcomes are not Nash equilibria, only about one-third (29/90) of the observed non-dominant-strategy outcomes were not Nash equilibria. This suggests that deviations from the dominant strategy equilibria are not random, but are instead more likely to correspond to Nash equilibria. The frequency of bad outcomes was 30.[15] Only one pair in one period played a bad Nash equilibrium. All other Nash equilibrium outcomes were good. Why were almost all Nash equilibria good? To see the reason, suppose that a type 1 subject succeeds in discovering a dominant strategy, say 16, but a type 2 subject fails to find a dominant strategy. Even then a good Nash equilibrium is achieved as long as the type 2 subject chooses a best response to the type 1's strategy (her best response to 16 is to choose an integer more than or equal to 12). It would be much easier to find a best response to a given strategy than a dominant strategy. Therefore, if at least one of two subjects find a dominant strategy, then the outcome is likely to lie in the region of good Nash equilibria containing dominant

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[14] Notice that the dominant strategy equilibria (16, 12) and (16, 13) are Pareto-dominated by the dominant strategy equilibria (17, 12) and (17, 13). The frequency of Pareto-dominated dominant strategy equilibria (16,12) and (16,13) was 61, while the frequency of the dominant strategy equilibria (17,12) and (17,13) was 29. Seventy-two percent of the dominant strategies played by Type 1 subjects were 16 rather than 17, even though these two strategies provide identical payoffs. The greater frequency of 16 declines in later periods, however, and only in periods 1 and 3 is 16 significantly more frequent than 17 at the 5-percent level (two-tailed) according to a binomial test. Recall that each subject chose her number by looking at her own payoff table only, without knowing the payoff table of the other subject. Therefore, it was not possible for a type 1 subject to know that choosing 16 gives a type 2 subject a worse payoff than choosing 17, that is, choosing 16 leads to Pareto dominated equilibria. We think type 1 subjects merely happened to choose 16 more frequently in this experiment, without realizing that choosing 16 could result in Pareto dominated outcomes.

[15] Because of our linear transformation of payoff functions and renaming of strategies, the areas of good and bad outcomes in Table 3 become as follows: the outcome is good if the sum of two types' numbers is greater than or equal to 28; otherwise, it is bad.

strategy equilibria. Table 8 of overall data frequency shows this happened in Treatment P. Indeed, 88% (=151/171) of type 1 subjects' choices were their best responses when type 2 subjects chose dominant strategies and 97% (=166/171) of type 2 subjects' choices were their best responses when type 1 subjects selected dominant strategies.

Links to Figure 4 AND Table 8

We conducted period by period tests of the hypothesis that the median choice is equal to a dominant strategy (16 or 17 for type 1 and 12 or 13 for type 2). A nonparametric Wilcoxon signed rank test rejects the hypothesis that type 1 subjects' median choice equals the dominant strategy of 17 in five out of ten periods (periods 1, 2, 3, 7 and 8), but this test never rejects the null hypothesis that the median choice corresponds to the dominant strategy of 16 (two-tailed test, five-percent significance level). Similarly, this nonparametric test rejects the hypothesis that type 2 subjects' median choice equals the dominant strategy of 12 in eight out of ten periods (periods 1, 2, 3, 5, 6, 7, 8 and 9), but this test never rejects the null hypothesis that the median choice corresponds to the dominant strategy of 13.[16]

These Treatment P results lead to the following observations:

Observation 1:

(a) The frequency of dominant strategy equilibria was 50% across all periods in Treatment P.

(b) The data do not reject the hypothesis that subjects' median choice is a dominant strategy for either type in any period in Treatment P.

(c) The frequency of Nash equilibria was 84% across all periods in Treatment P. 68% of the observed non-dominant-strategy outcomes were Nash equilibria.

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[16] The key advantage of the Wilcoxon test is that it does not require any assumptions regarding the probability distribution underlying the data. The test does, however, assume that the observations are statistically independent. This assumption is satisfied exactly in period 1, and is satisfied approximately in the later periods because each observation used in each test is generated by a different individual. Subjects in the same session interact in earlier periods, however, which make their later period choices not strictly independent.

(d) The frequency of bad outcomes that did not recommend funding of the public good was 17% across all periods in Treatment P. Almost all (98%) of the observed Nash equilibria that involved dominated strategies were good Nash equilibria that recommended funding of the public good.

6.2 Treatment S

Figure 5 shows the frequency distribution of all data in Treatment S. The maximum frequency pair was the dominant strategy equilibrium (13, 18) with 146 of the 180 outcomes. Pairs played no other single outcome more than 4 times.

Link to Figure 5

We conducted period by period tests of the hypothesis that the median choice equals the dominant strategy (13 for type 1 and 18 for type 2). A Wilcoxon signed rank test never rejects the dominant strategy equilibrium hypothesis for any type in any period.

Summarizing the above results, we have the following:

Observation 2:

(a) The frequency of dominant strategy equilibrium was 81% across all periods in Treatment S.

(b) The data do not reject the hypothesis that subjects' median choice equals the dominant strategy for either type in any period in Treatment S.

6.3 Comparing the Two Mechanisms

Here we compare the frequency that subjects play dominant strategies and that pairs implement dominant strategy equilibria in the two mechanisms. Recall that an advantage of our experimental design is that we can compare these two mechanisms while holding constant their complexity. We did not present to subjects any explanation on the rules of a mechanism, and instead we simply used payoff tables to explain the relationship between choices and outcomes.

This is likely to have reduced the confusion experienced by subjects when deciding upon which strategies to play, although it is unlikely to have eliminated confusion completely.

Figure 6 displays the rates that subjects play dominant strategies separately for all periods. Individuals are more likely to play dominant strategies in Treatment S than in Treatment P according to Fisher's exact test in 7 out of 10 periods (periods 2, 6, 7, 8 and 9 at the 5% significance level, and periods 4 and 5 at the 10% significance level).[17] Notice that differences are not significant in most early periods, suggesting that confusion may have influenced behavior initially while subjects learned how their choices affected their earnings. A more powerful parametric test is possible by pooling the data across periods. Since individual subjects contribute an observation for each period, the multiple observations generated by individuals are not independent and it is appropriate to model the panel nature of the data. We do this with a subject random effect specification for the error term $\varepsilon_{it} = u_i + v_{it}$, where u_i represents the idiosyncratic error for subject i and v_{it} is iid.[18] Column 1 of Table 9 reports a probit model of the likelihood that the subject selects a dominant strategy. The positive and significant dummy variable for the mechanism treatment indicates that subjects are more likely to play a dominant strategy in the secure mechanism.[19]

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[17] As discussed in the previous footnote for the Wilcoxon test, Fisher's exact test also requires statistically-independent observations. This holds strictly only in the first period, since subjects in the same session interact in earlier periods. Our design features multiple periods of decisions, as in the most other experiments, because we are interested in decisions when subjects have some experience in order to test *equilibrium* predictions. This has the drawback of clouding the interpretation of some nonparametric statistical tests due to imperfect statistical independence. But additional parametric tests, such as those shown in Table 9, explicitly accounts for the dependence in the errors and can provide robustness checks on our conclusions.

[18] Session rather than subject random effects provide similar results, also with highly significant estimated mechanism treatment effects (dummy treatment variable estimate = 0.644, p-value < 0.01). We also estimated this probit model with clustering at the session level and obtained a similar treatment dummy estimate (0.643) that is also highly significant (p-value < 0.01). As a further robustness check we also estimated this model with clustering at the subject level and also find a significant treatment effect (p-value < 0.01).

[19] Recall that subjects also indicated the reasons for their choices on their record sheets and in a post-experiment questionnaire. These responses provide an additional (noisy) source of data revealing subjects' motivations. We reviewed their responses and found that more individual subjects provided explanations that were clearly identifiable as dominant strategy arguments (e.g., "This is the highest payoff column no matter what the other person chooses.") in Treatment S (23 individuals) than in Treatment P (13 individuals). This difference is statistically

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Links to Figure 6 AND Table 9

Figure 7 shows that the differences in the individual dominant strategy rates are magnified for the pair rates. Pairs are more likely to play a dominant strategy equilibrium in Treatment S according to Fisher's exact test in 8 out of 10 periods (periods 2, 4, 6, 7, 8 and 9 at the 5% significance level, and periods 3 and 5 at the 10% significance level). Column 2 of Table 9 reports a probit model of the likelihood that pairs play a dominant strategy equilibrium, pooling across periods. A random subject effect specification is not possible since the composition of the individuals in each pair changes each period. But we include a dummy variable for the Purdue sessions to capture any (fixed effect) differences across sessions, and we report robust standard errors that account for clustering at the session level. This accounts directly for the fact that observations are independent across sessions but not within sessions. The mechanism treatment dummy variable is highly significant, indicating the substantially greater frequency of dominant strategy equilibrium play in Treatment S. Recall that neither Treatment S nor Treatment P have strictly dominant strategies, but only Treatment S involves a secure mechanism.

