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Simultaneous and Sequential Provision under Endowment Heterogeneity: Theory and Experimental Evidence

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Abstract

We study public-good provision in a three-player environment with Cobb–Douglas preferences and heterogeneous endowments. Across treatments we vary the distribution of endowments while holding the group's total endowment constant. We conduct two comparisons: (i) within-mechanism, contrasting theoretical benchmarks with experimental outcomes; and (ii) across mechanisms, contrasting simultaneous with sequential play under the same role–endowment mapping. In the sequential mechanism, the richest participant is exogenously assigned as the leader, and the two followers move simultaneously in the second stage. Taking Varian (1994) as a testable null (sequential provision should not exceed simultaneous provision), we report both aggregate provision and role-level contributions and document alignment and gaps between theory and data within mechanisms, as well as the pure timing effect across mechanisms. This design extends the literature that has largely studied heterogeneous endowments under simultaneous play by adding a systematic analysis of heterogeneous endowments under sequential play.

Keywords：Endowment heterogeneity; Simultaneous moves；Sequential moves; Public goods; Theory; Experiment

JEL classification: C91; C92; D63; H41

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1. Introduction

In real-world contexts—such as community crowdfunding campaigns, alumni fundraising drives, and neighborhood improvement initiatives—public goods are often financed through one of two common mechanisms. In some cases, all participants decide on their contributions simultaneously without observing others' decisions. In other cases, contributions occur sequentially, typically beginning with a lead donor whose early commitment establishes a reference point and potentially influences subsequent contributors. These contrasting contribution structures can shape individuals' beliefs, coordination, and willingness to contribute, making them central to understanding cooperative behavior in public good environments.

As a theoretical starting point, Varian (1994) predicts a clear directional ranking: in his framework, the sequential (leader–follower) mechanism should not generate a higher total provision of the public good than the simultaneous mechanism. Experimental evidence under equal endowments offers conditional support for this prediction while also highlighting important role-specific deviations. For example, Gächter et al. (2010) compare sequential and simultaneous contributions in a quasi-linear two-person public good environment and find that, across several parameterizations, total provision under sequential play does not exceed that under simultaneous play, and in some cases the two outcomes are statistically indistinguishable. At the individual level, however, the first-mover advantage predicted by certain theoretical models rarely materializes in laboratory settings. Instead, followers frequently "punish" low leader contributions by reducing their own, rather than symmetrically rewarding generous leadership, revealing behavioral patterns that diverge from standard theoretical assumptions. Potters et al. (2007) examine simultaneous and sequential contributions in a two-person linear public good game under both asymmetric and full information conditions. In all treatments, leaders were informed of the return from contributing to the public good and when they made their choices, followers were either informed of this return (in the full-information treatments) or told that the return from a contribution can be either 0, 0.75 or 1.5 with each of the three values being equally likely (in the asymmetric-information treatments). The main findings form this experiment show that, in the full-information treatments, sequential moves do not significantly increase overall contributions, while in the asymmetric treatments, contributions are significantly higher when moves are sequential compared to when they are simultaneous.

By contrast, several studies document positive effects of leadership on contribution behavior. For example, Güth et al. (2007) examine leadership in a four-person linear voluntary contribution experiment with equal endowments. They compare fixed and rotating leadership, with and without exclusion power. Leadership by example produces a marginally significant increase in contributions relative to simultaneous play, while exclusion power raises contributions further and helps sustain cooperation. They also find that followers' contributions are positively correlated with leaders' contributions, although followers contribute less and earn more than leaders. Their study therefore examines both the effectiveness of leadership in raising provision

and the unequal contribution burdens associated with leadership. In a step-level public good experiment, Normann & Rau (2015) investigate how the order of moves (simultaneous vs. sequential) and the number of step levels (one vs. two) affects public goods provision in a two-person game. They find that the sequential order of moves significantly improves public good provision and payoffs, even though second movers often punish first movers who give less than half of the threshold contribution.

