Public goods provision by asymmetric agents: experimental evidence

Matthew McGinty · Garrett Milam

Abstract Economic theory predicts that individuals will free-ride, providing sub-optimal Nash equilibrium quantities of public goods. However, 25 years of experimental evidence indicates that individuals' behavior often differs from the Nash prediction. This experiment examines provision in the context of asymmetric benefits and asymmetric costs of providing a public good with declining marginal benefits and increasing marginal costs. The design eliminates the coordination problem at the individual level inherent in previous declining marginal benefit experiments. Yet, even with the improved theoretical design, over-contribution persists, suggesting that it is a behavioral phenomenon rather than a design artifact. Analysis of individual contributions indicates that subjects' responses to asymmetry match the theoretical prediction in 3 out of 4 single asymmetry cases. Thus, although over-contribution remains, the theoretical role of asymmetry is confirmed.

1 Introduction

Standard neoclassical economic theory predicts that public goods will be under-provided as individuals' free-ride on the efforts of others. However, voluntary public good contribution is observed in both real-world and laboratory settings. Public good contribution has been widely studied in the laboratory using the voluntary contributions mechanism (VCM). Ledyard (1995) and Laury and Holt (2005) detail the

M. McGinty (✉)
Department of Economics, University of Wisconsin-Milwaukee, P. O. Box 413,
Milwaukee, WI 53201, USA
e-mail: mmcginty@uwm.edu

G. Milam
Department of Economics, University of Puget Sound, Tacoma, WA, USA
e-mail: gmilam@pugetsound.edu

development of experimental work in this area and describe a set of stylized facts regarding common patterns of behavior. Most robust of these is persistent contributions in excess of the Nash equilibrium, greatest initially and then decaying as rounds progress.

An important application of this research involves voluntary environmental agreements, under which agents commit to costly abatement activities. Such agreements range in scale from local community-based organization to efforts to abate global emissions of greenhouse gases by countries. Generally, parties receive different benefits from abatement, and there are vast differences in the cost of abatement. Nations that use a relatively clean mix of fuels, such as Japan, face a much steeper marginal cost curve than nations that have a more carbon intensive mix of fuels (Ellerman et al. 1998). These asymmetries alter the incentives to free-ride on the abatement of others in important ways. McGinty (2007) models the impact of such asymmetry on Nash equilibrium and optimal abatement, showing that asymmetry can increase both the Nash and optimal levels of public good contribution, compared to the seminal symmetric model of Barrett (1994).

This paper investigates the impact of asymmetry in a voluntary public goods environment by proposing an improved design that clearly isolates individual incentives without assuming a dominant strategy. We do so by introducing asymmetry with both declining marginal benefits and increasing marginal costs. Subjects have either a high, low or symmetric benefit from the public good. Furthermore, the marginal cost curves have either a high, low or symmetric slope. This generates unique interior individual Nash equilibria for each of the nine combinations, and allows a much richer set of hypothesis tests. The Nash predictions range from 9 to 52 % of subjects' endowments. Following Willinger and Ziegelmeyer (2001), over-contribution is defined as that portion of the endowment beyond the Nash equilibrium that is contributed to the public good (Over-contribution $\equiv \frac{\text{actual} - \text{Nash}}{\text{endowment} - \text{Nash}}$). We find an overall average over-contribution rate of 17.8 %, which is lower than previous standard VCM experiments, and a significant pattern of time decay.

While over-contribution persists both with and without asymmetry, the influence of asymmetry on contribution levels is as predicted. Controlling for individual, treatment order, and time period fixed effects, we find that subjects respond to asymmetry of either costs or benefits as predicted in three of four cases. In these cases, we fail to reject the hypothesis that the coefficients measuring the influence of asymmetry are identical to those predicted by theory. When both benefits and costs are asymmetric the responses are smaller in magnitude than predicted, but in the proper direction. After controlling for other factors, the point estimate of the intercept is significantly greater than predicted, indicating over-contribution. Over-contribution is robust to an improved design, suggesting it is a behavioral phenomenon rather than a design artifact.

The experimental literature on public goods contribution examines only limited forms of asymmetry. Ledyard (1995) surveys the linear public goods literature featuring asymmetry of agent benefits and conjectures a negative effect on contributions, but concludes with a call for further study. Subsequently, Croson and Marks (1999) examined asymmetry in a threshold public goods environment and found little impact on average aggregate contributions but higher volatility with asymmetry. Chan et al.

(1999) examine the impact of communication and information in an environment where benefits and endowments are asymmetric. They find that benefit asymmetry has a positive effect on contributions, but only in conjunction with endowment asymmetry. In the present paper, asymmetry takes the unique form of allowing both the marginal benefit and the marginal cost slopes to simultaneously differ. As the practical example of IEAs makes clear, it is important to allow asymmetry in both dimensions, which previous literature has not considered.

Similar to our model, three previous experiments obtain a unique interior Nash equilibrium without inducing a dominant strategy solution. Andreoni (1993) pioneered the use of a Cobb-Douglas utility function in VCM experiments. This generates declining marginal benefit and increasing marginal cost. Andreoni's subjects have symmetric payoff functions and interact in small groups of three. He tests whether government contributions financed by an income tax crowd out private contributions to a public good. What is relevant for this paper is that, unlike prior work, Andreoni finds contributions below the Nash equilibrium when there is no government contribution.

Cason et al. (2002) and Cason et al. (2004) also utilize a symmetric Cobb–Douglas utility function. Group size is two, which allows for an analysis of pair-wise punishment. They implement a two-stage VCM where players can commit to contribute nothing in the first stage. The commitment decision is revealed to the other group member and then a standard VCM occurs in the second stage. They observe less commitment than predicted and commitment levels fall over time. The reason is that a commitment of zero is punished in the second stage by the other member of the group, and consequently there is less free-riding in later periods. The punishment is a contribution below the Nash level. The authors describe this punishment as spiteful since those who punish earn a lower payoff by doing so. However, this reduces the payoff difference between the two players since the punishment is greater than the cost. Their findings are consistent with Fehr and Schmidt (1999) model of inequity aversion.

While VCMs with government contribution or multiple stages provide additional insight into subjects' behavior, this paper argues that the incentives in a standard single stage VCM have not been fully investigated. We introduce asymmetry in two dimensions and test larger groups of six subjects.