Link to Figure 7

Summarizing the above results, we have the following:

Observation 3:

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significant according to Fisher's exact test (p-value=0.021). Of course, asking for subjects' reasoning could have influenced results, a conjecture that we cannot address with our data because we elicited these responses in all sessions. The only choice made by subjects before articulating their motivation was the period 1 choice, but as already noted we suspect that at least some subjects may have been confused when making their initial decision, and this makes the comparison of period 1 choices with later choices confounded by learning.

(a) Individuals play dominant strategies significantly more frequently in Treatment S than in Treatment P.

(b) Pairs implement dominant strategy equilibria significantly more frequently in Treatment S than in Treatment P.

6.4 Is the Pivotal Mechanism for Nash Implementation?

Figure 7 also illustrates the frequency of Nash equilibrium play at each period for Treatment P. The Nash equilibrium rate increased and became close to one as rounds advanced, while the dominant strategy equilibrium rate was around 50% across all periods in Treatment P. Thus, the concept of Nash equilibrium predicted long-run behavior much better than the concept of dominant strategies. Moreover, almost all Nash equilibria that were played were good, so in Treatment P the pivotal mechanism can be said to have succeeded in Nash implementing the socially efficient outcome.

Our findings contrast with those in Kawagoe and Mori's (2001) experiment on the pivotal mechanism with five agents. They conducted two different treatments, depending on whether or not payoff tables were given to subjects. First, when only the rule of the pivotal mechanism was explained, but no payoff table was used, the rate that individual subjects play dominant strategies was 16% (= 31/200), the frequency of dominant strategy equilibria was 0% (= 0/40), the frequency of Nash equilibria was 63% (=25/40), the frequency of bad outcomes was 45% (=18/40), and 44% (=11/25) of Nash equilibrium outcomes were bad. Therefore, the pivotal mechanism failed to achieve Nash implementation without using any payoff table.

On the other hand, when payoff tables were given to subjects in addition to an explanation of the rule, the individual dominant strategy play rate as well as the frequency of good Nash equilibria increased. The rate that individual subjects play dominant strategies became 47% (= 47/100), although the frequency of dominant strategy equilibria was only 5% (=

1/20). The frequency of Nash equilibria was 65% (=13/20), the frequency of bad outcomes was 10% (=2/20), and all Nash equilibrium outcomes were good, which is similar to our result.

Notice that about two-thirds of the observed non-dominant strategy outcomes were Nash equilibria regardless of whether payoff tables were used. That is, deviations from dominant strategy equilibria tended to correspond to Nash equilibria in Kawagoe and Mori's experiment, too. In itself, this provides some justification for looking at secure mechanisms.

But whether the Nash equilibria that involved dominated strategies resulted in good or bad outcomes seemed to depend on whether or not payoff tables were employed. The reason why all Nash equilibria were good with payoff tables seems to be similar to that why almost all Nash equilibria were good in Treatment P, discussed in Section 6.1. If some, but not necessarily all, subjects succeed in discovering dominant strategies and the others choose best responses, then the outcome is likely to lie in the region of good Nash equilibria containing dominant strategy equilibria. The use of payoff tables would help subjects to find dominant strategies and best responses more easily. Of course further study is needed to investigate how much information on payoff structures is necessary for subjects to discover dominant strategies or play good Nash equilibria in the pivotal mechanism. This is left for future research.

7. Conclusion

Recent experimental and theoretical findings have raised serious questions about the viability of dominant strategy mechanisms. A possible solution is the notion of *secure implementation* introduced in Saijo, Sjöström and Yamato (2003). Motivated by this theoretical concept this paper presents an experimental study of the pivotal mechanism and a Groves-Clarke mechanism with single-peaked preferences. Both mechanisms are strategy-proof. But the pivotal mechanism has Nash equilibria that differ from the dominant strategy equilibria, and players adopted dominant strategies significantly less often in the pivotal mechanism.

The purpose of this paper is a fairly limited one: we wanted to compare the performance of secure and non-secure mechanisms in an idealized laboratory experiment with a high signal-to-noise ratio. Accordingly, we have tried to minimize "noise" due to subject confusion about the payoffs. This is done by describing the payoffs as clearly as possible using payoff tables. In such an idealized environment, we find that replacing a non-secure by a secure mechanism significantly increases the likelihood that the players will use their dominant strategies. Indeed, in the non-secure pivotal mechanism the players failed to use their dominant strategies about half of the time. Deviations from dominant strategies were also systematic rather than random: they corresponded to Nash equilibria. Although almost all Nash equilibria were “good” in our experiment (which used payoff tables only), many Nash equilibria were “bad” in Kawagoe and Mori’s (2001) experiment when no payoff table was employed. The performance of the non-secure mechanism may be unstable, depending on how information on payoff structures is given to subjects. In contrast, we are optimistic about the performance of secure mechanisms, where “bad” Nash equilibria are non-existent.

We believe these findings may have implications for practical applications. Of course, a real world application would typically be "noisier" than our laboratory experiment, so the performance of both secure and non-secure mechanisms could be worse than in our idealized situation. But we this it is unlikely that noise would eliminate all potential problems caused by multiple Nash equilibria. Thus, we conjecture that, whatever the environment, secure mechanisms are likely to do better. In particular, we would not be surprised to find that non-secure mechanisms perform poorly in practice, because the players fail to use their dominant strategies even in our idealized laboratory environment. Therefore, if the non-secure mechanism fails in a practical application, this cannot be simply attributed to confusion due to the presentation of payoffs. Of course, using a secure mechanism in a practical application would not guarantee good absolute performance either (although it would probably do relatively better than a non-secure one). In a real world application, the subjects may become confused about the rules of the game and the payoffs. We leave for the future the task of studying how noise can be minimized in practical applications. But we believe that overly pessimistic conclusions about the future of mechanism design, which some researchers have drawn based on the poor performance of non-secure mechanisms in laboratory experiments, may not be justified at this point. Our experiment suggests that there is no inherent flaw in the game theoretic predictions that would rule out all possible practical applications.[20]

In practical applications, mechanisms should not be too complex, due to the finite information processing capacity of the players. It turns out that requiring secure implementation does not lead to more complex mechanisms: attention can be restricted to revelation mechanisms without loss of generality (Saijo, Sjöström and Yamato, 2003). By Proposition 1, the efficiency condition and strategy-proofness essentially pin down the revelation mechanism in the public goods environment. In order to compare the performance of two efficient strategy-proof revelation mechanisms, one that is secure and one that is not, the environment (specifically, the set of valuation functions) has to vary across treatments (as in Treatment P versus Treatment S). In our experiment, we do not think this matters too much, because the presentation of the payoff tables was similar in the two treatments. Still, in other situations it may be possible to make interesting comparisons of the performance of secure versus non-secure mechanisms *in the same environment*. This is left for future experiments.

Recently, Chen (2005) and Chen and Gazzale (2004) study whether mechanisms based on supermodularity conditions achieve convergence to Nash equilibria through learning. They find supermodular mechanisms converge significantly better than non-supermodular mechanisms in experiments. It would be interesting to investigate the role of supermodularity in accomplishing convergence to dominant strategy equilibria. It is easy to check that

[20] In contrast, if the secure mechanism had performed poorly in our experiment, this would have suggested that, no matter how well the mechanism could be explained to the participants, practical applications of mechanism design would have little hope of success.

Treatment S is both secure and supermodular, while Treatment P is neither secure nor supermodular. Therefore, it is not clear from the current analysis which condition, security or supermodularity, is more important for dominant strategy play. In Cason, Saijo, Wakayama, and Yamato (2004), however, we observe that individuals' rate of dominant strategy play is high in a secure but non-supermodular mechanism experiment. These initial results suggest that supermodularity may not be necessary in order to generate *dominant* strategy play.