Another important topic in the public good provision literature concerns the role of income inequality. In standard public good game experiments, subjects typically receive equal endowments, a feature that departs from naturally occurring decision-making environments where income distributions are rarely uniform. Introducing endowment heterogeneity into simultaneous-move settings yields mixed results for aggregate provision, although the overall tendency is for inequality to depress contributions. One-shot studies report lower total contributions when heterogeneity is present (Cherry et al., 2005), and publicly salient inequality further reduces contributions (Anderson et al., 2008). When income heterogeneity is controlled across weakly and strongly asymmetric conditions, aggregate contributions do not differ significantly in the weakly asymmetric setting but decline in the strongly asymmetric setting relative to homogeneous endowments (Keser et al., 2011). At the individual contribution level, findings are more consistent. Contributions by high-endowment ("rich") participants tend to fall under inequality compared with equal-endowment settings (Hargreaves Heap et al., 2016), and low-endowment ("poor") participants frequently contribute a higher share of their endowment than rich participants, even when absolute contributions are similar (Chan et al., 1996; Buckley & Croson, 2006). A notable exception is reported by Hofmeyr et al. (2007), who find that endowment heterogeneity has no significant impact on contributions among secondary school students, with both low- and high-endowment participants contributing the same fraction of their endowment to the public pool.

Levati et al. (2007) directly examine leadership under endowment heterogeneity in a four-person linear public goods game with two high-endowment and two low-endowment participants. They compare simultaneous provision with leadership, with and without exclusion power, under complete and incomplete information about the endowment distribution. In the exogenous phase, the leader role rotates among group members. Leadership significantly increases contributions when endowments are commonly known, but the increase is not significant under incomplete information. Exclusion power has no significant additional effect on average contributions. As in Güth et al. (2007), followers' contributions are positively correlated with leaders' contributions, while followers contribute less. Together, these studies examine both the effectiveness of leadership and the distribution of contribution burdens, including in groups with heterogeneous endowments.

Relatedly, Itaya et al. (2023) theoretically and experimentally examine the effects of income inequality on individuals' timing decisions and contributions when the timing of contribution is endogenously chosen. Our study instead compares exogenously specified simultaneous and sequential mechanisms and evaluates their contribution and payoff predictions. In the present study, we aim to integrate the two

strands of literature discussed above—namely, the order of moves and endowment heterogeneity—within the context of voluntary public good provision. To this end, we first develop a three-player public good provision model incorporating heterogeneous endowments under both simultaneous- and sequential-move environments. In the theoretical model, we adopt Cobb–Douglas preferences rather than quasi-linear or linear preferences. This choice allows us to capture more general preference structures, as Cobb–Douglas preferences incorporate income effects while remaining reasonably tractable (Itaya et al., 2023). In the sequential setting, the richest player is exogenously assigned to move first as the leader, while the two followers—the mid-endowed and least-endowed players—choose their contributions simultaneously in the second stage.[1] In this setting, we theoretically and experimentally examine the role of heterogeneous endowment of potential contributors in their public good provision behaviors under both simultaneous- and sequential-move environments.

The linear models used by Güth et al. (2007) and Levati et al. (2007) predict zero contributions under individual payoff maximization, whether participants move simultaneously or sequentially. Our Cobb–Douglas model allows positive equilibrium contributions under the same assumption. We test whether letting the highest-endowed participant move first changes total contributions and each participant's contribution and payoff as the model predicts. We also examine whether followers respond as predicted to the leader's actual contribution, even when the leader does not contribute the equilibrium amount.

Our theoretical analysis yields several testable predictions. First, the model provides treatment-specific equilibrium benchmarks for aggregate contributions, individual contributions, and payoffs under both simultaneous and sequential moves. In particular, holding the role–endowment mapping constant, aggregate public-good provision is predicted to be lower under sequential moves than under simultaneous moves, which is consistent with two-person games investigated by Varian (1994). The model also predicts a first-mover advantage for the highest-endowed participant: when acting as the leader in the sequential mechanism, this participant contributes less and earns a higher payoff than under simultaneous moves, while the lower-endowed followers contribute more and earn lower payoffs.

