THE PROVISION OF PUBLIC GOODS UNDER ALTERNATIVE PROTOCOLS AND SOCIAL COMPOSITION FUNCTIONS: REPORT ON AN EXPERIMENT

(Preliminary)

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Abstract

The experiments reported on here were designed to test whether subjects' voluntary private provision of public goods met theoretical expectations under the assumption of rational self-interested behavior. We go beyond the previous literature in examining individual choices under alternative social composition functions and alternative experimental protocols.

Three social composition functions were studied: (1) STANDARD SUMMATION -- where, as in the usual textbook case, the social aggregate of the public good is the sum of the amounts privately provided; (2) WEAKEST LINK -- where the available social aggregate is the minimum of the amounts individually provided; and (3) BEST SHOT -- where the social aggregate is the maximum of the individual provisions. Theoretical considerations indicated that the traditional result as to "underprovision" of public goods (in comparison with socially efficient totals) under STANDARD SUMMATION would be substantially mitigated under WEAKEST LINK, but aggravated under BEST SHOT.

Under our Sequential protocol, a trio of experiments, one for each of the social composition functions, was conducted. In these experiments the second-mover in each group of 2 could always make an explicit optimizing choice, but the first-mover had to act in ignorance of his or her partner's likely later behavior. All the Marginal Benefit and Marginal Cost schedules were identical but this fact was not revealed to the subjects. However, subjects had some

opportunity to learn about partners' likely behavior in the course of repeated periods of play. Even though the informational conditions did not meet the requirements for this solution concept, we "predicted" that the subjects would be able to attain the perfect equilibrium. As it turned out, the actual results averaged over periods and replications squared remarkably with those predicted.

Under our second protocol, Sealed bid, both group members were in the dark as to partners' likely behavior. The conditions for perfect equilibrium being inapplicable here, for purposes of "prediction" we used the weaker Nash equilibrium (NE) concept. To overcome non-uniqueness of the NE, two supplementary principles were appealed to: (i) only symmetrical solutions were considered, and (ii) among symmetrical solutions the one with maximum mutual gain was chosen. Since the learning problem was notably more difficult under Sealed-bid, and the very nature of the rational behavior subject to some question, we anticipated a poorer fit between observed and "predicted" results. While this indeed occurred, in some respects the subjects did manage to go a surprising distance toward theoretical anticipations.

For the Sequential experiments, the results may be regarded as confirming a compound hypothesis that the subjects: (a) acted in a rational, self-interested way, (b) believed that their partners would behave similarly, and (c) were able to learn the correspondence between their own and their partner's payoff functions. For the experiments conducted under the Sealed-bid protocol, this compound hypothesis cannot be regarded as confirmed. Further study will be necessary to specify which portions failed, and to what degree.

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THE PROVISION OF PUBLIC GOODS UNDER ALTERNATIVE PROTOCOLS AND SOCIAL COMPOSITION FUNCTIONS: REPORT ON AN EXPERIMENT*

(Preliminary)

1. Introduction

Standard economic theory predicts that self-interested agents will voluntarily provide relatively little in the way of public goods, in comparison with efficient social totals. (See e.g., Olson [1965], Chamberlin [1976], and for an application to animals Chase [1980].) Another way of putting this: the provision of public goods is a Prisoners' Dilemma in a continuous-strategy space.

On the other hand, in real-life and experimental settings human beings appear to solve this problem to a surprising degree: far less "free riding" occurs than anticipated. One possible explanation is that individuals in Prisoners' Dilemma environments are less selfish than standard theory indicates. However, there are alternative ways of interpreting these seeming "non-free-riding" results.

With regard to the experimental data, two recent surveys come to rather different conclusions. Kim and M. Walker (1984) identify a number of "invalidating factors" that have made certain previous experiments, purporting to show absence of free-riding, improper tests of the underlying theory. In

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an experiment designed to avoid these invalidating factors, they observed strong free-riding behavior consistent with the theory. But a similarly motivated study by Isaac, J.M. Walker, and Thomas (1984) concludes that even carefully designed experiments yield a range from zero to strong free-riding behavior, responding to not-yet-understood determining factors.

With regard to animal behavior, standard biological theory parallels standard economic theory in postulating ultimately selfish individual drives. (See e.g., Williams [1966], Ghiselin [1974], Dawkins [1976], and for a review and comparison of biological and economic models Hirshleifer [1978].) However, some question remains as to the degree to which "group selection" may provide for the survival of "altruistic" behavior (E.O. Wilson [1975, Ch. 5], D.S. Wilson [1980], Wade [1978]).

Observation of human behavior in adversity provides an additional clue. Specifically, it has been observed that people surprisingly often overcome the free-riding problem in disaster situations (Hirshleifer [1963], and see also the discussion in DeAlessi [1975] and Hirshleifer [1975 (1967)]). A frequent characteristic of such situations is that they correspond to "weakest-link" environments — as in a chain, where the failure of any unit may be fatal. In such environments seemingly self-sacrificing behavior may actually be selfishly optimal, if it makes the difference between group viability and general collapse.

A recent generalization of the theory of public goods (Hirshleifer [1983]) has been designed to explain the extent of free-riding versus cooperative behavior as a function of such environmental reward patterns, without calling upon anything beyond self-interest. In this generalization the "social composition function" implicit in public-goods theory, called here STANDARD SUMMATION — which specifies that the social aggregate of the public good is the sum of the amounts contributed by each and every individual -- becomes only one point on a spectrum. At one extreme of the spectrum the relevant social composition function tends to the WEAKEST LINK pattern, where the available aggregate of the public good reflects not the sum but the minimum of the individual contributions. Here the generalized theory predicts that free-riding will fall to quite small levels. (And disappear entirely if the population is homogeneous.) At the other extreme, where the socially available amount is the maximum of the individual contributions -- corresponding to the social composition function called BEST SHOT -- free-riding is predicted to be even more predominant and intractable than under STANDARD SUMMATION.

This discussion is compactly summarized in Table 1, where q_i is the amount of the public good provided for by the individual contribution of the i^{th} member of the group, and Q is the available social aggregate:

TABLE 1

Alternative Social Composition Functions

Social composition function	Formula	Predicted extent of free-riding
STANDARD SUMMATION	$Q = \sum_i q_i$	Intermediate
WEAKEST LINK	$Q = \min_i q_i$	Least
BEST SHOT	$Q = \max_i q_i$	Worst

A second major purpose of our study was to test the effects of alternative experimental "protocols" upon subjects' ability to overcome the free-riding impasse. This topic, which is related to the problem of the appropriate solution concept in game theory (see Hirshleifer [1984]), will be taken up under the heading of "Experimental Design" in the section following.