The points we have raised concerning bad Nash equilibria apply equally well to bad Bayesian-Nash equilibria in an incomplete information setting. If a social choice function is securely implemented, then it can be shown that all Bayesian-Nash equilibria are "good", no matter what the prior distribution over types may be. We believe that this point is relevant for practical mechanism design. For example, for certain prior distributions, the second-price (Vickrey) auction has "bad" Bayesian-Nash equilibria that yield different outcomes than the (efficient) dominant strategy, truth-telling equilibrium. Most proponents of this auction institution have not acknowledged this shortcoming. Before making predictions regarding how this institution might perform in the field, it would be valuable to conduct laboratory experiments with the information conditions that admit these other inefficient Bayesian-Nash equilibria. We suspect that the second price auction and many other strategy-proof mechanisms may not function as elegantly as designed on the theorist's blackboard.

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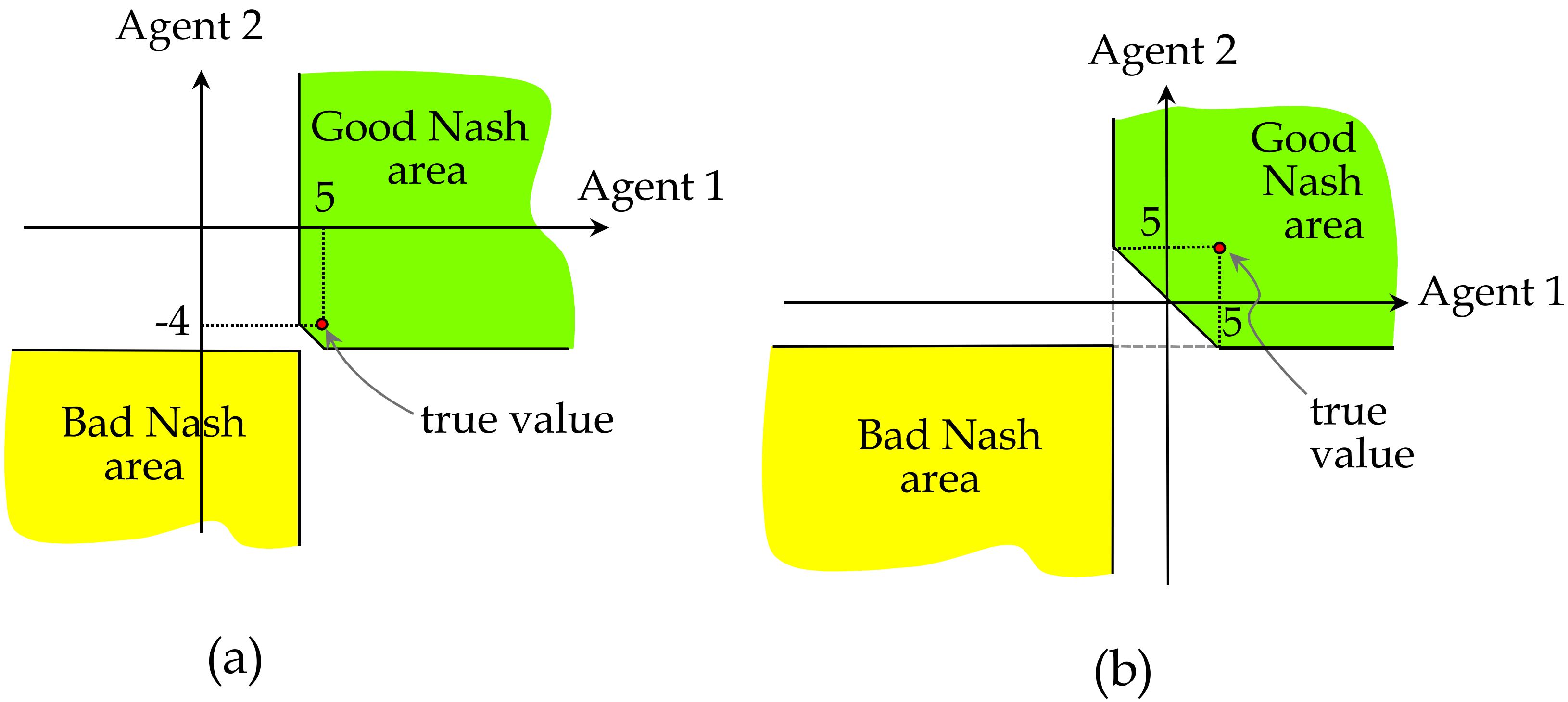