The remainder of the paper is organized as follows. The theoretical model is presented in Sect. 2, defining the Nash and optimal levels for both individuals and the group. A comparison with previous VCM experiments highlights the improved design. The experimental environment is described in Sect. 3 detailing the data set and how subjects interact. Section 4 presents descriptive and regression results from fixed effects models. Section 5 concludes and suggests further research.

2 Theoretical model with asymmetry

The experimental design utilizes a voluntary contribution mechanism (VCM) where agents divide their endowment, e, between a contribution q_i to the production of a public good and the remainder $e - q_i$ which solely generates private benefits. Benefits from public good production feature diminishing returns according to the function

$G_i(Q) = b\alpha_i \left(aQ - \frac{Q^2}{2}\right)$, where $Q = \sum_{i=1}^{n} q_i$ is aggregate contribution across the n members of the beneficiary group, and $\alpha_i > 0$ is the individual benefit parameter which allows for asymmetry of public benefits across agents. Endowment units retained for private consumption $(e - q_i)$ similarly generate diminishing marginal benefits, implying increasing marginal opportunity cost from public contributions. The private benefits are equal to $P_i(q_i) = c_i \left(d\,[e - q_i] - \frac{[e-q_i]^2}{2}\right)$, where $c_i > 0$ is the agent specific parameter which allows for asymmetry in this opportunity cost. The remaining variables, a, b, and d are non-negative scale parameters.

Following the convention of VCM games, total benefit to player i is simply the sum of these components.

$$\pi_i = G_i(Q) + P_i(q_i) \tag{1}$$

The scale parameters are defined such that agents with a variety of cost and benefit parameters face incentives for partial contribution toward public good production. This is easily seen by examination of the marginal per capita return (MPCR) to contributions toward the public good: MPCR $= (dG_i/dq_i)/(dP_i/dq_i)$. Diminishing returns from each resource use imply that the MPCR is decreasing in q_i. Our parameterization ensures that the MPCR reaches unity for all agents for levels of q_i which are strictly interior to the endowment space as described in the formal solution below.

Two restrictions allow us to simplify the payoff structure in order to focus on the impact of cost and benefit asymmetry. Setting a equal to the sum of all agents' endowments, ne, scales the public good benefit function such that full contribution by all generates zero marginal benefit from the last unit contributed. Coupled with positive marginal cost of contribution, this emphasizes the interior Nash equilibrium and social optimum contribution incentives. Similarly, we restrict d to be equal to the endowment level, e. This scales the private benefit such that allocating nothing to the public good generates zero marginal benefit on the final unit of endowment retained. To consolidate the analysis around the single choice variable q_i, we henceforth interpret this as the marginal cost of allocations toward the public good. The above restriction on d ensures non-negativity of cost for all agent types, as dP_i/dq_i becomes a ray from the origin with slope $-c_i$.

The individual optimum is the choice of q_i that maximizes (1). The reaction function for player i is

$$q_i^r = \frac{c_i(e - d) + b\alpha_i(a - Q_{-i})}{c_i + b\alpha_i} \tag{2}$$

where $Q_{-i} = \sum_{j \neq i}^{n} q_j$. Defining the ratio of benefit coefficient to marginal cost slope as $\theta_i \equiv \frac{\alpha_i}{c_i}$, the individual and aggregate Nash equilibrium levels of public good
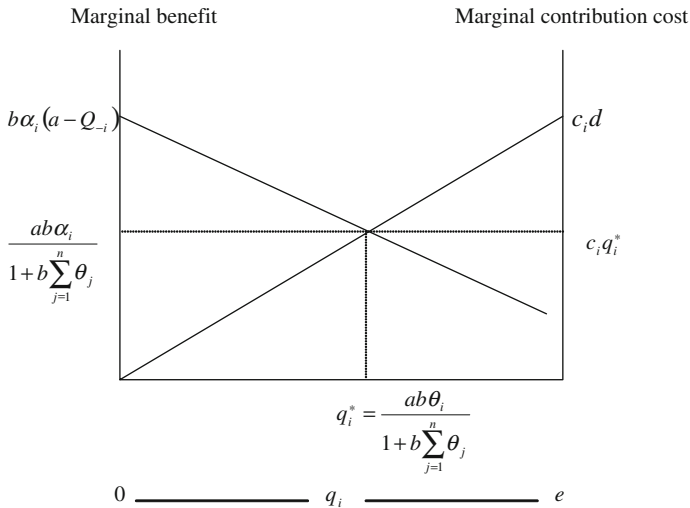
Marginal benefit   Marginal contribution cost

$b\alpha_i(a - Q_{-i})$ $c_i d$

$\dfrac{ab\alpha_i}{1+b\sum\limits_{j=1}^{n}\theta_j}$ $c_i q_i^*$

$q_i^* = \dfrac{ab\theta_i}{1+b\sum\limits_{j=1}^{n}\theta_j}$

0 ———————— q_i ———————— e

Fig. 1 Individual Nash equilibrium

contribution are q_i^* and Q^*, respectively.

$$q_i^* = \frac{ab\theta_i}{1 + b\sum_{j=1}^{n}\theta_j} \qquad (3)$$

$$Q^* = \frac{ab\sum_{j=1}^{n}\theta_j}{1 + b\sum_{j=1}^{n}\theta_j}$$

Equation (3) implies that subjects will contribute to the public good in proportion to their θ's. The individual Nash equilibrium for the experimental design is depicted in Fig. 1. In the figure, marginal benefit is dG_i/dq_i and marginal contribution cost is $-dP_i/dq_i$.

We adopt the common utilitarian social welfare function which places an equal weight on each group member's utility. Social welfare becomes a simple sum of subjects' payoffs, and the optimal level of Q maximizes aggregate payoff, $\Pi \equiv \sum_{i=1}^{n}\pi_i$. The combination of a utilitarian social welfare function, concave benefits and convex costs results in a unique optimal level of contribution. The experimental parameters in Sect. 3 ensure that the optimal level occurs in the interior of the endowment space. The optimal level internalizes the positive externality that accrues to other players from public good contribution, and results in a cost-minimizing allocation of public good contribution at the individual level.

$$\Pi = \sum_{i=1}^{n} c_i\left(d\,[e - q_i] - \frac{[e - q_i]^2}{2}\right) + \sum_{i=1}^{n} b\alpha_i\left(aQ - \frac{Q^2}{2}\right) \qquad (4)$$

Optimization yields the optimal levels of public good contribution, q_i^o and Q^o.

$$q_i^o = \frac{ab}{c_i \left[1 + b \sum_{j=1}^{n} \frac{1}{c_j} \right]}$$

$$Q^o = \frac{ab \sum_{j=1}^{n} \frac{1}{c_j}}{1 + b \sum_{j=1}^{n} \frac{1}{c_j}} \tag{5}$$

The optimal level is independent of the distribution of benefit coefficients. Asymmetric cost slopes result in a strictly greater optimal level of the public good, since the sum $\sum_{j=1}^{n} \frac{1}{c_j}$ is minimized for symmetry. At the individual optimum, subjects provide the public good at a unique level that is inversely proportional to their marginal cost slopes. A subject with twice the marginal cost slope of another subject will provide half as much of the public good.