2. Experimental Design

A summary of the experiments reported on here appears in Table 2. We actually conducted 15 experiments in all, but only 6 of these were relevant for the purposes of this paper (see below). All subjects were economics undergraduates at the University of Western Ontario or the University of Arizona.[1] In each session a relatively large group of subjects (typically 18) were segregated randomly into groups of two. No-one ever knew the identity of his or her partner within the larger population of subjects. Furthermore, the partners were changed each period. (This feature was designed to prevent possible extraneous influences, such as the desire to make friends, from contaminating the experiment.) All subjects were given the same fixed valuation schedule for the public good, valid for each experimental period, as shown in Table 3 and pictured in Figure 1. (But the fact that all valuation schedules were identical was not revealed to the subjects.)

Under each of two different experimental "protocols," a trio of experiments -- one member of the trio corresponding to each of the social composition functions of Table 1 — was conducted. (1) In the "Sequential" protocol (experiments SQ-1, SQ-2, and SQ-3), one subject in each pair was randomly selected to have the first move. The first-mover was required to declare his or her own irrevocable contribution to the pair's joint provision of the public good. The other member of the pair could then use that information in choosing a best response, in the form of a second-move decision as to

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[1]The dollar payoffs were adjusted on the basis of the exchange rate at the time of the experiments, approximately C$1.32 to the U.S. dollar.

TABLE 2

Summary of Experiments

Experiment	Protocol	Social Composition Function	Periods	Replications
SQ-1	Sequential	STANDARD SUMMATION	6	3
SQ-2	Sequential	WEAKEST LINK	6	3
SQ-3	Sequential	BEST SHOT	6	3
SB-1	Sealed bid	STANDARD SUMMATION	10	5
SB-2	Sealed bid	WEAKEST LINK	10	5
SB-3	Sealed bid	BEST SHOT	10	3

how much to contribute in turn. (It might be thought that this informational asymmetry would always work to the advantage of the last-mover in each pair, but as will be seen this was very far from the case.) (2) In the second trio of experiments under the "Sealed-bid" protocol (experiments SB-1, SB-2, and SB-3), each subject had to select a level of voluntary contribution in ignorance of the simultaneous choice being made by his or her partner. Here it might be thought that the poorer information available to the pair as a group would make it more difficult for them to arrive at their self-interested optimal choices. This inference was in fact supported, to a marked extent, by our experimental results.

The experiments that are not reported on here included two trios representing additional protocols that allowed for repeated interaction with the same partner (as would occur if two persons were bidding at an open rather than sealed-bid auction). In one of these protocols the "bidding," in the way of offered contribution to provision of the public good, lasted for 10 rounds; in the other it could go on indefinitely until one or the other player chose to pass. Still another trio of experiments was designed to test the influence upon behavior of a player's knowing whether or not his or her partner was "altruistic." These other experiments all raise issues beyond the scope of this paper, and will be reported upon elsewhere.

All subjects in the "Sealed-bid" experiments SB-1, SB-2 and SB-3 were made familiar with the following instructions:

> You are about to participate in a decision process in which one of numerous competing alternatives will be chosen. This is part of a study intended to provide insight into certain features of decision processes. The instructions are simple. If you follow them carefully and make good decisions, you might earn a considerable amount of money. You will be paid in cash.
>
> This decision process will proceed as a series of ten periods. In each period the level of a project will be determined and financed. The "level" can be at zero "units" or more.

Attached to the instructions you will find a sheet called the Redemption Value Sheet. It describes the value to you of decisions made in each period. You are not to reveal this information to anyone. It is your own private information.

During each period a level of the project will be determined. For the first unit provided during a period you will receive the amount listed in row 1 of the Redemption Value Sheet. If a second unit is also provided during the period, you will receive the additional amount listed in row 2 of the Redemption Value Sheet. If a third unit is provided, you will receive, in addition to the two previous amounts, the amount listed in row 3, etc. As you can see, your individual total payment in each period is computed as a sum of the redemption values of specific units. These totals of redemption values are tabulated for your convenience on the right-hand side of the page.

The earnings per period, which are yours to keep, are the differences between the total of redemption values of units of the project provided and your individual expenditures on the project. Suppose, for example, your Redemption Value Sheet was as below and two units were provided.

REDEMPTION VALUE SHEET (EXAMPLE)

Project Level (Units)	Redemption Value of Specific Units	Total Redemption Value of all Units
1	600	600
2	500	1100
3	400	1500

Your redemption value for the two units would be 1100 and your earnings would be computed by subtracting your individual expenditures from this amount. If 2.5 units were provided, the redemption value would be determined by the redemption values of the first and second unit plus half of the third unit, that is, 600 + 500 + (0.5)400 = 1300.

The process by which the level of the project is decided will proceed as follows. Each unit of the project costs $0.82. At the beginning of each period you are to write on the Expenditure Form the amount you will spend individually. This number should also be recorded on row 2 of your Individual Record of Earnings. These individual Expenditure Forms will be collected. The number of units of the project is then determined by applying one of the following three Rules:

Rule I: The number of units provided is the total of the individual expenditures divided by the cost per unit.

Rule II: The number of units provided is the smallest of the individual expenditures divided by the cost per unit.

TABLE 3

Redemption Value Sheet

Project Level (Units)	Redemption Value of Specific Units	Total Redemption Value of All Units
1	$1.00	$1.00
2	0.95	1.95
3	0.90	2.85
4	0.85	3.70
5	0.80	4.50
6	0.75	5.25
7	0.70	5.95
8	0.65	6.60
9	0.60	7.20
10	0.55	7.75
11	0.50	8.25
12	0.45	8.70
13	0.40	9.10
14	0.35	9.45
15	0.30	9.75
16	0.25	10.00
17	0.20	10.20
18	0.15	10.35
19	0.10	10.45
20	0.05	10.50
21	0.00	10.50

Rule III: The number of units provided is the largest of the individual expenditures divided by the cost per unit.

You will be told at the beginning of each period which of these Rules applies to you in that period. After the level of the project has been determined it will be announced. Your individual expenditures will not be made public. Note that your individual expenditures are binding on you, irrespective of the Rule used to determine the level of the project.

When the level of the project is announced, you should enter the Total Redemption Value of all units obtained from the Redemption Value Sheet on row 1 of your Individual Record of Earnings. You should then subtract row 2 from row 1 on this record to determine your earnings for this period. Row 4 provides a place for you to record the number of units of the project provided in each period.

During this process you are not to speak to anyone or otherwise attempt to communicate. There may be several groups making decisions at once. You will be told which group you are participating with in each period and how many members are in your group. Your Individual Record of Earnings identifies your Individual Number, and has a row for you to note your Group Number in each period. The group you are assigned to in making the decision in each period will be dissolved immediately thereafter, and your new group assignment will be different each period. Furthermore, in no event will you ever be told who else is in the group with you.