Figure 1: Equilibria of the Pivotal Mechanism

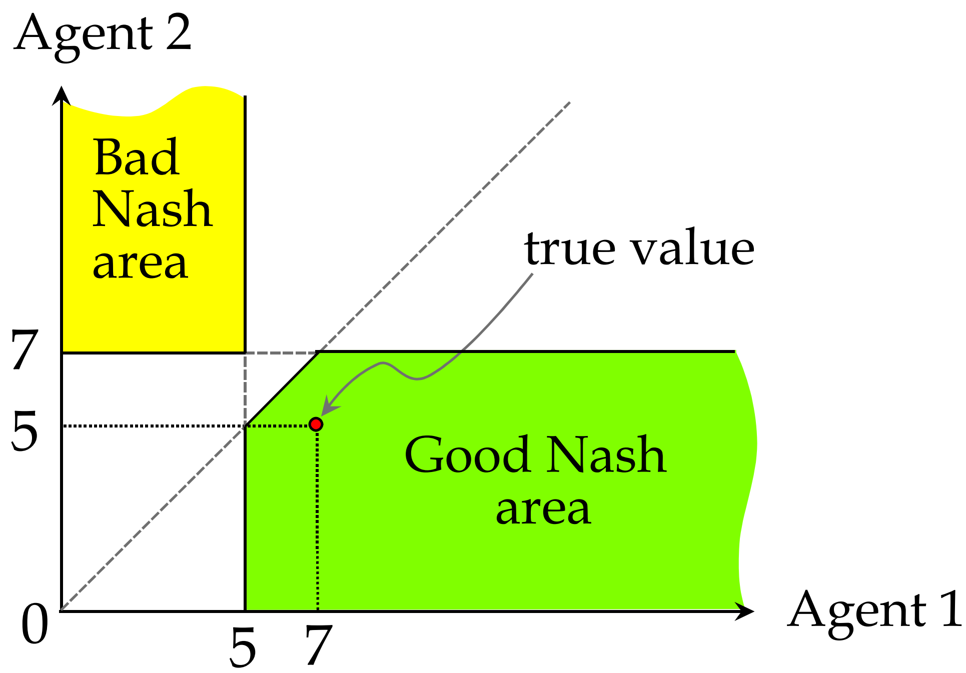

Figure 2: Equilibria of the Second Price Auction

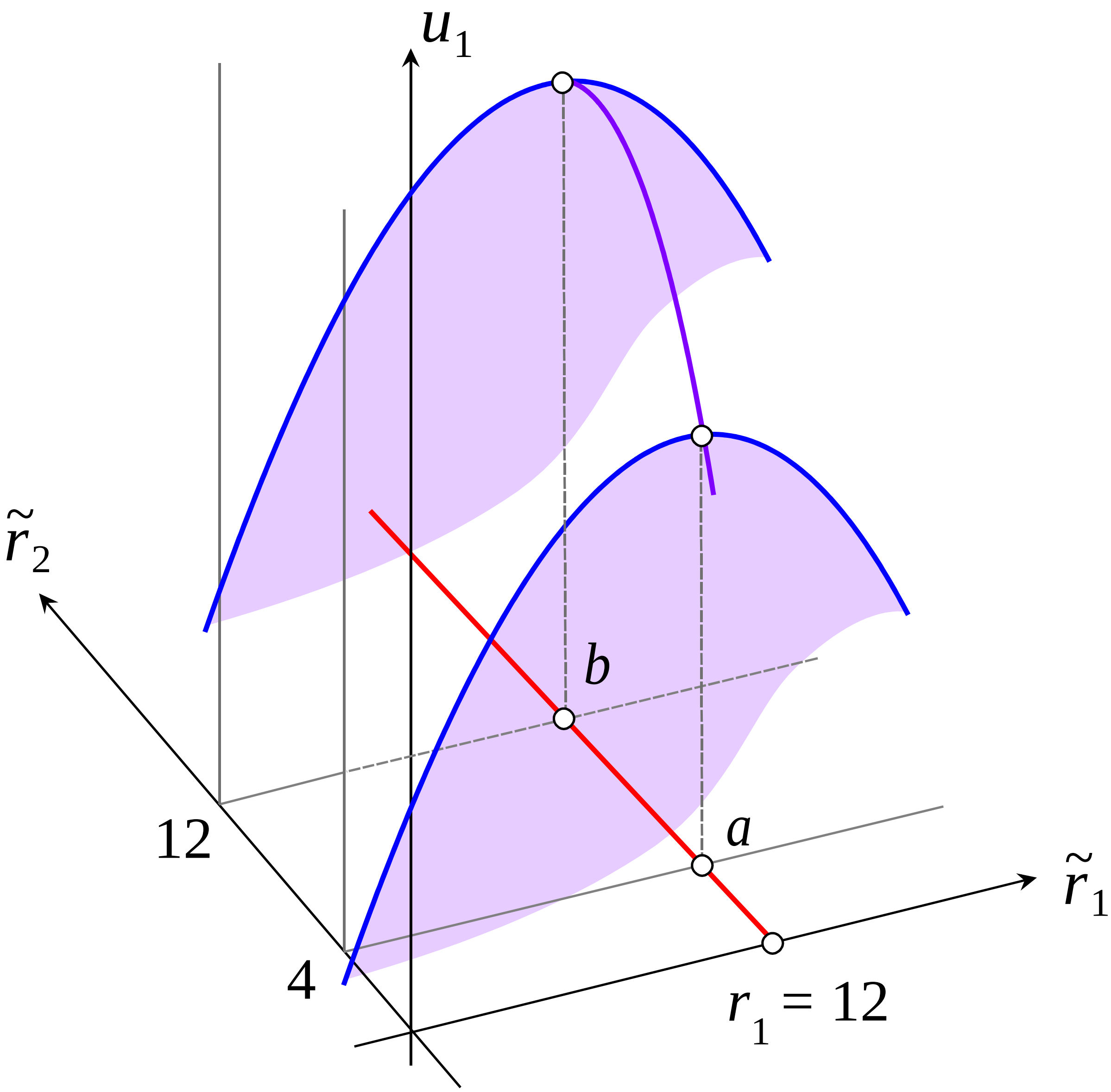

Figure 3: Payoff function of a Groves Mechanism
with Single-Peaked Preferences

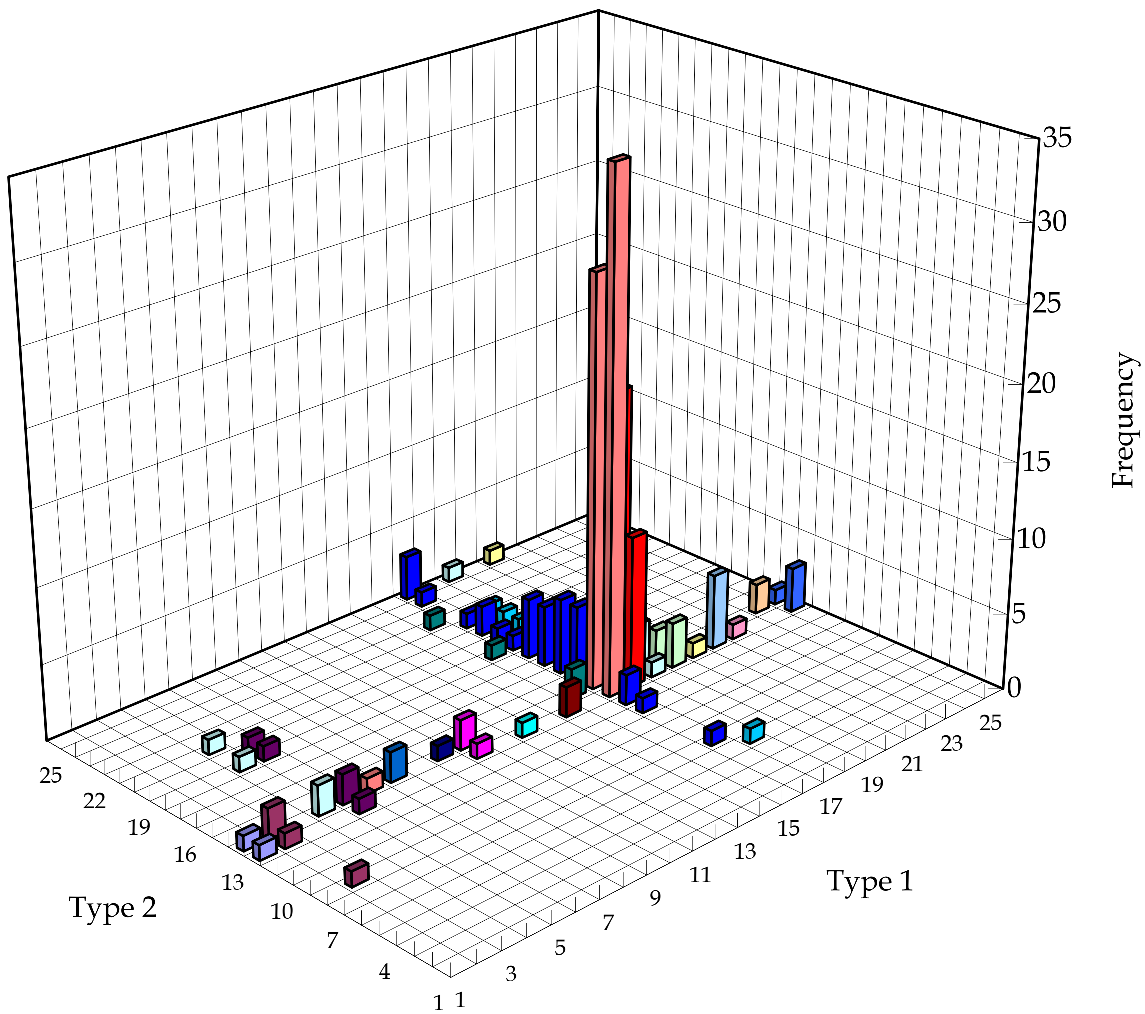

Figure 4: Treatment P -- All Pairs Choices