This design clearly isolates individuals' incentives. Nash equilibrium behavior given in Eq. (3) indicates that subjects will provide the public good in proportion to their benefit coefficient-cost slope ratio θ. There are unique interior Nash and optimal predictions at the individual level for nine different values of θ, without assuming orthogonal reaction functions.

Early VCM experiments obtain a unique contribution at the individual level only when there is a dominant strategy. Marwell and Ames (1981), and Isaac et al. (1984) pioneered the VCM in which subjects divide an endowment between a public and a private good. These VCM experiments utilize a linear payoff structure with constant marginal benefit for both goods. Since marginal benefit from the public good is below that of private consumption, the constant MPCR < 1 implies a unique Nash equilibrium strategy of $q_i = 0$ or complete free riding. Pareto optimality requires contributing the entire endowment to the public good. Isaac et al. (1984) find over-contribution is 42 %, typical of corner equilibria experiments. However, any contribution to the public good is over-contribution in this environment.

Responding to the call of Ledyard (1995), subsequent researchers introduced nonlinear payoffs for either the public or private good in order to generate an interior Nash equilibrium. However, both of these approaches have significant limitations. Following Isaac et al. (1985) the majority of researchers (for example Laury et al. 1999, and Sefton and Steinberg 1996) have adopted a declining marginal benefit, constant marginal cost VCM payoff structure. With symmetric agents, this payoff structure generates a unique Nash equilibrium allocation to public good provision. However, any sum of individual contributions that achieves Q^* is a Nash equilibrium. Individuals face a multiplayer "chicken game" where subjects benefit from free-riding on others' contributions and try to reduce their own portion of the group Nash as much as possible. Subjects have a strategic incentive to reduce their portion of Q^* knowing that other subjects will then have an incentive to increase their contribution. Thus, it is possible that the lack of a unique individual Nash equilibrium increases the volatility of subjects' behavior in a laboratory setting. With a concave payoff function over-contribution can easily result as an equal reduction below Nash generates a greater payoff difference than an equivalent increase above Nash.

Conversely, constant marginal benefit, increasing marginal cost experiments have a unique, interior, dominant strategy Nash equilibrium at the individual level. This approach has been taken by Keser (1996), Sefton and Steinberg (1996), and Willinger and Ziegelmeyer (2001). A unique, dominant strategy equilibrium results here at a contribution level which equates the constant marginal benefit from the public good with individual opportunity cost. However, there is no response to changes in others' level of contribution since marginal benefit is constant. While the individual Nash prediction is unique, an important component of the free-rider problem associated with public goods is assumed away. Typically, individuals reduce their contribution when others' contribution is high. However, with constant marginal benefit the reaction functions are orthogonal and each individual's contribution has no impact on the incentives of others. Even with a dominant strategy, the average over-contribution rate is 25 % for Keser (1996). Willinger and Ziegelmeyer (2001) find over-contribution is 30 % when the dominant strategy is to contribute 35 % of the subject's endowment. Willinger and Ziegelmeyer (2001) vary the equilibrium contribution levels and obtain interesting results. They find an average over-contribution rate of 2 % when the dominant strategy is 65 % of the endowment, but surprisingly this rises to 20 % when the dominant strategy is 85 % of the endowment.

3 Experimental environment

The treatment variables are the individuals' benefit coefficient from public good production, α_i, and the slope of their marginal cost curve c_i. The design is a three by two factorial where marginal cost slope and benefit coefficient are either symmetric or asymmetric. There are five treatments: symmetry, two with single asymmetry, and two with dual asymmetry. The single asymmetry treatments have either asymmetric benefits or costs, but not both, and the dual asymmetry have both asymmetric benefits and costs. Marginal cost slope is 3 for all players in the symmetric cost treatments. The asymmetric cost treatments have three high cost players with a slope of 4 and three low cost players with slope 2. Group size is six, so the symmetric benefit treatments have $\alpha_i = 1/6$ for all players. The asymmetric benefit treatments have three players with a 3/12 coefficient and three with a 1/12 coefficient. Both types of asymmetries are a mean preserving spread, however the benefit coefficients have a greater variance. Subjects received an endowment of 20 tokens each period for all treatments. Subjects were allowed to make contributions in 0.1 token increments. The remaining parameters are: $a = ne = 120$, and $b = 1$.

Table 1 presents the Nash and optimal levels for all five treatments. There are nine different values of θ_i, each resulting in a different Nash prediction at the individual level. There are four different Nash predictions at the group level. Optimal contributions respond only to differences in marginal cost slope, whereas Nash equilibrium values are uniquely determined by θ. All Nash and optimal contributions fall in the interior of the endowment space.

Table 1 allows us to examine a range of hypotheses regarding contribution behavior. If subjects exhibit Nash behavior, then the contribution levels for each θ type will change with the treatments. For example, we expect that a subject with high benefit

Table 1 Nash and optimal theoretical predictions at the individual and group level

	Individual					Group	
	Benefit	Cost	θ	Nash	Optimum	Nash	Optimum
Treatment	α_i	c_i	θ_i	q_i^*	q_i^o	Q^*	Q^o
Sym benefit, sym cost (SS)	1/6	3	1/18	5	13.3	30	80
Asy benefit, sym cost (AS)						30	80
High benefit individuals	3/12	3	3/36	7.5	13.3		
Low benefit individuals	1/12	3	1/36	2.5	13.3		
Sym benefit, asy cost (SA)						32.7	83.1
High cost individuals	1/6	4	1/24	3.6	9.2		
Low cost individuals	1/6	2	2/24	7.3	18.4		
Asy benefit, asy cost (AAHH)						28.6	83.1
High benefit, high cost individuals	3/12	4	3/48	5.7	9.2		
Low benefit, low cost individuals	1/12	2	2/48	3.8	18.4		
Asy benefit, asy cost (AAHL)						36.5	83.1
High benefit, low cost individuals	3/12	2	6/48	10.4	18.4		
Low benefit, high cost individuals	1/12	4	1/48	1.7	9.2		

will increase their contribution by 2.5 units in treatment 2, and a high benefit, low cost subject will increase their contribution by 5.4 units in treatment 5, relative to the symmetric benchmark. In the analysis below, we systematically test these predictions using a fixed effect panel regression to identify the degree to which agents respond to the incentives induced by the experiment. This allows us to more clearly identify links between public good contribution and the incentive effects resulting from different types of asymmetry.