Are there any questions?

The Redemption Value Sheet referred to is shown in Table 3, and was common to each participant in all the experiments. Our instructions closely follow those used by Isaac, McCue and Plott [1982], except for the references to alternative Rules and the shuffling of subjects from group to group.

The instructions to subjects in the "Sequential" experiments SQ-1, SQ-2, and SQ-3 were simple modifications of those reproduced above, in accordance with the changed protocol.

3. Efficient Outcomes Under Alternative Social Composition Functions

To clarify the nature of the social composition functions, and to illustrate the basis for our theoretical predictions as to the outcomes, the three pairs of matrices shown in Table 4 represent simplified versions of the

TABLE 4

Simplified Illustration of the

Three Social Composition Functions

WEAKEST LINK

Algebraic

	P	N
P	b-c,b-c	-c,0
N	0,-c	0,0

Numerical (b = 2, c = 1)

	P	N
P	1,1	-1,0
N	0,-1	0,0

BEST SHOT

Algebraic

	P	N
P	b-c,b-c	b-c,b
N	b,b-c	0,0

Numerical (b = 2, c = 1)

	P	N
P	1,1	1,2
N	2,1	0,0

STANDARD SUMMATION

Algebraic

	P	N
P	B-c,B-c	b-c,b
N	b,b-c	0,0

Numerical (B = 4, c = 3, b = 2)

	P	N
P	1,1	-1,2
N	2,-1	0,0

decision processes involved. In this illustration (but not in the actual experiments), cooperation — in the form of a decision to contribute to the provision of the public good — is simply a yes/no affair: the individual is either a provider (P) or a non-provider (N).

Starting with the WEAKEST LINK case, the matrix on the left shows the respective payoffs to the four possible combinations of P and N strategies, where b is the benefit received by each player should both contribute, and c is the cost to either of contributing. If the WEAKEST LINK model is to apply, it is necessary that $b > c$. The matrix on the right is a numerical illustration for $b = 2$ and $c = 1$.

For the BEST SHOT case, b is the benefit received by each player should either contribute, while c remains the cost to either of contributing. Again, a necessary condition is $b > c$. As before, the matrix on the right is a numerical illustration assuming $b = 2$ and $c = 1$.

In the STANDARD SUMMATION case, matters are a bit more complex since we must now distinguish two possible levels of benefits obtained. Specifically, let B signify the benefit to each player when both contribute, and b the benefit to each when only one contributes. The necessary conditions here can be expressed as $B > c > b$, but $B - c < b$. The numerical illustration on the right assumes $B = 4$, $c = 3$, and $b = 2$. (As is well known, this STANDARD SUMMATION situation for the private provision of public goods is a Prisoners' Dilemma.)

The efficient levels of provision of the public good are easily visualized in the simplified numerical illustrations of Table 4. For WEAKEST LINK, the maximum joint payoff is $1+1 = 2$, achieved if the parties adopt the strategy-pair [P,P]. Since, under the social composition function represented by WEAKEST LINK, when each party chooses P only 1 unit of the public good becomes available, the efficient quantity of public good provided is 1. For BEST SHOT, the maximum joint payoff of 2+1 = 3 is achieved at either of the off-diagonal cells. Here one player chooses P, and the other N, which under BEST SHOT suffices to generate 1 unit of the public good. For STANDARD SUMMATION, finally, the maximum joint payoff is 1+1 = 2, achieved if the parties each choose P. Under this social composition function, the number of units of the public good thus provided is 2.

Turning from these simplified illustrations to the actual experimental situation, with benefits and costs as pictured in Figure 1, the efficiency conditions and corresponding numerical results are shown in Table 5. Notice that the efficient outcomes depend only upon the social composition functions, and not at all upon the protocols.

The interpretation of Table 5 is as follows. Under STANDARD SUMMATION, each individual's contribution goes toward purchasing units of the public good to be enjoyed by both. As shown in Figure 1, each individual can always purchase a unit of the public good at a constant individual Marginal Cost MC = $.82. The individual Marginal Benefit schedule MB shown in the diagram corresponds of course to the benefits tabulated in Table 3 as "Redemption Values of Specific Units." Since the social Marginal Benefit is simply twice the individual MB, inspection of the diagram reveals that the efficiency condition under STANDARD SUMMATION, to wit, $MC_1 = MC_2 = MB_1 + MB_2$ -- where the subscripts identify members of the participating pairs — is met when each individual provides 6 units of the public good. Thus, $q_1 = q_2 = 6$, so that the efficient aggregate quantity is $Q = 12$.

Under WEAKEST LINK, both members must contribute if a unit of the public good is to be generated that both can enjoy. Here the efficiency condition is $MC_1 + MC_2 = MB_1 + MB_2$, which is met when $q_1 = q_2 = 4$. Since under WEAKEST

TABLE 5

Efficient Outcomes Under Experimental Conditions

SOCIAL COMPOSITION FUNCTION	EFFICIENCY CONDITION	NUMERICAL q_1	q_2	Q
STANDARD SUMMATION	$MC_1 = MC_2 = MB_1 + MB_2$	6	6	12
WEAKEST LINK	$MC_1 + MC_2 = MB_1 + MB_2$	4	4	4
BEST SHOT	$MC_1 = MB_1 + MB_2$ and $q_2 = 0$	12	0	12
	or $MC_2 = MB_1 + MB_2$ and $q_1 = 0$	0	12	12

LINK the social amount provided is the lesser of q_1 and q_2, the efficient social aggregate is $Q = 4$. Finally, under BEST SHOT, a unit of the public good is provided when either contributes. For efficiency here, one party should contribute zero while the other should set his or her $MC_i = MB_1 + MB_2$. Numerically, the member contributing should provide $q_i = 12$, so that the social amount generated -- the greater of q_1 and q_2 -- is $Q = 12$.

4. "Predicted" versus Actual Outcomes

We now come to the crucial point, comparing the experimental outcomes with those "predicted" under the assumption of rational self-interested behavior. There is a problem here, however, in that the experimental setup did not always give the subjects a solid informational basis for rational choice. The informational pattern in fact differed very significantly as between the Sequential and the Sealed-bid protocols.

The Sequential Experiments

In these experiments the second-mover, knowing his own benefit and cost schedule and having seen his partner's prior choice, could in principle always calculate his privately optimal contribution toward purchase of the public good. However, the rational choice for the first-mover would depend upon his partner's anticipated response. There are two difficulties here: (i) The first-mover might not be sure that his partner is a rational self-interested decision-maker, and (ii) even presuming such rationality, the first-mover in these experiments was not informed of his partner's benefit and cost schedule. To some extent, however, the subjects were in a position to learn about partners' likely behavior. Since each subject participated in 6 choice "periods" (in this group of experiments), decisions in the later periods could be guided by results achieved earlier. But learning was not trivially easy, since each subject was told (as in fact occurred) that the partnership assignments were to be re-shuffled each period. Hence there was no chance of mutual education and accommodation as between any given pair.