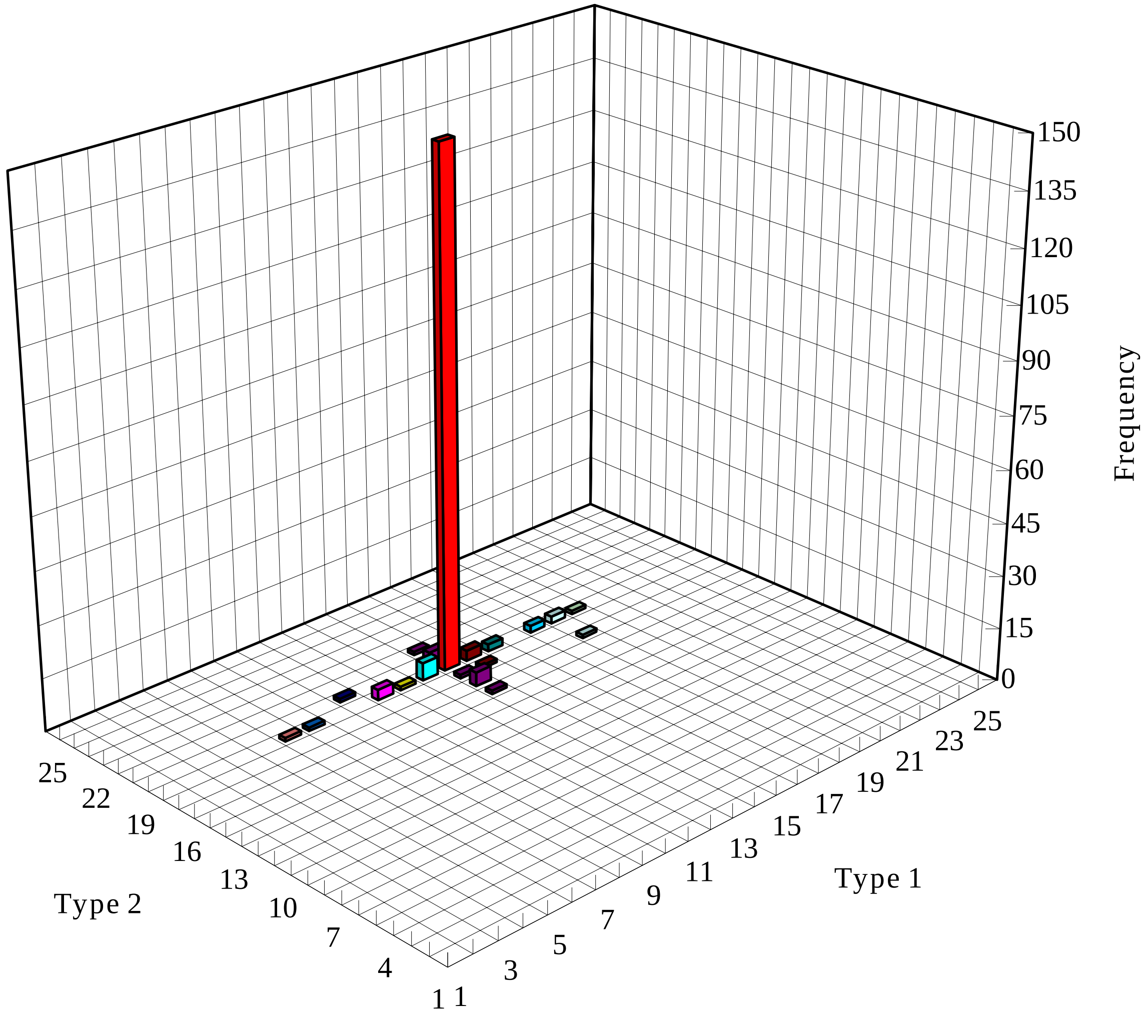

Figure 5: Treatment S -- All Pairs Choices

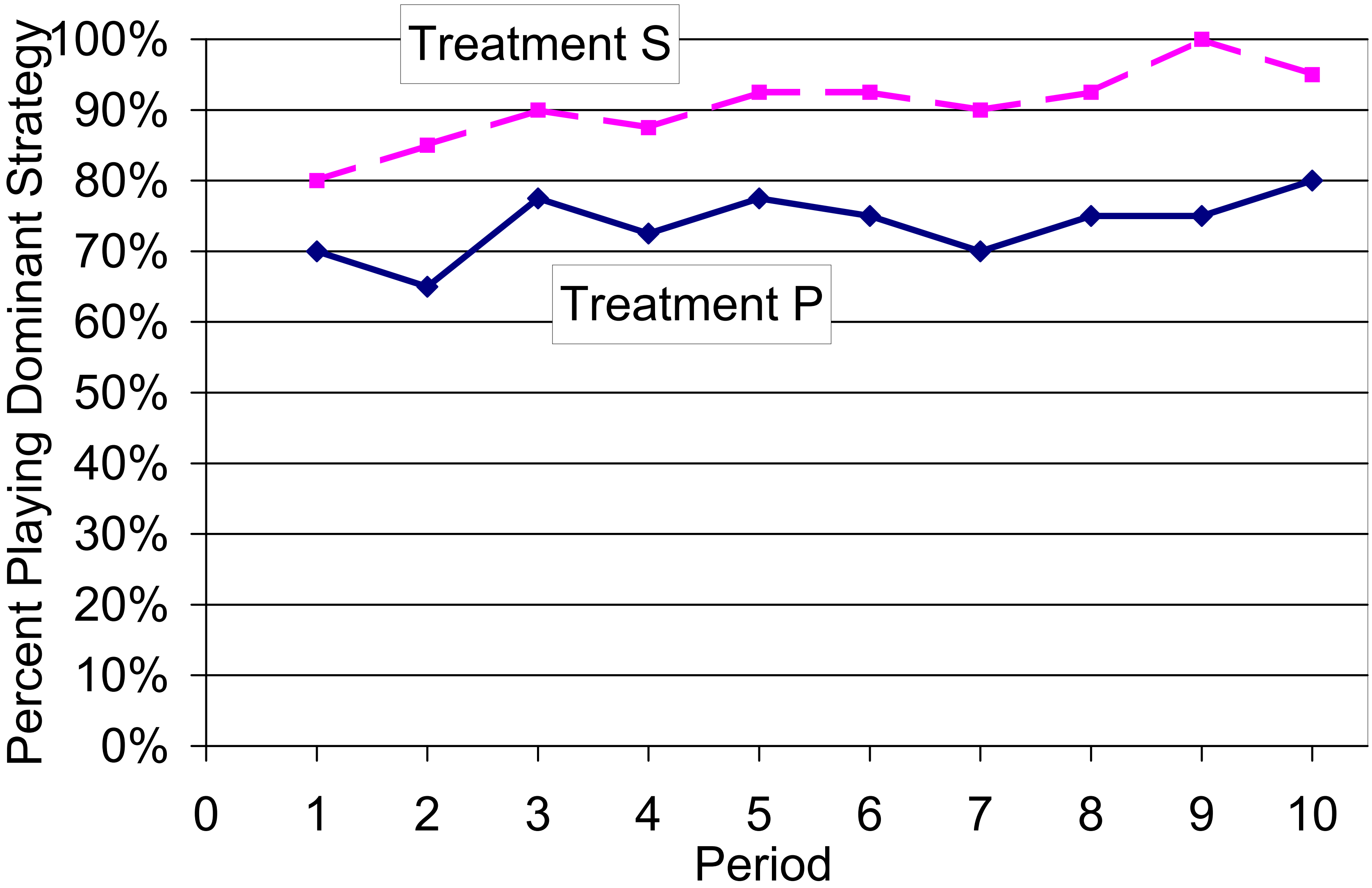

Figure 6: Rates that Individuals Play Dominant Strategies

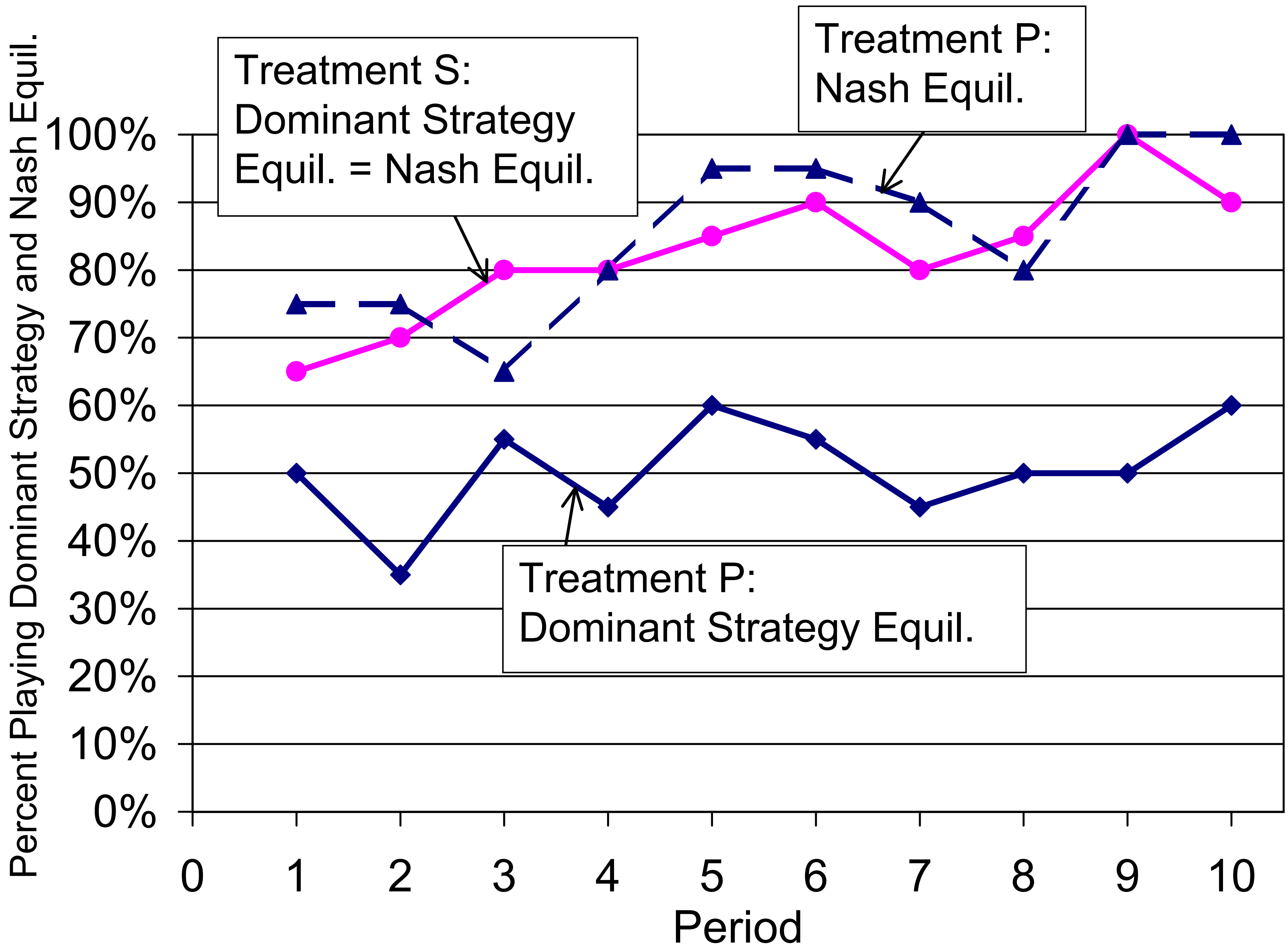

Figure 7: Rates that Pairs Play Dominant Strategy and Nash Equilibria

P1

The number which you choose (Type 1)