Six laboratory sessions were conducted, three each at Ryerson University in Toronto and the University of Wisconsin-Milwaukee using undergraduate subjects recruited from a range of classes. Experimental sessions featured twelve subjects, randomly assigned to two separate groups. Subjects did not know the identity of the other group members. Each session consisted of five runs of the experiment, and each run lasted fifteen periods. Each subject participated in all five treatments, where the order was randomly determined. Subjects were randomly assigned to new groups at the end of each treatment. All six sessions were completed in under two hours, including instructions and trial periods. Subjects were paid their earnings in cash at the end of the session. Subjects earned an average of $28 including the $5 show-up fee. Earnings ranged from a low of $21 to a high of $35. The data set has 5,400 observations consisting of 75 contributions by 72 subjects. [1]

The experiment was programmed and conducted using the z-Tree software (Fischbacher 2007). Subjects were told their own cost and benefit parameters, as well as

---

[1] The matching procedure results in a "partial strangers" design. For this reason the regression analysis incorporates subject and time period specific fixed effect dummy variables and standard errors are adjusted for autocorrelation via Yule–Walker estimation since all 5,400 observations are not independent.
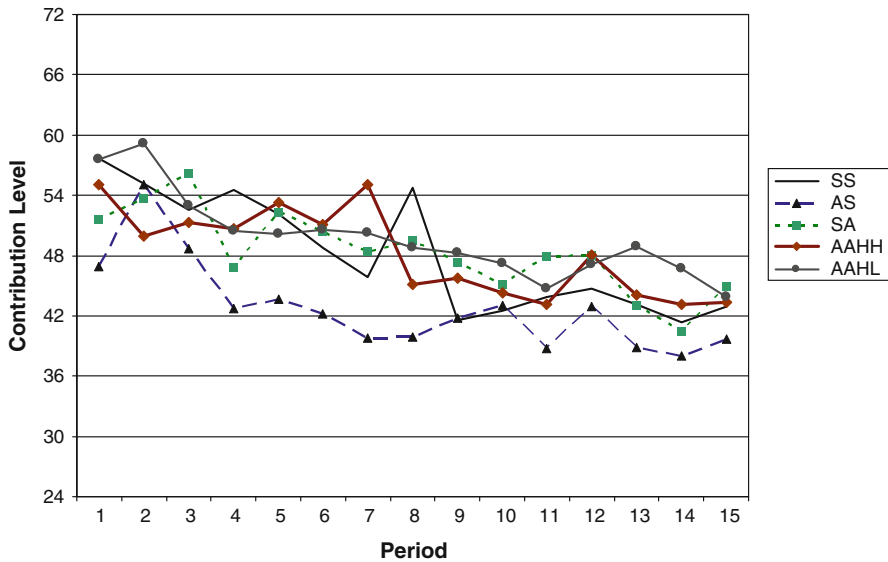
Fig. 2 Mean group contribution levels

those of other group members. Subjects were given a payoff table that showed the payoffs for each group member and the instructions in the Appendix. Subjects were provided a history of their allocation between private and public goods, and the total group contribution to the public good. However, subjects did not have information on the distribution of contributions by the other group members. Subjects had information on their payoff for the current and all previous periods.

4 Results

Figure 2 shows that contributions follow a common pattern in public goods experiments. For all five treatments, contributions are highest initially and then decline as periods progress. We isolate the role of asymmetry on these contributions by using a fixed effects panel regression with subject specific and period specific dummy variables. First, we begin with some basic descriptive statistics.

4.1 Descriptive statistics

Table 2 shows that over-contribution rates are between 14 and 22 % for the five treatments. These are generally lower than previous studies featuring interior Nash equilibria, where rates range from 42 to 20 % (Keser 1996; Willinger and Ziegelmeyer 2001; Laury et al. 1999). One contributing factor to this reduction is that our design has both declining marginal benefits and increasing marginal costs, making over-contributions increasingly costly in two dimensions. Over-contribution rates decline in later periods, but never fall below 10 %.

Table 2 Individual over-contribution percentage

	Periods			
	All	Early	Middle	Late
Treatment	1–15	1–5	6–10	11–15
Sym benefit, sym cost (SS)	20.1	27.3	18.5	14.6
Asy benefit, sym cost (AS)	14.2	19.3	18.5	10.7
Sym benefit, asy cost (SA)	18.9	22.3	12.6	13.9
Asy benefit, asy cost (AAHH)	21.2	24.6	21.5	17.5
Asy benefit, asy cost (AAHL)	14.4	17.9	13.9	11.6

Over-contribution $\equiv \frac{\text{actual}-\text{Nash}}{\text{endowment}-\text{Nash}}$

Next, we consider the impact of asymmetry on the aggregate level of public good contribution. Ledyard (1995) conjectures that asymmetry should reduce the level of contribution. Subsequent studies find little or no evidence of an impact of cost or benefit asymmetry on aggregate contributions, though these feature different environments.[2] Table 1 provides the four group Nash equilibrium predictions, ranging from 28.6 to 36.5. The levels of contribution in Fig. 2 are very similar across treatments, with the exception of treatment 2, asymmetric benefit. That is, the only identifiable impact occurs in the case for which Nash equilibrium predicts no difference from the symmetric benchmark. [3] In general, we find little support for Ledyard's conjecture that asymmetry leads to reduced contribution levels.

Apart from the asymmetric benefit treatment, contributions appear to stabilize at around 40 % of the aggregate endowment. This may lead one to infer that agents are largely ignoring rational incentives in their contribution decisions. However, a look at individual contributions across our nine agent types, shown in Fig. 3a–e, suggests otherwise. Subjects are clearly responding to the asymmetry of costs and benefits as expected, even if over-contribution persists. Contributions adjust toward the individual Nash equilibrium predictions over time for all treatments.