Beyond these standard equilibrium predictions, we consider several behavioral predictions motivated by social norms and conditional cooperation. Under endowment inequality, participants may perceive the highest-endowed member as bearing greater responsibility for public-good provision, while lower-endowed members may feel less obligated to contribute. If this responsibility norm affects behavior, the highest-endowed participant's actual contribution should exceed the theoretical benchmark, whereas the lower-endowed participants' actual contributions should fall below their respective benchmarks. Consequently, the highest-endowed participant's realized payoff should be lower than theoretically predicted, while the lower-endowed participants' realized payoffs should be higher. Because these opposing individual-

[1] Alternative leader-selection rules—such as appointing the mid-endowed or least-endowed player as the leader, or determining leadership randomly—are beyond the scope of the present study and are left for future work.

level deviations may offset one another, aggregate contributions may remain relatively close to the theoretical benchmark.

Finally, in the sequential mechanism, the leader's contribution may serve as a signal or reference point for the followers. If followers behave as conditional cooperators or respond positively to leadership by example, a higher leader contribution should induce higher follower contributions (Güth et al., 2007; Levati et al., 2007). This behavioral prediction contrasts with the standard equilibrium prediction, according to which a higher leader contribution crowds out followers' contributions.

We experimentally investigate these theoretical predictions. Our experimental results provide four main findings. First, at the aggregate level, the theoretical predictions fit the data more closely in the simultaneous-move treatments than in the sequential leader–follower treatments. In the simultaneous treatments, mean aggregate contributions are close to the corresponding theoretical benchmarks, whereas in most sequential treatments aggregate contributions are significantly higher than predicted.

Second, at the individual level, subjects' contribution behavior systematically deviates from the theoretical predictions in both mechanisms. In the simultaneous treatments, the highest-endowed subjects contribute less than predicted, while the lower-endowed subjects generally contribute more than predicted. In contrast, in the sequential treatments, the highest-endowed subjects, acting as leaders, contribute more than predicted, whereas the lower-endowed subjects, acting as followers, contribute less than predicted. However, when follower predictions are conditioned on the leader's observed contribution using the both-followers-contribute benchmark, we find no significant differences between predicted and actual follower contributions in most comparisons.

Third, these deviations are also reflected in subjects' payoffs. In the simultaneous treatments, the highest-endowed subjects tend to earn more than the theoretical predictions, while the lower-endowed subjects earn less. In the sequential treatments, the pattern is reversed: leaders tend to earn less than predicted, whereas followers earn more than predicted.

Fourth, when we directly compare the simultaneous and sequential mechanisms under the same role–endowment mapping, we find significant differences in aggregate contribution levels, but no significant differences in individual contributions or payoffs for any subject type. Regression analysis further shows that subjects exhibit positive persistence in their own contribution behavior. Moreover, in the sequential treatments, followers tend to reduce their contributions when the leader contributes more, suggesting a crowding-out or free-riding response to leadership.

The remainder of the paper is organized as follows. Section 2 presents the three-player public good model with heterogeneous endowments in both simultaneous- and sequential-move settings. Section 3 outlines the experimental design and procedures. Section 4 reports the results of the experiment. Section 5 offers a discussion of the main findings and concludes with directions for future research.

2. Theoretical Framework

We study a three-player public good game with heterogeneous endowments $w_1 > w_2 > w_3$. Across treatments, the total endowment is held constant, while the distribution of endowments varies. Each player $i \in \{1,2,3\}$ allocates her endowment w_i between private consumption x_i and a contribution z_i to the public good, i.e., $x_i + z_i = w_i$, where the aggregate level of public-good provision is given by

$$G = z_1 + z_2 + z_3 \quad (1)$$

We assume that each player has an identical Cobb–Douglas preference over private consumption and the public good. Specifically, player i's utility function is given by

$$u_i(x_i, G) = x_i^{\alpha} G^{1-\alpha}, \qquad \alpha \in (0,1) \quad (2)$$

where α captures the relative weight placed on private consumption.

We consider two timing protocols:

- Simultaneous: all players choose their own contributions simultaneously.
- Sequential (leader–followers): player 1, the richest player, first chooses her contribution in stage 1; after observing player 1's contribution, players 2 and 3 simultaneously choose their own contributions in stage 2.

2.1 Theoretical Prediction in the Simultaneous Contribution Game

We first derive the theoretical benchmark for the simultaneous contribution game. Consider a three-player voluntary public goods game in which players are indexed by $i \in \{1,2,3\}$. Player i is endowed with $w_i > 0$ and chooses a nonnegative contribution $z_i \geq 0$ to the public good. Private consumption is denoted by x_i, and the budget constraint is given by $w_i = x_i + z_i$. The aggregate level of public-good provision is the sum of individual contributions: $G = z_1 + z_2 + z_3$.