The number which the other person chooses (Type 2)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294
2	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294
3	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	182
4	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	196	196
5	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	210	210	210
6	280	280	280	280	280	280	280	280	280	280	280	280	280	280	280	280	280	280	280	280	280	210	210	210	210
7	266	266	266	266	266	266	266	266	266	266	266	266	266	266	266	266	266	266	266	266	210	210	210	210	210
8	252	252	252	252	252	252	252	252	252	252	252	252	252	252	252	252	252	252	252	210	210	210	210	210	210
9	238	238	238	238	238	238	238	238	238	238	238	238	238	238	238	238	238	238	210	210	210	210	210	210	210
10	224	224	224	224	224	224	224	224	224	224	224	224	224	224	224	224	224	210	210	210	210	210	210	210	210
11	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210
12	196	196	196	196	196	196	196	196	196	196	196	196	196	196	196	210	210	210	210	210	210	210	210	210	210
13	182	182	182	182	182	182	182	182	182	182	182	182	182	182	210	210	210	210	210	210	210	210	210	210	210
14	168	168	168	168	168	168	168	168	168	168	168	168	168	210	210	210	210	210	210	210	210	210	210	210	210
15	154	154	154	154	154	154	154	154	154	154	154	154	210	210	210	210	210	210	210	210	210	210	210	210	210
16	140	140	140	140	140	140	140	140	140	140	140	210	210	210	210	210	210	210	210	210	210	210	210	210	210
17	126	126	126	126	126	126	126	126	126	126	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210
18	112	112	112	112	112	112	112	112	112	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210
19	98	98	98	98	98	98	98	98	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210
20	84	84	84	84	84	84	84	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210
21	70	70	70	70	70	70	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210
22	56	56	56	56	56	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210
23	42	42	42	42	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210
24	28	28	28	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210
25	14	14	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210

Table 1. Payoff Table of Type 1 in Treatment P.

The number which you choose (Type 2)

The number which the other person chooses (Type 1)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182
2	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182
3	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	14
4	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	28	28
5	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	42	42	42
6	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	56	56	56	56
7	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	70	70	70	70	70
8	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	84	84	84	84	84	84
9	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	98	98	98	98	98	98	98
10	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	112	112	112	112	112	112	112	112
11	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	126	126	126	126	126	126	126	126	126
12	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	140	140	140	140	140	140	140	140	140	140
13	182	182	182	182	182	182	182	182	182	182	182	182	182	182	154	154	154	154	154	154	154	154	154	154	154
14	182	182	182	182	182	182	182	182	182	182	182	182	182	168	168	168	168	168	168	168	168	168	168	168	168
15	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182	182
16	182	182	182	182	182	182	182	182	182	182	182	196	196	196	196	196	196	196	196	196	196	196	196	196	196
17	182	182	182	182	182	182	182	182	182	182	210	210	210	210	210	210	210	210	210	210	210	210	210	210	210
18	182	182	182	182	182	182	182	182	182	224	224	224	224	224	224	224	224	224	224	224	224	224	224	224	224
19	182	182	182	182	182	182	182	182	238	238	238	238	238	238	238	238	238	238	238	238	238	238	238	238	238
20	182	182	182	182	182	182	182	252	252	252	252	252	252	252	252	252	252	252	252	252	252	252	252	252	252
21	182	182	182	182	182	182	266	266	266	266	266	266	266	266	266	266	266	266	266	266	266	266	266	266	266
22	182	182	182	182	182	280	280	280	280	280	280	280	280	280	280	280	280	280	280	280	280	280	280	280	280
23	182	182	182	182	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294
24	168	168	168	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294
25	154	154	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294

Table 2. Payoff Table of Type 2 in Treatment P.

Dominant Strategy Equilibrium

Good Nash Equilibrium
Bad Nash Equilibrium

Type 2's number (columns); Type 1's number (rows)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	294, 182	294, 182	294, 182	294, 182	294, 182	280, 182	266, 182	252, 182	238, 182	224, 182	210, 182	196, 182	182, 182	168, 182	154, 182	140, 182	126, 182	112, 182	98, 182	84, 182	70, 182	56, 182	42, 182	28, 182	14, 182
2	294, 182	294, 182	294, 182	294, 182	294, 182	280, 182	266, 182	252, 182	238, 182	224, 182	210, 182	196, 182	182, 182	168, 182	154, 182	140, 182	126, 182	112, 182	98, 182	84, 182	70, 182	56, 182	42, 182	28, 182	14, 182
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4	294, 182	294, 182	294, 182	294, 182	294, 182	280, 182	266, 182	252, 182	238, 182	224, 182	210, 182	196, 182	182, 182	168, 182	154, 182	140, 182	126, 182	112, 182	98, 182	84, 182	70, 182	56, 182	42, 182	210, 28	210, 28
5	294, 182	294, 182	294, 182	294, 182	294, 182	280, 182	266, 182	252, 182	238, 182	224, 182	210, 182	196, 182	182, 182	168, 182	154, 182	140, 182	126, 182	112, 182	98, 182	84, 182	70, 182	56, 182	210, 42	210, 42	210, 42
6	294, 182	294, 182	294, 182	294, 182	294, 182	280, 182	266, 182	252, 182	238, 182	224, 182	210, 182	196, 182	182, 182	168, 182	154, 182	140, 182	126, 182	112, 182	98, 182	84, 182	70, 182	210, 56	210, 56	210, 56	210, 56
7	294, 182	294, 182	294, 182	294, 182	294, 182	280, 182	266, 182	252, 182	238, 182	224, 182	210, 182	196, 182	182, 182	168, 182	154, 182	140, 182	126, 182	112, 182	98, 182	84, 182	210, 70	210, 70	210, 70	210, 70	210, 70
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18	294, 182	294, 182	294, 182	294, 182	294, 182	280, 182	266, 182	252, 182	238, 182	210, 244	210, 244	210, 244	210, 244	210, 244	210, 244	210, 244	210, 244	210, 244	210, 244	210, 244	210, 244	210, 244	210, 244	210, 244	210, 244
19	294, 182	294, 182	294, 182	294, 182	294, 182	280, 182	266, 182	252, 182	210, 238	210, 238	210, 238	210, 238	210, 238	210, 238	210, 238	210, 238	210, 238	210, 238	210, 238	210, 238	210, 238	210, 238	210, 238	210, 238	210, 238
20	294, 182	294, 182	294, 182	294, 182	294, 182	280, 182	266, 182	210, 252	210, 252	210, 252	210, 252	210, 252	210, 252	210, 252	210, 252	210, 252	210, 252	210, 252	210, 252	210, 252	210, 252	210, 252	210, 252	210, 252	210, 252
21	294, 182	294, 182	294, 182	294, 182	294, 182	280, 182	210, 266	210, 266	210, 266	210, 266	210, 266	210, 266	210, 266	210, 266	210, 266	210, 266	210, 266	210, 266	210, 266	210, 266	210, 266	210, 266	210, 266	210, 266	210, 266
22	294, 182	294, 182	294, 182	294, 182	294, 182	210, 280	210, 280	210, 280	210, 280	210, 280	210, 280	210, 280	210, 280	210, 280	210, 280	210, 280	210, 280	210, 280	210, 280	210, 280	210, 280	210, 280	210, 280	210, 280	210, 280
23	294, 182	294, 182	294, 182	294, 182	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294
24	294, 168	294, 168	294, 168	196, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294
25	294, 154	294, 154	182, 294	196, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294

Table 3. Dominant Strategy Equilibria and Nash Equilibria in Treatment P.