4.2 Regression results: identifying the influence of asymmetry

The nine Nash equilibrium predictions allow us to use regression analysis to identify the sources of contribution behavior. Due to repeated interaction and the pattern of time decay we estimate a fixed effect panel data model with subject and time period fixed effect dummy variables. In addition, due to repeated subject interaction within a treat-

---

[2] Croson and Marks (1999) study threshold public goods and Chan et al. (1999) feature endowment and benefit asymmetry, along with various information conditions.

[3] This is supported by a pooled t test of mean equality not reported here but available from the authors by request. Treatment 2 is significantly lower at a 1 % level than each of the other treatments.
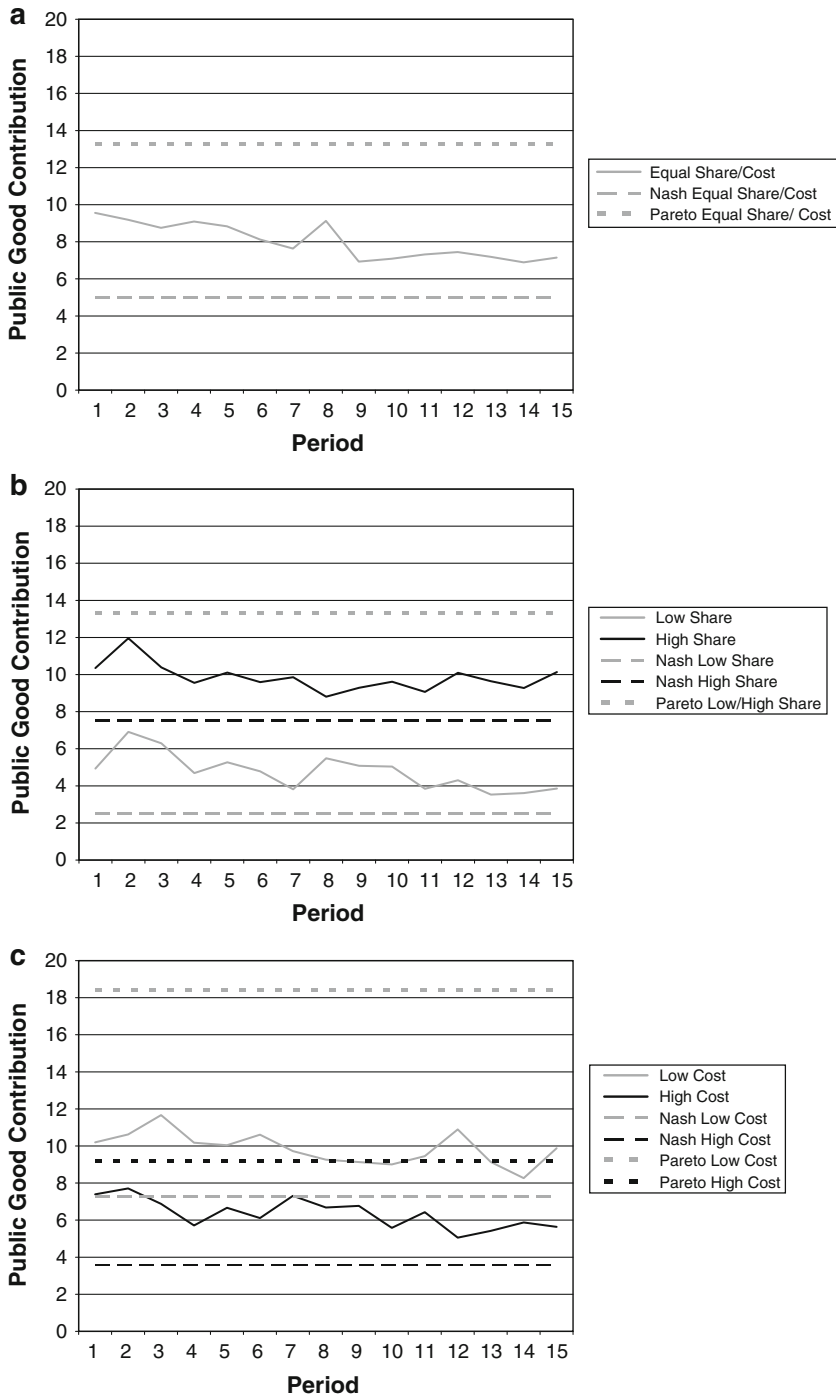
Fig. 3 **a** SS-mean individual contributions by share/marginal cost **b** AS-mean individual contributions by share/marginal cost **c** SA-mean individual contributions by marginal cost **d** AAHH-mean individual contributions by share/marginal cost **e** AAHL-mean individual contributions by share/marginal cost
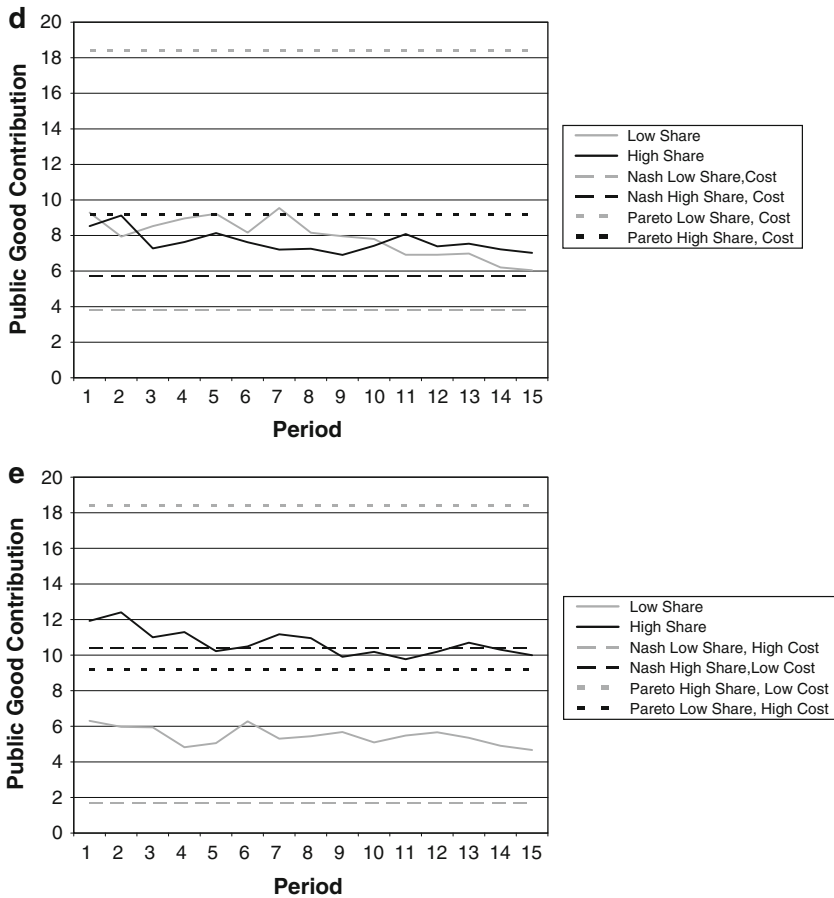
d