Nevertheless, in order to have a precise target for purposes of comparison, we "predicted" that the first-mover would always be able to cut through this fog of uncertainty. I.e., that he would be able to make the correct self-interested rational choice as if: (i) he were certain that his partner was also a self-interested rational player, and (ii) he knew that the partner's benefit and cost functions were the same as his own. In game theory terms, the mutual rationality condition (i) means that we are making use of the "perfect equilibrium" concept (Selten [1975]). Since the experimental informational conditions diverged rather seriously from the "ideal" of conditions (i) and (ii), our experiments put the underlying theory to a rather severe test. We did expect, however, to observe at least a better approximation to the predicted results for the later periods of each experimental replication, as the parties gained experience.

On these assumptions, our "predicted" outcomes for the Sequential group of experiments can be read from Table 6, and are pictured in Figures 2a through 2c. The subscripts 1 and 2 here identify the first-mover and second-mover of each trial pair.

Under the STANDARD SUMMATION social composition function, the predicted rational choice on the part of first-mover is to contribute nothing (to choose $q_1 = 0$). Should he do so, second-mover is then forced in his own self-interest to provide $q_2 = 4$ units, making the social aggregate also $Q = 4$. It would be foolish for first-mover to "generously" choose any positive q_1. If, for example, first-mover set $q_1 = 1$ then a self-interested second-mover would rationally respond by cutting his own provision back to $q_2 = 3$ —

TABLE 6

Predicted and Actual Outcomes — Sequential Experiments

Social Composition Function	q_1	q_2	Q	% of Efficient Total
STANDARD SUMMATION (SQ-1)				
Predicted	0.0	4.0	4.0	33.3
Actual	0.436	3.778	4.204	35.0
WEAKEST LINK (SQ-2)				
Predicted	4.0	4.0	4.0	100.0
Actual	3.938	3.889	3.889	97.2
BEST SHOT (SQ-3)				
Predicted	0.0	4.0	4.0	33.3
Actual	0.629	3.500	4.061	33.8

leaving the total $Q = 4$ as before.[2]

Turning to the WEAKEST LINK social composition function, here the public good will be provided only to the extent that both contribute. Therefore the first-mover can be confident that his partner will exactly match his contribution, up to $q_1 = 4$. Our consequent prediction is $q_1 = q_2 = 4$, which means that the available social total is $Q = 4$ as well. Finally, BEST SHOT is like STANDARD SUMMATION in that a rational first-mover will contribute nothing ($q_1 = 0$), realizing that his partner would once again be left holding the bag and forced in his own self-interest to set $q_2 = 4$. Since Q under BEST SHOT is the larger of q_1 and q_2, the social aggregate is once again $Q = 4$.

Summarizing, $Q = 4$ is the predicted social aggregate in all three cases. (Under WEAKEST LINK this corresponds to efficient provision of the public good, but in the other two instances it is only 1/3 of the efficient amount.) But the predicted distributions of the individual contributions differ drastically over the three cases, as indicated in Table 6. It is also of interest to notice that, in the two cases where there is an advantage of one player over another (STANDARD SUMMATION and BEST SHOT), the benefit goes to the first-mover -- despite the informational asymmetry in favor of the second-mover.

Getting finally to the bottom line, the "actual" figures reported in Table 6 and shown in Figure 2 are the experimental results averaged over 6

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[2]This is of course a standard proposition in public-goods theory. As a slight qualification, however, there will in general be some "wealth effect" owing to the fact that each party's contribution enriches the other, thus making each of them reciprocally willing to purchase somewhat more of the public good. No wealth effect is allowed for in the experimental Marginal Benefit schedule given to the subjects. It has been shown, however, that in the provision of public goods any such wealth effect will essentially always be of negligible magnitude [McGuire (1974), Margolis (1982), pp. 19-21].

periods and 3 replications, or 18 trial-pairs for each of the three social composition functions. As can be seen, the observed results square remarkably with the theoretical predictions. Furthermore, detailed inspection of the trial-by-trial data reveals that essentially all of such discrepancies as appear in the pooled averages were due to mistaken choices of subjects in their very first or second decision periods. (These discrepancies almost always took the form of an "excessive" contribution by the first-mover in the STANDARD SUMMATION and BEST SHOT cases, or a "deficient" contribution in the WEAKEST LINK case.) Thus, the parties were able to learn, despite the informational handicap to rationally optimal choice-making, very rapidly indeed. Hence our "predicted" results were satisfied quite remarkably, under what we regarded as a somewhat severe test.

One possibly puzzling aspect of the data is why, since under BEST SHOT the relation $Q = \max(q_1,q_2)$ applies on any given trial, the average observed social aggregate $Q = 4.062$ was not identical with the average observed $q_2 = 3.501$ -- which is the larger of the averaged q_1 and q_2. The reason is that although (as predicted) under BEST SHOT the second-mover's q_2 was in fact almost always larger than his partner's q_1, there were a few instances — particularly in early decision periods — in which q_1 was larger than q_2. Thus, the overall averaged Q ended up higher than the averaged q_2. A corresponding discrepancy in the other direction could have occurred under WEAKEST LINK, where $Q = \min(q_1,q_2)$ for any given trial. But in fact it never did; in the WEAKEST LINK experiments second-mover's contribution never exceeded first-mover's, and so the average of the Q provided was the same as the averaged q_2. Of course, given his informational situation it would never be rational under WEAKEST LINK for second-mover to exceed first-mover's contribution. This difference between the BEST SHOT and WEAKEST LINK outcomes is therefore another subsidiary confirmation of our rationality prediction.

The Sealed-bid Experiments

The informational obstacles to rational decision-making, already rather severe under the Sequential protocol, are considerably more onerous under the Sealed-bid protocol. In the Sequential experiments, one player at least -- the second-mover -- could always make his or her decision with all relevant information in the open. Under Sealed-bid, in contrast, both players must act in the dark. Not only does this make the decision at any moment more difficult, but it also makes learning from experience much harder. So in this group of experiments we anticipated a considerably less perfect match between theoretical and actual results. (Indeed, as will be shown shortly, the theoretical "predictions" themselves become somewhat problematic.) Because of the greater anticipated variability of results, in this group of experiments we generally allowed for more periods of learning and more replications as indicated in Table 2. Table 7 and Figures 3a through 3c summarize the predictions and actual observations under the Sealed-bid protocol.