Type 1		Type 2: 5	Type 2: 12
	8	(294, 182)	(194, 182)
	17	(294, 182)	(210, 210)

Table 4. The payoff table when type 1 chooses 8 or 17 and type 2 chooses 5 or 12 in Treatment P.

Dominant Strategy Equilibrium

Pareto Efficient Outcome

Good Nash Equilibrium

Bad Nash Equilibrium

Outcomes Pareto-dominated by Dominanat Strategy Equilibrium Outcomes

Type 2's number (columns); Type 1's number (rows)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	294, 182	294, 182	294, 182	294, 182	294, 182	280, 182	266, 182	252, 182	238, 182	224, 182	210, 182	196, 182	182, 182	168, 182	154, 182	140, 182	126, 182	112, 182	98, 182	84, 182	70, 182	56, 182	42, 182	28, 182	14, 182
2	294, 182	294, 182	294, 182	294, 182	294, 182	280, 182	266, 182	252, 182	238, 182	224, 182	210, 182	196, 182	182, 182	168, 182	154, 182	140, 182	126, 182	112, 182	98, 182	84, 182	70, 182	56, 182	42, 182	28, 182	14, 182
3	294, 182	294, 182	294, 182	294, 182	294, 182	280, 182	266, 182	252, 182	238, 182	224, 182	210, 182	196, 182	182, 182	168, 182	154, 182	140, 182	126, 182	112, 182	98, 182	84, 182	70, 182	56, 182	42, 182	28, 182	210, 14
4	294, 182	294, 182	294, 182	294, 182	294, 182	280, 182	266, 182	252, 182	238, 182	224, 182	210, 182	196, 182	182, 182	168, 182	154, 182	140, 182	126, 182	112, 182	98, 182	84, 182	70, 182	56, 182	42, 182	210, 28	210, 28
5	294, 182	294, 182	294, 182	294, 182	294, 182	280, 182	266, 182	252, 182	238, 182	224, 182	210, 182	196, 182	182, 182	168, 182	154, 182	140, 182	126, 182	112, 182	98, 182	84, 182	70, 182	56, 182	210, 42	210, 42	210, 42
6	294, 182	294, 182	294, 182	294, 182	294, 182	280, 182	266, 182	252, 182	238, 182	224, 182	210, 182	196, 182	182, 182	168, 182	154, 182	140, 182	126, 182	112, 182	98, 182	84, 182	70, 182	210, 56	210, 56	210, 56	210, 56
7	294, 182	294, 182	294, 182	294, 182	294, 182	280, 182	266, 182	252, 182	238, 182	224, 182	210, 182	196, 182	182, 182	168, 182	154, 182	140, 182	126, 182	112, 182	98, 182	84, 182	210, 70	210, 70	210, 70	210, 70	210, 70
8	294, 182	294, 182	294, 182	294, 182	294, 182	280, 182	266, 182	252, 182	238, 182	224, 182	210, 182	196, 182	182, 182	168, 182	154, 182	140, 182	126, 182	112, 182	98, 182	84, 182	210, 84	210, 84	210, 84	210, 84	210, 84
9	294, 182	294, 182	294, 182	294, 182	294, 182	280, 182	266, 182	252, 182	238, 182	224, 182	210, 182	196, 182	182, 182	168, 182	154, 182	140, 182	126, 182	112, 182	210, 98	210, 98	210, 98	210, 98	210, 98	210, 98	210, 98
10	294, 182	294, 182	294, 182	294, 182	294, 182	280, 182	266, 182	252, 182	238, 182	224, 182	210, 182	196, 182	182, 182	168, 182	154, 182	140, 182	126, 182	210, 112	210, 112	210, 112	210, 112	210, 112	210, 112	210, 112	210, 112
11	294, 182	294, 182	294, 182	294, 182	294, 182	280, 182	266, 182	252, 182	238, 182	224, 182	210, 182	196, 182	182, 182	168, 182	154, 182	140, 182	210, 126	210, 126	210, 126	210, 126	210, 126	210, 126	210, 126	210, 126	210, 126
12	294, 182	294, 182	294, 182	294, 182	294, 182	280, 182	266, 182	252, 182	238, 182	224, 182	210, 182	196, 182	182, 182	168, 182	154, 182	210, 140	210, 140	210, 140	210, 140	210, 140	210, 140	210, 140	210, 140	210, 140	210, 140
13	294, 182	294, 182	294, 182	294, 182	294, 182	280, 182	266, 182	252, 182	238, 182	224, 182	210, 182	196, 182	182, 182	168, 182	210, 154	210, 154	210, 154	210, 154	210, 154	210, 154	210, 154	210, 154	210, 154	210, 154	210, 154
14	294, 182	294, 182	294, 182	294, 182	294, 182	280, 182	266, 182	252, 182	238, 182	224, 182	210, 182	196, 182	182, 182	210, 168	210, 168	210, 168	210, 168	210, 168	210, 168	210, 168	210, 168	210, 168	210, 168	210, 168	210, 168
15	294, 182	294, 182	294, 182	294, 182	294, 182	280, 182	266, 182	252, 182	238, 182	224, 182	210, 182	196, 182	210, 182	210, 182	210, 182	210, 182	210, 182	210, 182	210, 182	210, 182	210, 182	210, 182	210, 182	210, 182	210, 182
16	294, 182	294, 182	294, 182	294, 182	294, 182	280, 182	266, 182	252, 182	238, 182	224, 182	210, 182	210, 196	210, 196	210, 196	210, 196	210, 196	210, 196	210, 196	210, 196	210, 196	210, 196	210, 196	210, 196	210, 196	210, 196
17	294, 182	294, 182	294, 182	294, 182	294, 182	280, 182	266, 182	252, 182	238, 182	224, 182	210, 210	210, 210	210, 210	210, 210	210, 210	210, 210	210, 210	210, 210	210, 210	210, 210	210, 210	210, 210	210, 210	210, 210	210, 210
18	294, 182	294, 182	294, 182	294, 182	294, 182	280, 182	266, 182	252, 182	238, 182	210, 244	210, 244	210, 244	210, 244	210, 244	210, 244	210, 244	210, 244	210, 244	210, 244	210, 244	210, 244	210, 244	210, 244	210, 244	210, 244
19	294, 182	294, 182	294, 182	294, 182	294, 182	280, 182	266, 182	252, 182	210, 238	210, 238	210, 238	210, 238	210, 238	210, 238	210, 238	210, 238	210, 238	210, 238	210, 238	210, 238	210, 238	210, 238	210, 238	210, 238	210, 238
20	294, 182	294, 182	294, 182	294, 182	294, 182	280, 182	266, 182	210, 252	210, 252	210, 252	210, 252	210, 252	210, 252	210, 252	210, 252	210, 252	210, 252	210, 252	210, 252	210, 252	210, 252	210, 252	210, 252	210, 252	210, 252
21	294, 182	294, 182	294, 182	294, 182	294, 182	280, 182	210, 266	210, 266	210, 266	210, 266	210, 266	210, 266	210, 266	210, 266	210, 266	210, 266	210, 266	210, 266	210, 266	210, 266	210, 266	210, 266	210, 266	210, 266	210, 266
22	294, 182	294, 182	294, 182	294, 182	294, 182	210, 280	210, 280	210, 280	210, 280	210, 280	210, 280	210, 280	210, 280	210, 280	210, 280	210, 280	210, 280	210, 280	210, 280	210, 280	210, 280	210, 280	210, 280	210, 280	210, 280
23	294, 182	294, 182	294, 182	294, 182	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294
24	294, 168	294, 168	294, 168	196, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294
25	294, 154	294, 154	182, 294	196, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294	210, 294

Table 5. Dominant Strategy Equilibria, Nash Equilibria, Pareto Efficient Outcomes in Treatment P.