e

Fig. 3 continued

ment, we correct for autocorrelation in the errors using the Yule–Walker estimation method.[4]

First, we examine the evidence regarding the hypothesis that the contributions of all subject types correspond to the Nash equilibrium prediction once the order and fixed effects are removed.[5] The variables Run_j, $j \in [1..4]$ are dummy variables indicating the observation is from an experiment that was the jth run of the session. The excluded category is the 5th run. FE_i, $i \in [1..71]$ denotes a vector of subject specific dummy variables and similarly FE_t, $t \in [1..14]$ a vector of time period dummies.

---

[4] We considered dealing explicitly with repeated interaction by modeling contributions as quasi-best responses by backward looking agents to the contributions of other group members. This proved to have very little explanatory power.

[5] Excluded categories include period 15 and a subject whose contributions were on average very near the aggregate mean across treatments and sessions (subject 12, session 6).

Table 3 Model 1 and 2 regression results against null hypothesis of zero

Variable	Parameter estimate (*t* value) Model 1	Model 2	Variable	Parameter estimate (*t* value) Model 1	Model 2
Intercept	2.90 (4.82)	6.40 (10.61)	Period 1	1.66 (4.90)	1.66 (4.94)
Nash	0.65 (24.1)	na	Period 2	1.82 (5.38)	1.82 (5.43)
Alpha low	na	−2.63 (−10.41)	Period 3	1.40 (4.12)	1.40 (4.12)
Alpha high	na	1.96 (7.78)	Period 4	0.95 (2.81)	0.95 (2.83)
Cost low	na	2.56 (9.87)	Period 5	1.09 (3.21)	1.09 (3.24)
Cost high	na	−1.44 (−5.56)	Period 6	0.84 (2.47)	0.84 (2.49)
Alpha low cost low	na	0.12 (0.45)	Period 7	0.77 (2.27)	0.77 (2.28)
Alpha high cost high	na	0.05 (0.20)	Period 8	0.88 (2.59)	0.88 (2.61)
Alpha low cost high	na	−2.03 (−7.96)	Period 9	0.31 (0.90)	0.31 (0.91)
Alpha high cost low	na	2.65 (10.41)	Period 10	0.24 (0.70)	0.24 (0.71)
Run 1	0.71 (3.63)	0.87 (4.13)	Period 11	0.22 (0.64)	0.22 (0.64)
Run 2	1.44 (7.39)	1.50 (7.21)	Period 12	0.39 (1.14)	0.39 (1.15)
Run 3	0.53 (2.70)	0.54 (2.35)	Period 13	0.01 (0.34)	0.01 (0.34)
Run 4	−0.09 (−0.45)	−0.01 (−0.07)	Period 14	−0.21 (−0.62)	−0.21 (−0.62)

$N = 5400$, Model 1 $R^2 = 0.35$, Model 2 $R^2 = 0.36$

Excluded variables are a single subject ($i = 72$) and the 15th time period.

$$q_{it} = \text{Intercept} + \beta_1 q_i^* + \beta_2 \text{Run1} + \beta_3 \text{Run2} + \beta_4 \text{Run3} + \beta_5 \text{Run4} + \gamma_i FE_i$$
$$+ \delta_t FE_t + \epsilon_{it} \tag{6}$$

The regression results are given as Model 1 in Table 3. Tests of specific predictions appear in Table 4. The treatment order, which was randomized across sessions, appears to influence behavior. The first three of these are significant and positive, with higher coefficients for the first and second treatments. However, even controlling for order we see significant restart effects after each new group matching. The coefficients on the first eight period dummy variables are significant and positive. So, new group matches have a positive effect on contribution levels which decays with experience within the match. Thus, we are able to capture the contribution decay with these controls. This provides a sharper focus on our primary hypotheses.

The Nash equilibrium is a significant predictor of actual contributions at the 1 % level ($H_0 : \beta_1 = 0$). Nearly 2/3 of the variation in subject contributions is explained by the Nash prediction. However, subjects respond imperfectly as we are able to reject the hypothesis that contributions move in line with the Nash prediction ($H_0 : \beta_1 = 1, Intercept = 0$). The t statistic of 24.1 indicates that a very tight distribution around the 0.65 point estimate, rather than a large difference from the Nash prediction, accounts for the rejection of perfect correspondence to Nash. But do all subjects respond imperfectly or do the responses vary by type of asymmetry? Answering this question requires a closer look at the impact of each θ type separately.

Table 4 Model 1 and 2 hypothesis tests of equality versus predicted value

	Variable	Predicted	Point estimate (t stat)
Model 1	Intercept	0	2.90
			(4.82)**
	Nash	1.00	0.65
			(17.77)**
Model 2	Intercept	5.00	6.40
			(2.32)**
	Alpha low	−2.50	−2.62
			(0.51)
	Alpha high	2.50	1.96
			(2.12)*
	Cost low	2.30	2.55
			(0.99)
	Cost high	−1.40	−1.43
			(0.14)
	Alpha low cost low	0.70	0.12
			(2.15)*
	Alpha high cost high	−1.20	0.05
			(4.68)**
	Alpha low cost high	−3.3	−2.02
			(20.9)**
	Alpha high cost low	5.4	2.65
			(10.8)**

The null hypothesis is equality of predicted and actual values. $N = 5400$, Model 1 $R^2 = 0.35$, Model 2 $R^2 = 0.36$. * significant at 5 % level, ** significant at the 1 % level

Using a similar panel method but replacing the Nash prediction variable with eight θ-specific dummy variables (symmetric, symmetric is the excluded category) we are able to address variations across type. Model 2 in Table 3 reports the results.