In the Sequential experiments discussed previously, for purposes of prediction we were able to employ the "perfect equilibrium" concept -- subject to the usual proviso about failure of the experimental environment to fully meet the informational conditions needed to guide the first-mover's rational decision. In the Sealed-bid experiments, for lack of any clear rational-choice basis for prediction we used the weaker "Nash equilibrium" (NE) solution concept. The Nash equilibrium, for present purposes, may be defined as a strategy-pair such that neither player would find it advantageous to revise his choice given the other's selected strategy. But it turns out that the NE is not unique in any of the cases considered, hence a supplementary principle or principles must be appealed to. We called upon two such

TABLE 7

Predicted and Actual Outcomes — Sealed-Bid Experiments

SOCIAL COMPOSITION FUNCTION	q_L	q_S	$\bar{q}$	Q	% of efficient total
STANDARD SUMMATION (SB-1)					
Predicted	2.0	2.0	2.0	4.0	33.3
Actual	3.063	.782	1.922	3.845	32.0
WEAKEST-LINK (SB-2)					
Predicted	4.0	4.0	4.0	4.0	100.0
Actual	4.287	3.290	3.659	3.290	82.3
BEST SHOT (SB-3)					
Predicted	.856	.052	.454	.856	7.1
Actual	3.129	.944	2.036	3.129	26.1

principles. The first is <u>symmetry</u>. Given the completely parallel situations of the two players in the Sealed-bid experiments, we selected as our predicted solution only among those NE's such that the members of each pair make equal contributions to the public good. We also had to employ one other supplementary principle, called <u>maximum mutual gain</u>, to be discussed shortly when the WEAKEST LINK case is taken up below.

Under STANDARD SUMMATION, the NE's constitute an infinite class of outcomes, to wit, the continuum of paired non-negative public-good provisions that sum to 4. Among the possibilities are $(q_1,q_2) = (0,4)$, $(3,1)$, $(2.5,1.5)$, etc. If, for example, the parties had chosen the respective provisions $(q_1,q_2) = (3,1)$, neither would be able to profit by a unilateral revision of his choice (see Figure 1). The sole symmetrical member of this class of solutions is obviously (2,2). Hence our predicted provisions of the public good are 2 for each player. In summarizing the actual data it will turn out to be convenient to report separately the average of the larger provisions in each pair, denoted q_L, and of the smaller, denoted q_S. In this symbolism, then, our prediction is $q_L = q_S = 2$, so that the social aggregate under STANDARD SUMMATION is $Q = 4$. Notice that while this predicted aggregate is the same as for STANDARD SUMMATION under the previous Sequential protocol, the predicted distribution within pairs is drastically different.

Turning now to WEAKEST LINK, here the Nash equilibria once again comprise a continuum of outcomes — to wit, all the pairs of the form (x,x) such that $0 \leq x \leq 4$. Possible instances include (0,0), (1.5,1.5), (3,3), and (4,4). Reference once again to Figure 1 will indicate that, for example, if the parties had each chosen to provide 3 units then neither member of the pair would want to unilaterally revise his choice. Here, since <u>all</u> the NE's are symmetrical, we must call upon our second supplementary principle -- maximum mutual gain. The justification is that since all the NE's pay off equally to the parties, the most attractive and only reasonable NE should be a "meeting of the minds" such that the mutual profit is as favorable as possible. Using this supplementary principle in addition to symmetry, the predicted provisions are $q_L = q_S = 4$. Under the WEAKEST LINK social composition function, the aggregate quantity of the public good will be $Q = 4$.

Finally, under the BEST SHOT social composition function matters are somewhat complicated. There are only two deterministic NE's -- in each of which one player provides 4 units of the public good, and the other none. Both of these solutions evidently fail to satisfy the symmetry principle. There is however a mixed-strategy NE that is symmetrical. We will have to digress somewhat to explain the calculation involved.

First, when probabilities are taken into account the parties would have to calculate in terms of their respective net dollar payoffs, or "profits". Table 8a shows the respective profits for the strategy-pairs involving integer values of q -- a limitation employed for tabular convenience only, since the experimental subjects were not constrained to choose integer values. Unfortunately, calculation of the mixed-strategy Nash equilibrium is no trivial task; the true symmetrical NE is a probability density over the entire interval from $q = 0$ to $q = 4$. We will instead cut the Gordian knot, and choose a probability mixture involving only $q = 0$ and $q = 4$ -- the two strategies that had entered into the deterministic but asymmetrical NE's. This mixture will not properly be an NE, but is a practicable strategy whose payoffs are a reasonable approximation of the true symmetrical NE. Thus our

TABLE 8a

Profits For BEST-SHOT Strategy-Pairs

	4	3	2	1	0
4	.42,.42	.42,1.24	.42,2.06	.42,2.88	.42,3.70
3	1.24,.42	.39, .39	.39,1.21	.39,2.03	.39,2.85
2	2.06,.42	1.21, .39	.31, .31	.31,1.13	.31,1.95
1	2.88,.42	2.03, .39	1.13, .31	.18, .18	.18,1.00
0	3.70,.42	2.85, .39	1.95, .31	1.00, .18	0,0

TABLE 8b

Calculation of Expected Profit and Provision if $p = .1135$

Outcome	q_L	q_S	$\bar{q}$	Q	Profit to Row player	Probability
(4,4)	4	4	4	4	.42	.0129
(4,0)	4	0	2	4	.42	.1006
(0,4)	4	0	2	4	3.70	.1006
(0,0)	0	0	0	0	0	.7859
						1.0
EXPECTATIONS	.856	.052	.454	.856	.42	

"predicted" mixed strategy for each player is:[3,4]

Provide $q = 4$ with probability .1135

Provide $q = 0$ with probability .8865

The corresponding expected (probability-weighted) outcomes and profits, if the parties indeed adopt this mixed strategy, are calculated in Table 8b. Notice that, as shown in Table 8b and also Table 7, the average social aggregate predicted, Q, equals the average $q_L = .856$ units. But Q is somewhat less than twice the average provision $\bar{q} = .454$, because the contributions entering into the smaller provisions within each pair, q_S, are wasted from the social point of view.

As summarized in Table 7, the results in the Sealed-bid experiments are disappointing in comparison with the excellent matches between predicted and actual results under the Sequential protocol. The one exception is the WEAKEST LINK case, where the observed results here do track the theoretical prediction reasonably well — though still not nearly as closely as under the previous protocol.

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[3]The basis for the calculation is as follows. Each player wishes to choose a probability p of providing $q = 4$ units and $1-p$ of providing $q = 0$ units, such that his partner is indifferent between playing $q = 0$ or $q = 4$ (or any mixture thereof). Using the profits in Table 8a, if the opponent is the Column player, the Row player will set:

$$.42p + .42(1-p) = 3.70p + 0(1-p)$$

or,

$$.42 = 3.70p$$

Thus the solution is $p = .1135$. Because of the symmetry of the situation, the other player comes to the same conclusion.