Payoff Table (for the Actual Experiment)

The number which you choose (columns); The number which the other person chooses (rows)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	116	124	131	138	144	150	154	158	161	164	166	167	167	167	166	164	161	158	154	150	144	138	131	124	116
2	124	132	140	146	152	158	162	166	170	172	174	175	175	175	174	172	170	166	162	158	152	146	140	132	124
3	131	140	147	154	160	165	170	174	177	180	181	182	183	182	181	180	177	174	170	165	160	154	147	140	131
4	138	146	154	161	167	172	177	181	184	186	188	189	190	189	188	186	184	181	177	172	167	161	154	146	138
5	144	152	160	167	173	178	183	187	190	192	194	195	196	195	194	192	190	187	183	178	173	167	160	152	144
6	150	158	165	172	178	184	188	192	195	198	200	201	201	201	200	198	195	192	188	184	178	172	165	158	150
7	154	162	170	177	183	188	193	197	200	202	204	205	206	205	204	202	200	197	193	188	183	177	170	162	154
8	158	166	174	181	187	192	197	201	204	206	208	209	210	209	208	206	204	201	197	192	187	181	174	166	158
9	161	170	177	184	190	195	200	204	207	210	211	212	213	212	211	210	207	204	200	195	190	184	177	170	161
10	164	172	180	186	192	198	202	206	210	212	214	215	215	215	214	212	210	206	202	198	192	186	180	172	164
11	166	174	181	188	194	200	204	208	211	214	216	217	217	217	216	214	211	208	204	200	194	188	181	174	166
12	167	175	182	189	195	201	205	209	212	215	217	218	218	218	217	215	212	209	205	201	195	189	182	175	167
13	167	175	183	190	196	201	206	210	213	215	217	218	219	218	217	215	213	210	206	201	196	190	183	175	167
14	167	175	182	189	195	201	205	209	212	215	217	218	218	218	217	215	212	209	205	201	195	189	182	175	167
15	166	174	181	188	194	200	204	208	211	214	216	217	217	217	216	214	211	208	204	200	194	188	181	174	166
16	164	172	180	186	192	198	202	206	210	212	214	215	215	215	214	212	210	206	202	198	192	186	180	172	164
17	161	170	177	184	190	195	200	204	207	210	211	212	213	212	211	210	207	204	200	195	190	184	177	170	161
18	158	166	174	181	187	192	197	201	204	206	208	209	210	209	208	206	204	201	197	192	187	181	174	166	158
19	154	162	170	177	183	188	193	197	200	202	204	205	206	205	204	202	200	197	193	188	183	177	170	162	154
20	150	158	165	172	178	184	188	192	195	198	200	201	201	201	200	198	195	192	188	184	178	172	165	158	150
21	144	152	160	167	173	178	183	187	190	192	194	195	196	195	194	192	190	187	183	178	173	167	160	152	144
22	138	146	154	161	167	172	177	181	184	186	188	189	190	189	188	186	184	181	177	172	167	161	154	146	138
23	131	140	147	154	160	165	170	174	177	180	181	182	183	182	181	180	177	174	170	165	160	154	147	140	131
24	124	132	140	146	152	158	162	166	170	172	174	175	175	175	174	172	170	166	162	158	152	146	140	132	124
25	116	124	131	138	144	150	154	158	161	164	166	167	167	167	166	164	161	158	154	150	144	138	131	124	116

Table 6. Payoff Table of Type 1 distributed in Treatment S.

Payoff Table (for the Actual Experiment) S2

The number which you choose

The number which the other person chooses

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	12	24	35	45	55	64	72	80	86	92	98	102	106	110	112	114	115	115	115	114	112	110	106	102	98
2	24	36	47	57	67	76	84	91	98	104	110	114	118	121	124	126	127	127	127	126	124	121	118	114	110
3	35	47	58	68	78	87	95	102	109	115	121	125	129	132	135	137	138	138	138	137	135	132	129	125	121
4	45	57	68	79	88	97	105	113	120	126	131	136	140	143	145	147	148	149	148	147	145	143	140	136	131
5	55	67	78	88	98	107	115	122	129	135	141	145	149	152	155	157	158	158	158	157	155	152	149	145	141
6	64	76	87	97	107	116	124	131	138	144	150	154	158	161	164	166	167	167	167	166	164	161	158	154	150
7	72	84	95	105	115	124	132	140	146	152	158	162	166	170	172	174	175	175	175	174	172	170	166	162	158
8	80	91	102	113	122	131	140	147	154	160	165	170	174	177	180	181	182	183	182	181	180	177	174	170	165
9	86	98	109	120	129	138	146	154	161	167	172	177	181	184	186	188	189	190	189	188	186	184	181	177	172
10	92	104	115	126	135	144	152	160	167	173	178	183	187	190	192	194	195	196	195	194	192	190	187	183	178
11	98	110	121	131	141	150	158	165	172	178	184	188	192	195	198	200	201	201	201	200	198	195	192	188	184
12	102	114	125	136	145	154	162	170	177	183	188	193	197	200	202	204	205	206	205	204	202	200	197	193	188
13	106	118	129	140	149	158	166	174	181	187	192	197	201	204	206	208	209	210	209	208	206	204	201	197	192
14	110	121	132	143	152	161	170	177	184	190	195	200	204	207	210	211	212	213	212	211	210	207	204	200	195
15	112	124	135	145	155	164	172	180	186	192	198	202	206	210	212	214	215	215	215	214	212	210	206	202	198
16	114	126	137	147	157	166	174	181	188	194	200	204	208	211	214	216	217	217	217	216	214	211	208	204	200
17	115	127	138	148	158	167	175	182	189	195	201	205	209	212	215	217	218	218	218	217	215	212	209	205	201
18	115	127	138	149	158	167	175	183	190	196	201	206	210	213	215	217	218	219	218	217	215	213	210	206	201
19	115	127	138	148	158	167	175	182	189	195	201	205	209	212	215	217	218	218	218	217	215	212	209	205	201
20	114	126	137	147	157	166	174	181	188	194	200	204	208	211	214	216	217	217	217	216	214	211	208	204	200
21	112	124	135	145	155	164	172	180	186	192	198	202	206	210	212	214	215	215	215	214	212	210	206	202	198
22	110	121	132	143	152	161	170	177	184	190	195	200	204	207	210	211	212	213	212	211	210	207	204	200	195
23	106	118	129	140	149	158	166	174	181	187	192	197	201	204	206	208	209	210	209	208	206	204	201	197	192
24	102	114	125	136	145	154	162	170	177	183	188	193	197	200	202	204	205	206	205	204	202	200	197	193	188
25	98	110	121	131	141	150	158	165	172	178	184	188	192	195	198	200	201	201	201	200	198	195	192	188	184

Table 7. Payoff Table of Type 2 distributed in Treatment S.

Dominant Strategy Equilibrium

Good Nash Equilibrium

Bad Nash Equilibrium

Type 2's number

Type 1's number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	sum
1												1	1													2
2								1				1	2													4
3																										0
4													2					1		1						4
5												1	2					1	1							5
6													1													1
7													2													2
8																										0
9													1													1
10												1	2													3
11																										0
12												1														1
13																										0
14												2														2
15													2					1				1				4
16						1				1	2	34	27	5	5	4	4	1	1	2	1			1	3	92
17					1							10	19			1		1	1	1	1					35
18												1	3												1	5
19												3	2													5
20												1													1	2
21												5														5
22												1														1
23																										0
24													2													2
25												3	1													4
sum	0	0	0	0	1	1	0	1	0	1	2	65	69	5	5	5	4	5	3	4	2	1	0	1	5	180

Table 8. Data Frequency in Treatment P.

	(1) Individuals play dominant strategies	(2) Pairs play dominant strategy equilibrium
Dummy variable=1 for Treatment S	0.720** (0.346)	0.887** (0.077)
Dummy variable=1 for sessions at Purdue		0.170** (0.075)
Intercept	1.236** (0.266)	-0.095 (0.064)
$\rho = \sigma_u^2 / (\sigma_v^2 + \sigma_u^2)$ (random effects significance)	0.627** (0.069)	
Observations	720	360
Log-likelihood	-247.2	-211.3
Restricted log-likelihood	-344.5	-231.8

Notes: Standard errors shown in parentheses. ** denotes significantly different from zero at five-percent. The model in column (1) is estimated with a random subjects effect error term $\varepsilon_{it} = u_i + v_{it}$, and the model in column (2) is estimated with clustering at the session level.

Table 9. Probit Models of Individual and Pair Dominant Strategy Play