$$q_{it} = \text{Intercept} + \beta_1 \alpha_{Hi} + \beta_2 \alpha_{Lo} + \beta_3 c_{Hi} + \beta_4 c_{Lo} + \beta_5 \alpha_{Hi} c_{Hi} + \beta_6 \alpha_{Lo} c_{Lo}$$
$$+ \beta_7 \alpha_{Hi} c_{Lo} + \beta_8 \alpha_{Lo} c_{Hi} + \beta_9 \text{Run1} + \beta_{10} \text{Run2} + \beta_{11} \quad (7)$$
$$\text{Run3} + \beta_{12} \text{Run4} + \gamma_i FE_i + \delta_t FE_t + \epsilon_{it}$$

The coefficients for each θ-type are significantly different from zero at the 1 % level with the exception of $\alpha_{Hi} c_{Hi}$ and $\alpha_{Lo} c_{Lo}$ from treatment 4. This supports the visual evidence in Fig. 3. Subjects are clearly responding to the individual payoff incentives and in the predicted directions. Table 4 tests the hypothesis that the subjects responses are equal to those predicted. It shows the predicted change from the symmetric benchmark, the point estimates, and the t statistic for the null hypothesis of equality of the two. In the four cases where either benefit or cost is asymmetric, the point estimates are very close to the predicted values, and in all but the high benefit case we can

not reject the null hypothesis of equality with predicted values. This suggests that, in cases of single asymmetry, subjects respond nearly as predicted to the introduction of asymmetry.In cases where benefit and cost asymmetry appear together, responses are smaller in magnitude than predicted. In all of these cases, we can reject equality of our point estimates and predicted responses. However, there are some noteworthy differences between the treatments. In treatment 4 where high (low) benefit subjects also face high (low) cost, the incentives of each type of asymmetry offset each other. Though the benefit asymmetry is predicted to have a stronger impact (making a net positive response for high benefit subjects and net negative for low benefit), looking at Table 3 we observe that the actual impact is not significantly different from zero.

In treatment 5 the asymmetries work in the same direction, resulting in the largest predicted differences from the symmetric Nash. Agents have a high benefit and a low cost, both of which increase the Nash equilibrium. The other agents have a low benefit and a high cost, both reducing the Nash equilibrium. Even though each combination of asymmetry exhibits significant responses in the proper direction, neither approaches the magnitude predicted by Nash behavior in treatment 5. Thus, compounding the benefit and cost asymmetry has a weaker impact than expected.

Taken together with the summary evidence from Fig. 3e, this suggests an important implication. Recall that for this treatment, median contributions were very near the Nash level of 10.4 for high benefit, low cost agents. Yet our regression results indicate that their response to Nash is incomplete. This suggests an interaction between the incentives leading to Nash behavior and those which explain observed over-contribution interact to achieve this result. That is, though we observe behavior in Fig. 3e which matches well with the Nash prediction, in fact a combination of underlying behavioral incentives and individual payoff maximization incentives contribute to this outcome.

This observation is further supported by examining the behavior of low benefit, high cost agents whose contributions in excess of Nash, as shown in Fig. 3e, are among the highest in spite of having the weakest individual payoff incentives. Thus the dampened, but significant, responses observed in this treatment indicate that behavioral motives for public good contribution persist even where incentives for individual payoff maximization are strong.

5 Discussion and extensions

Subjects clearly respond in the predicted manner to the introduction of benefit and cost asymmetries in the VCM. Even though subjects contribute in excess of the Nash prediction, we see that over-contribution rates are lower relative to previous designs. One source of this reduction is the structure of the payoff function. With decreasing marginal benefits and increasing marginal costs, the opportunity cost of public good contributions in excess of the equilibrium level increases more rapidly. The greater the deviation from Nash behavior, the greater the penalty.

The magnitude of subjects' responses is almost exactly as predicted in the single asymmetry treatments, even though over-contribution is present in all treatments. We fail to reject equality of the point estimates of the coefficients on the single asymmetry

dummy variables with their predicted values, with the exception of the high benefit coefficient dummy. Dual asymmetry results in responses that are smaller in magnitude than predicted by Nash behavior, after accounting for subject specific factors, order effects, and decay across periods. As the incentives from asymmetry predict larger deviations from the symmetric benchmark subjects respond, but incompletely. Our findings support the notion that over-contribution is a behavioral phenomenon, and that it is robust to an improved design with unique individual predictions in the interior of the endowment space.

None of our treatments approaches the optimal level, even though we observe significant over-contribution. The three treatments with the highest optimal levels: 3, 4, and 5, generate the greatest level of contributions. Policy instruments which exploit cost asymmetries could therefore play a welfare enhancing role, potentially facilitating contributions which more closely approach optimality.

Several behavioral factors may be generating the over-contribution. While it is possible that subjects are learning to the Nash levels across treatments, the significant restart effects suggest other motivations. Restart effects refer to the fact that contribution levels are initially high, but then decay, for each treatment after new groups of subjects were formed. It is more likely that many of the subjects hope that cooperation can be sustained, but revert to Nash behavior as other group members do so. While over-contribution persists, none of the nine types approach the optimal level.

A natural direction for future research concerns the potential for mutual gains from exchange in this asymmetric environment. Extending the experiment to allow low benefit, low cost agents to provide the public good in return for a set price would emulate a system of tradable pollution permits, such as the Kyoto Protocol. Theoretically, high benefit, high cost subjects would provide the public good up to the efficient level and then purchase units of the public good until the marginal benefit of the final unit is equal to the price. Such a trading scheme should increase the level of public good contribution, particularly when the price of a unit of the public good is set at the level that maximizes social surplus. The volume of permit trades and overall efficiency of the permit system would provide insight into permit markets. One factor such work might consider is the impact of various market institutions on the efficiency of exchange.

Appendix: Instructions

Overview

You have been randomly assigned to a group of six people. There are two six-person groups in this room. Each period you will be given a specific number of tokens to invest in two accounts. These accounts are called the individual fund and the group fund. Each token you invest in the individual fund will earn a return that depends on your

contribution and an individual return factor. Group members will be assigned either an equal or unequal return factor, x. For equal individual return runs all members will have $x = 3$. For unequal individual return runs, three members will have $x = 2$ and the other three will have $x = 4$. This factor represents a number by which your return from the individual fund is multiplied. The return from the individual fund is explained below and given on your payoff sheet in the table labelled "individual fund."