[4]In the true continuous Nash equilibrium, there would be no profit gain to either player from diverging. The 2-point approximation given in the text does allow a gain of around 20% to optimal divergence. The next-order approximation would have the players choose $q = 4$, $q = 2$, and $q = 0$ with respective probabilities .0629, .0961, and .8410. This 3-point approximation allows a gain of only about 5% from optimal divergence.

For STANDARD SUMMATION, the predicted equal distribution of the public-good provision, $q_L = q_S = 2$, was not borne out. It looks as if the partners were groping in the dark, trying out all kinds of possibilities, as evidenced by the huge spread between the average of the larger provisions $q_L = 3.063$ and $q_S = .782$ of the smaller. Surprisingly, the average social aggregate $Q = 3.845$ was quite close to the theoretical prediction $Q = 4$. But this average is misleading, as it hides the serious undershooting and overshooting that occurred in many cases and caused a loss of profit to the players. (As will be discussed further in the section following.)

Finally, for BEST SHOT the shoe is somewhat on the other foot. Here the larger vs. smaller relative provisions are heavily disproportionate as predicted. But in aggregate, far more units are being provided than predicted. (In consequence, however, the parties are getting substantially closer to the efficient solution -- in fact, they are generating an average 26.1% of the efficient number of units, rather than the mere 7.1% that the theory indicated.)

As another point of interest, recall that under BEST SHOT the true mixed-strategy NE was too onerous for us to compute. Our "predictions" were therefore based upon an approximation, the best mixture of the two pure strategies $q = 0$ and $q = 4$. Inspection of the detailed trial-by-trial results indicates that, after the first few periods, almost all the subjects indeed actually chose either $q = 0$ or $q = 4$ -- implying that they had arrived at the same simplification of the problem as had suggested itself to us in our theoretical development. However, even in the later trials, the subjects chose $q = 4$ too often. The result looks almost as if, short-cutting the detailed calculation of Table 8b, the subjects had guessed intuitively at a 50:50 ratio between the two undominated strategies. Unfortunately, given the very divergent profits, the correct proportions assign much more weight to $q = 0$ than to $q = 4$. Nevertheless, despite the considerable quantitative discrepancies between the predicted and actual results on average, the detailed picture is not entirely discouraging as evidence of rational behavior on the part of the subjects.

5. Provision Versus Profit

Up to now our discussion has run entirely in terms of individual and social provisions of the public good: the efficient, predicted, and experimentally observed magnitudes q_i and Q. For some purposes, particularly with regard to degree of efficiency achieved, it is more accurate to think in terms of "profits". In Figure 1, an individual's profit π_i is the sum of his Marginal Benefits for the number of units socially provided by both partners together, less the cost of whatever units he provides himself.

Table 9 compactly summarizes our previous results in terms of the provision (q) magnitudes, and juxtaposes them against the corresponding profit (π) magnitudes. In the first part of the Table, reporting on the Sequential protocol (experiments SQ-1 through SQ-3), q_1 and q_2 signify as before the individual provisions of the public good and π_1 and π_2 the respective profits — subscript 1 referring to the first-mover and subscript 2 to the second-mover in each trial. In the second part of the Table, reporting on the Sealed-bid protocol (experiments SB-1 through SB-3), subscripts L and S again refer to the larger and the smaller contributor to the public good in each pair.

Among the points of interest brought out, in comparing the results in terms of public-good provisions versus profits, are the following:

1. Quite commonly, the partner contributing the smaller provision reaps the larger profit, a result stemming from the nature of public goods and the

TABLE 9

Tabulation of Provisions of Public Good (Q) and Profits (π)

Sequential protocol

	q_1	q_2	Q	% of efficient Q	π_1	π_2	Π	% of efficient Π
STANDARD SUMMATION (SQ-1)								
Efficient	Indeterminate		12	100%	Indeterminate		7.56	100%
Predicted	0	4	4	33.3	3.70	.42	4.12	54.5
Observed	.436	3.778	4.204	35.0	3.493	.744	4.237	56.0
WEAKEST LINK (SQ-2)								
Efficient	4	4	4	100%	.42	.42	.84	100%
Predicted	4	4	4	100	.42	.42	.84	100
Observed	3.938	3.889	3.889	97.2	.377	.417	.794	94.5
BEST SHOT (SQ-3)								
Efficient	12 or 0	0 or 12	12	100%	8.70 or -1.24	-1.24 or 8.70	7.56	100%
Predicted	0	4	4	33.3	3.70	.42	4.12	54.5
Observed	.629	3.501	4.062	33.8	3.227	.873	4.100	54.2

Table 9 (continued)

	q_L	q_S	Q	% of efficient Q	π_L	π_S	Π	% of efficient Π
Sealed-bid protocol								
STANDARD SUMMATION (SB-1)								
Efficient	Indeterminate		12	100%	Indeterminate		7.56	100%
Predicted	2	2	4	33.3	2.06	2.06	4.12	54.5
Observed	3.063	.782	3.845	32.0	.828	2.640	3.468	45.9
WEAKEST LINK (SB-2)								
Efficient	4	4	4	100%	.42	.42	.84	100%
Predicted	4	4	4	100	.42	.42	.84	100
Observed	4.287	3.290	3.290	82.3	-.386	.381	-.005	-0.6
BEST SHOT (SB-3)								
Efficient	12 or 0	0 or 12	12	100%	8.70 or -1.24	-1.24 or 8.70	7.56	100%
Predicted	.857	.052	.857	7.1	.090	.750	.84	11.1
Observed	3.129	.944	3.129	26.1	.288	2.080	2.368	31.3

benefit of free-riding.

2. In terms of efficiency achieved, the results tend to "look better" when scaled in terms of aggregate profit Π rather than in terms of aggregate social provision Q. The reason is that an efficiency failure essentially always takes the form of a shortfall in the social provision of the public good; given the fact of diminishing returns, the shortfall involves units of lower Marginal Benefit than the units actually provided. This argument also indicates why efficiency is more correctly measured in terms of aggregate profit, not in terms of the number of units of the public good provided.

3. One notable exception to the preceding generalization is the result for WEAKEST LINK under the Sealed-bid protocol. Here the observed individual and aggregate provisions q_S, q_L, and Q all are not too far from the 100% efficiency predictions, but the π_L and Π profit observations are way off the mark -- in fact, π_L is so heavily negative as to just tilt Π into the negative region. But these anomalies are somewhat "accidental." It so happened that in WEAKEST LINK the theoretical aggregate profits are very small in magnitude compared to the other two social composition functions -- .84 versus 7.56. Since each single unit provided costs .82, any substantial error made by any individual -- particularly an overshooting -- even on a single trial was liable to seriously affect the overall average. What occurred here, specifically, is that in the very first period when the subjects were still operating entirely in the dark, one player in each of two experimental pairs overshot by enough to generate a relatively huge negative profit. These two instances were numerically heavy enough to dominate the average calculated over 50 trials, since in all the other cases the observed profits were (as predicted) quite close to zero in numerical magnitude.