All players have the same Cobb–Douglas preferences over private consumption and the public good: $U_{\mathrm{i}}(x_{\mathrm{i}}, G) = \sqrt{x_{\mathrm{i}} G}$. Throughout the theoretical analysis below and the experiment, we specialize to $\alpha = 1/2$ and derive continuous-contribution benchmarks. We are ready to define a Nash equilibrium.

For deterministic optimization, it is convenient to use the squared-utility index $V_{\mathrm{i}} := U_{\mathrm{i}}^2 = x_{\mathrm{i}} G$. The square root is strictly increasing, so this transformation preserves optimal contributions and the ranking of deterministic outcomes. The theoretical payoff entries in Table 2 are reported on the V_{i} scale; they must be distinguished from U_{i} and from the experimental payment rule.

Definition. Let $\{1,2,3\}$ be a set of three players. Let w_i and U_i be the endowment of the private good and the utility function respectively, for player $i \in \{1,2,3\}$. Then $(z_1^*, z_2^*, z_3^*, G^*)$ is a ***Nash equilibrium for the public goods game*** $(\{1,2,3\}, w_1, w_2, w_3, U_1, U_2, U_3)$ if

$(z_1^*, z_2^*, z_3^*) \in [0, w_1] \times [0, w_2] \times [0, w_3]$;

$U_1(w_1 - z_1^*, z_1^* + z_2^* + z_3^*) \geq U_1(w_1 - z_1, z_1 + z_2^* + z_3^*) \; for \; each \; z_1 \in [0, w_1]$;

$U_2(w_2 - z_2^*, z_1^* + z_2^* + z_3^*) \geq U_2(w_2 - z_2, z_1^* + z_2 + z_3^*)\ for\ each\ z_2 \in [0, w_2]$;
$U_3(w_3 - z_3^*, z_1^* + z_2^* + z_3^*) \geq U_3(w_3 - z_3, z_1^* + z_2^* + z_3)\ for\ each\ z_3 \in [0, w_3]$;
and $G^* = z_1^* + z_2^* + z_3^*$

In addition, we assume that the endowments is strictly ordered as $w_1 > w_2 > w_3$. Thus, player 1 has the highest endowment, player 2 has the intermediate endowment, and player 3 has the lowest endowment. In the simultaneous game, all players choose their contributions at the same time. For an interior solution, the first-order condition is

$$\frac{\alpha}{w_i - z_i} = \frac{1-\alpha}{G} \tag{3}$$

With α = 1/2, this condition becomes $w_i - z_i = G$. Equivalently, the desired contribution of player i can be written as $z_i = w_i - G$.

Because contributions are constrained to be nonnegative, a player contributes only when her endowment is sufficiently large relative to total public-good provision. Therefore, the set of active contributors depends on the distribution of endowments. The simultaneous game has three relevant equilibrium regimes. First, when the poorest player's endowment is sufficiently large, namely $w_3 > (w_1 + w_2)/3$, all three players contribute. The equilibrium total provision is then $G^* = (w_1 + w_2 + w_3)/4$.

Second, when the poorest player is constrained but the middle-endowed player still contributes, namely $w_3 \leq (w_1 + w_2)/3$ and $w_2 > w_1/2$, players 1 and 2 contribute, while player 3 contributes zero. The equilibrium total provision is $G^* = (w_1 + w_2)/3$.

Finally, when the endowment gap is sufficiently large, namely $w_2 \leq w_1/2$, only the richest player contributes. The equilibrium total provision is $G^* = w_1/2$.

The corresponding individual equilibrium contributions are reported in Appendix A. These predictions imply that endowment inequality may affect not only the level of individual contributions but also the identity of active contributors. When inequality is relatively small, all three players are predicted to contribute. As inequality increases, the poorest player first becomes a non-contributor. Under sufficiently high inequality, only the richest player contributes. Thus, the theoretical benchmark explicitly allows for corner solutions. This benchmark provides the basis for interpreting behavior in the simultaneous contribution treatment. If observed contributions differ from the Nash predictions, such deviations suggest that subjects respond to endowment inequality or strategic uncertainty in ways that are not fully captured by the standard voluntary-contribution model. The full derivation, individual equilibrium contributions, and graphical illustration are provided in Appendix A.