Group members will receive either an equal or an unequal share of the group fund. For equal shares, each member of the group will receive 1/6 of the earnings from the group fund. For unequal shares, three members of your group will receive 1/12 of the earnings and three members will receive 3/12 of the earnings from the group fund. The return from the group fund will depend on the total number of tokens your group invests in the group fund. The returns from the group fund are given on your payoff sheet in the table labelled "group fund." You must invest all of your tokens each period.

Each member of the group receives an equal amount (20) of tokens to invest in each period. A run of the experiment will consist of 15 periods. At the end of the first experiment you will be randomly assigned to a new group with the possibility of a different individual return factor and a different share of the group fund. You will participate in five experimental runs, lasting approximately two hours. You will be paid your earnings in cash at the end of the experiment.

Procedure

Each period you will decide how many tokens to invest in the individual fund and how many to invest in the group fund on the computer screen (you can choose fractional amounts, i.e. 12.4 tokens). After all group members have made their decisions then you will have information on the total invested in the group fund, your earnings from the group fund and your earnings from the individual fund. Your earnings for the period are your earnings from the individual fund and group fund added together. Do not discuss your investment decision with anyone in the room. Only the monitors will learn of your decisions.

Investment Opportunities Each period you will be choosing between two investment opportunities, the individual fund and the group fund.

(1) The individual fund

Tokens invested in the individual fund earn a return that is determined by the number of tokens you invest and your individual scale factor, x. As you can see on the payoff table, the return from each additional token invested in the individual fund decreases with each token invested.

Example: If you invested 12 tokens in the individual fund and $x = 3$ you would earn a return from the individual fund of $0.126. If your $x = 2$ you would earn $0.084 and if your $x = 4$ you would earn $0.168.

Example: If you invested 18 tokens in the individual fund, your return from the individual fund is $0.149 for an $x = 3$, $0.099 for an $x = 2$, and $0.198 for an $x = 4$.

Example: If you invested 0 tokens in the individual fund, your return from the individual fund is $0.00.

(2)   The group fund

Your return from the group fund depends on the amount invested by the group and your share of the group fund. With equal shares, each person in the group receives the same return from the group fund regardless of the amount they invested in the group fund. Similarly, with unequal shares, your payoff will depend only on the total, not on the amount you individually contributed to the group fund. The table attached at the end of the instructions shows earnings from the group fund, depending on the amount invested by the group and your share of the group fund. Here are some examples.

Equal shares of the group fund, 1/6 for each member:

Example: If the group invests a total of 55 tokens in the group fund, then the value of the group fund is $1.272, and each member of the group earns $0.212 from the group fund.

Example: If the group invests a total of 0 tokens in the group fund, then the value of the group fund is $0.00, and each member of the group earns $0.00 from the group fund.

Example: If the group invests a total of 90 tokens in the group fund, then the value of the group fund is $1.688, and each member of the group earns $0.281 from the group fund.

Unequal shares of the group fund, 1/12 for three members and 3/12 for three members:

Example: If the group invests a total of 55 tokens in the group fund, then the value of the group fund is $1.272. The three members of the group who earn 1/12 share each receive $0.106 from the group fund. The three members of the group who earn 3/12 share each receive $0.318 from the group fund.

Example: If the group invests a total of 0 tokens in the group fund, then the value of the group fund is 0. The three members of the group who earn 1/12 share receive $0.00 from the group fund. The three members of the group who earn 3/12 share receive $0.00 from the group fund.

Example: If the group invests a total of 90 tokens in the group fund, then the value of the group fund is $1.688. The three members of the group who earn 1/12 share receive $0.141 from the group fund. The three members of the group who earn 3/12 share receive $0.422 from the group fund.

References

Andreoni J (1993) An experimental test of the public-goods crowding out hypothesis. Am Econ Rev 83(5):1317–1327

Barrett S (1994) Self-enforcing international environmental agreements. Oxf Econ Papers 46:878–894

Cason T, Saijo T, Yamato T (2002) Voluntary participation and spite in public good provision experiments: an international comparison. Exp Econ 5:133–153

Cason T, Saijo T, Yamato T, Yokotani K (2004) Non-excludable public good experiments. Games Econ Behav 49:81–102

Chan K, Mestelman S, Moir R, Muller RA (1999) Heterogeneity and the voluntary provision of public goods. Exp Econ 2:5–30

Croson RTA, Marks MB (1999) The effect of heterogeneous valuations for threshold public goods: an experimental study. Risk Decis Policy 4(2):99–115

Ellerman AD, Jacoby H, Decaux A (1998) The effect on developing countries of the Kyoto protocol and CO_2 emissions trading. MIT joint program on the science and policy of global climate change report #41

Fehr E, Schmidt KM (1999) A theory of fairness, competition, and cooperation. Q J Econ 114(3):817–868

Fischbacher U (2007) z-Tree: zurich toolbox for ready-made economic experiments. Exp Econ 10:171–178

Isaac RM, Walker J, Thomas S (1984) Divergent evidence on free-riding: an experimental examination of possible explanations. Public Choice 43:113–149

Isaac RM, McCue K, Plott C (1985) Public goods provision in an experimental environment. J Public Econ 26:51–74

Keser C (1996) Voluntary contributions to a public good when partial contribution is a dominant strategy. Econ Lett 50:359–366

Laury S, Holt C (2005) Voluntary provision of public goods: experimental results with interior nash equilibria. In: Plott C, Smith V (eds) Handbook of experimental economics results, vol 1. Elsevier Science, Amsterdam

Laury S, Walker J, Williams A (1999) The voluntary provision of a pure public good with diminishing marginal returns. Public Choice 99:139–160

Ledyard J (1995) Public goods: a survey of experimental research. In: Kagel J, Roth A (eds) Handbook of experimental economics. Princeton University Press, Princeton pp 111–194

Marwell G, Ames R (1981) Economists free ride, does anyone else? Experiments on the provision of public goods. J Public Econ 15:295–310

McGinty M (2007) International environmental agreements among asymmetric nations. Oxf Econ Papers 59:45–62

Sefton M, Steinberg R (1996) Reward structures in public goods experiments. J Public Econ 61:263–287

Willinger M, Ziegelmeyer A (2001) Strength of the social dilemma in a public goods experiment: an exploration of the error hypothesis. Exp Econ 4:131–144