4. In one case (STANDARD SUMMATION under the Sealed-bid protocol), the aggregate Q observed squares nicely with prediction whereas the aggregate Π observed does not. The reason is, as indicated earlier, that the average aggregate Q represented a cancelling-out of some instances of serious undershooting and overshooting. Hence in this case the efficiency achieved as measured by profit looks worse (and actually is worse) than the efficiency indicated by the Q measure.

6. Summary and Discussion

The experiments reported on here were intended to test the voluntary private provision of public goods when individual choices are subject to alternative social composition functions and to alternative decision protocols. With regard to social composition functions, the usual assumption is that the available social aggregate of a public good is simply the sum of the amounts individually provided — called here STANDARD SUMMATION. Recent theoretical investigations have indicated that this case is only one point along a spectrum of possibilities. At one extreme of the spectrum (called here WEAKEST LINK) the social aggregate is the minimum of the individual provisions; at the other extreme (called BEST SHOT) it is the maximum of the individual provisions. In comparison with the well-known tendency for under-provision of the public good (relative to the efficient social aggregate) in the STANDARD SUMMATION case, this theoretical development indicates that social groups in WEAKEST LINK environments should do substantially better, whereas in BEST SHOT environments the extent of underprovision should be even worse.

Attending to the necessity of conducting an actual real-world experiment highlights the importance of precisely specifying the protocol under which individual decisions are made. The protocol represents, essentially, the "rules of the game." Among other things it indicates in what sequence the players move, and what information is at their disposal at each step. In the experiments reported upon here two alternative protocols were employed: Sequential and Sealed-bid. Our groups were always of size 2, with the partner's identity unknown to the subjects (and changing each period). Individuals knew their own benefit and cost functions, but were not given the corresponding data about their partners; in fact, these were identical for all the subjects. One of the objects of the experiment was to test the ability of the subjects to (in effect) learn this missing information as they gained experience through multiple periods of play.

In the experiments conducted under the Sequential protocol, the second-mover in each trial was informed of his partner's prior move, and hence could directly compute his profit-maximizing choice. Learning was therefore useful mainly for first-movers. In the Sealed-bid experiments, in contrast, choices were made simultaneously so that both partners were in the dark. Here the informational obstacle to rational decision-making was far more onerous, the need to learn therefore greater, but the problem of making inferences from previous observations also more difficult. Despite these informational handicaps, our hypothesis for both protocols was that the subjects would on average make the "correct" rational self-interested choices. More specifically, our "predicted" results in effect assumed that (i) each individual was a rational self-interested decision-maker, who knew that his partner was as well, and that (ii) everyone acted as if he had learned that his partner's cost and benefit functions were the same as his own.

For the Sequential experiments, these "correct" choices correspond to the perfect equilibrium solution concept in game theory. The observed results in all these experiments squared with prediction quite remarkably — both in terms of the aggregate amounts voluntarily provided and the distribution of provision between first-mover and second-mover.

For the Sealed-bid experiments, the informational obstacles are such that even the theoretical solution concept may be subject to some question. The perfect equilibrium concept being inapplicable, we employed the weaker Nash equilibrium (NE) solution concept. But, as the NE is non-unique, we supplemented it by calling upon the symmetry principle (justified by the parallel situations of the partners in each trial) plus the assumption that, among symmetrical solutions, the partners would find the one involving maximum mutual gain. The observed experimental results, in general, did not square very well with predictions under the Sealed-bid protocol. Only for WEAKEST LINK were both the aggregate magnitude of provision and the distribution between partners reasonably close. For STANDARD SUMMATION the aggregate was not too far off, but the average spread between larger and smaller contributors in the different pairs was much too great. For BEST SHOT, on the other hand, the proportions between larger and smaller contributors were fairly reasonable, but the aggregate provided was far greater than called for in the theoretical solution.

For the Sequential experiments, our results may be interpreted as confirming a compound hypothesis, to wit, that the subjects: (a) acted in a rational self-interested way, (b) believed that their partners would do the same, and (c) were able to learn (or at any rate, to act as if they had learned) that their partners' benefit and cost functions corresponded to their own. For the Sealed-bid experiments, this compound hypothesis was not confirmed. But it is not entirely clear which portion or portions failed. In particular, three possible sources of difficulty suggest themselves. First, just what "rational" behavior consists of under Sealed-bid (simultaneous-move) conditions is not absolutely evident, even had the subjects been informed about the partners' benefit and cost functions. That the Nash equilibrium concept, supplemented as it had to be with two ancillary principles needed to narrow down to a unique prediction, can be equated with rational behavior may be somewhat debatable. Second, as our main text showed, in at least some cases the actual computations involved (see Tables 8a and 8b) are far from trivial even for a subject deliberately attempting to employ the solution concept. And third, for all these reasons the problem of learning about partners' payoffs was correspondingly more difficult. It is hoped that future experiments will cast additional light upon why the results under the alternative protocols were so different.

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Figure 1

MARGINAL BENEFIT (MB) AND MARGINAL COST (MC) SCHEDULES

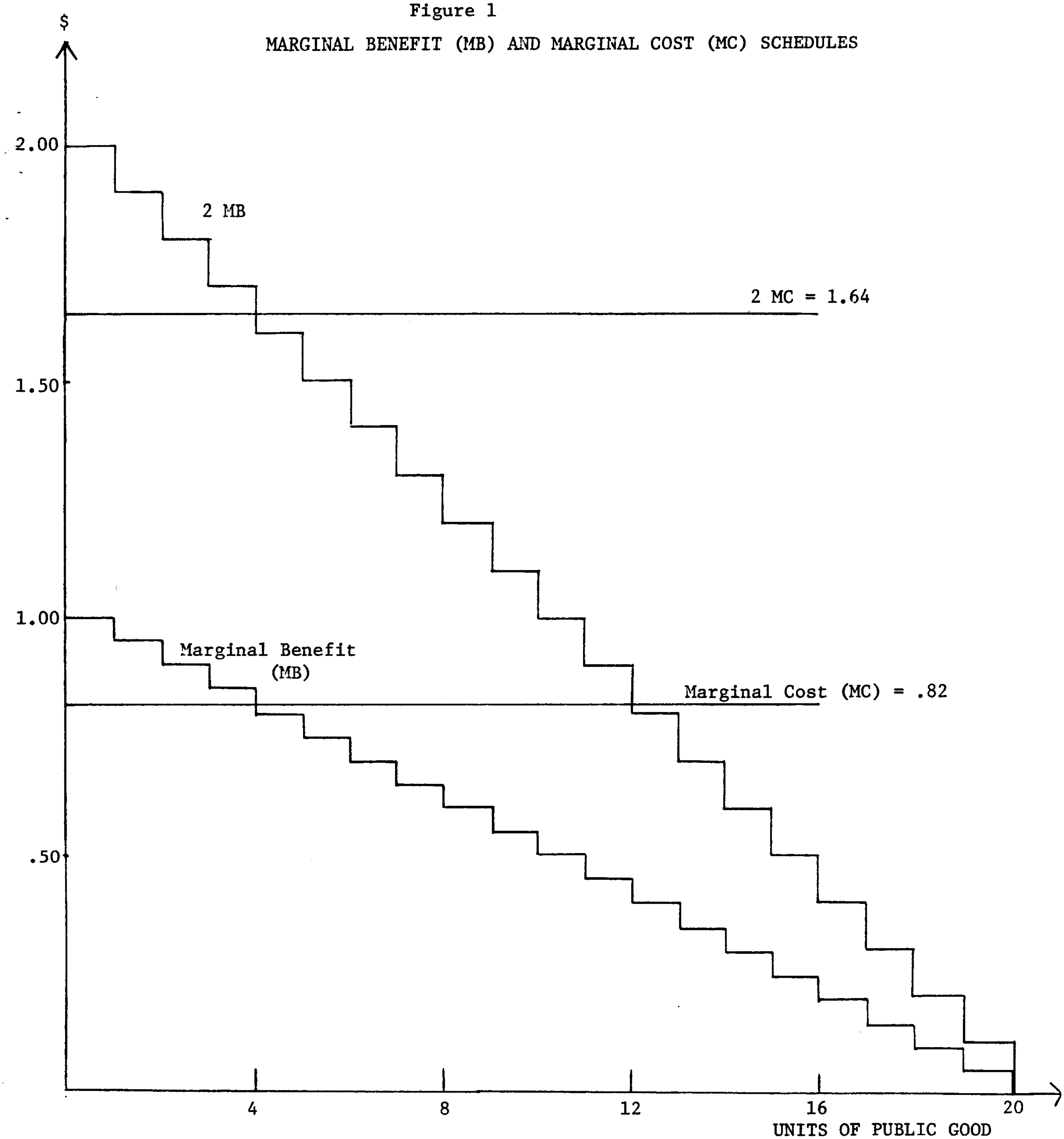

Figure 2
PREDICTED AND ACTUAL OUTCOMES OF SEQUENTIAL EXPERIMENTS

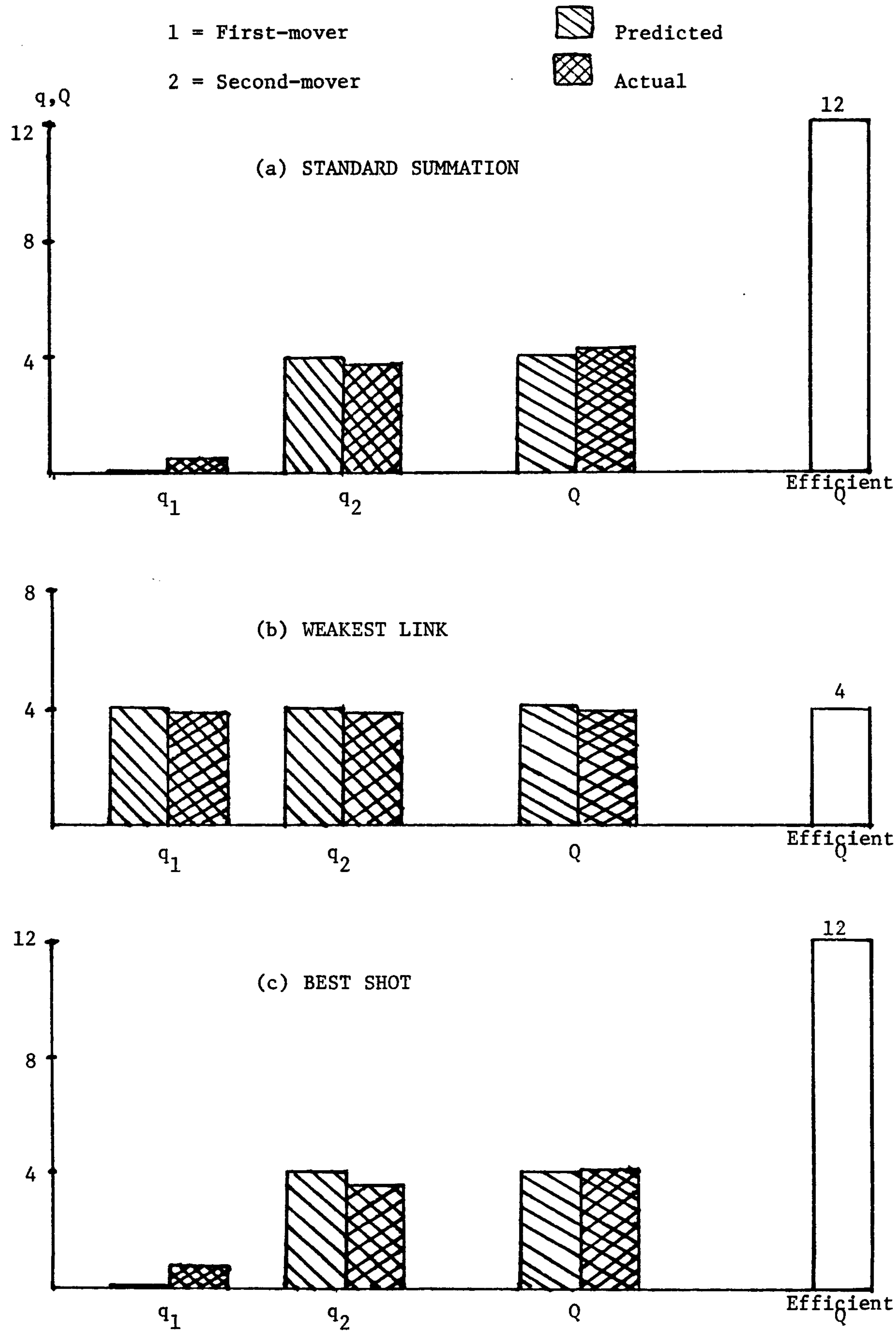

Figure 3
PREDICTED AND ACTUAL RESULTS OF SEALED-BID EXPERIMENTS