2.2 Theoretical Prediction in the Sequential Contribution Game

We next derive the theoretical benchmark for the sequential contribution game. As in the simultaneous game, there are three players with strictly ordered endowments: $w_1 > w_2 > w_3$. Player 1 is the richest player and moves first as leader. After observing the leader's contribution, players 2 and 3 simultaneously choose their contributions as followers. Denote by g_1, z_2 and z_3 the leader's contribution, the contributions of players 2 and 3, respectively. Total public-good provision is $G = g_1 + z_2 + z_3$, and

private consumption is $x_1 = w_1 - g_1$, $x_2 = w_2 - z_2$, and $x_3 = w_3 - z_3$. Each player has the same Cobb–Douglas preference $U_i(x_i, G) = x_i^{1/2} G^{1/2}$ as in the simultaneous game. We newly define *Nash equilibrium function* for the subgame of players 2 and 3, and *Stackelberg equilibrium* for the sequential game as below:

Definition. Let $\{1,2,3\}$ be a set of three players. Let w_i and U_i be the endowment of the private good and the utility function respectively, for player $i \in \{1,2,3\}$. Then, the triple $\big(B_2(\cdot), B_3(\cdot), G(\cdot)\big)$ of functions of the leader's contribution g is a ***Nash equilibrium function for the subgame*** $(\{2,3\},\ w_2, w_3, U_2, U_3)$ if

$\big(B_2(g), B_3(g)\big) \in [0, w_2] \times [0, w_3]$;

$U_2\big(w_2 - B_2(g), g + B_2(g) + B_3(g)\big) \geq U_2\big(w_2 - z_2, g + z_2 + B_3(g)\big)$

$for\ each\ z_2 \in [0, w_2]$;

$U_3\big(w_3 - B_3(g), g + B_2(g) + B_3(g)\big) \geq U_3(w_3 - z_3, g + B_2(g) + z_3)$

$for\ each\ z_3 \in [0, w_3]$; and $G(g) = g + B_2(g) + B_3(g)$ for each $g \in [0, w_1]$.
The functions $B_2(g)$ and $B_3(g)$ are respectively called the ***Nash equilibrium functions of players 2 and 3***. The quadruple $\big(g^*, B_2(g^*), B_3(g^*), G(g^*)\big)$ is a ***Stackelberg equilibrium for the public goods game*** $(\{1,2,3\},\ w_1, w_2, w_3, U_1, U_2, U_3)$ with leader player 1 if $g^* \in [0, w_1]$,

$U_1\big(w_1 - g^*, G(g^*)\big) \geq U_1\big(w_1 - g, G(g)\big)\ for\ each\ g \in [0, w_1]$;and $G^* = G(g^*)$.

Notice that the Nash equilibrium functions are different from the *reaction functions* in the standard sense: B_i assigns to each g the action of player i at the Nash equilibrium for the subgame reduced by g, and the reaction function of player i associates with each profile of strategies selected by the other players the action of player i to maximize the payoff of player i.

Next, we solve the game step by step.
Backward induction. Because the game is sequential, the formal concept of Stackelberg equilibrium in game theory is subgame-perfect equilibrium. We thus solve the game by backward induction. For each possible leader contribution g_1, we first characterize the equilibrium of the followers' subgame. We then substitute the followers' response functions into the leader's optimization problem. Given g_1, follower i = 2, 3 solves

$$\max_{z_i \geq 0} (g_1 + z_2 + z_3)^{1/2} (w_i - z_i)^{1/2} \tag{4}$$

For an interior solution, the first-order condition is

$$\frac{1}{2(g_1 + z_2 + z_3)} - \frac{1}{2(w_i - z_i)} = 0 \tag{5}$$

which implies $g_1 + z_2 + z_3 = w_i - z_i$.

Thus, a follower contributes only when her endowment is sufficiently large relative to the public good already provided by the leader and the other follower.

Followers' regimes: Let $h = 2w_3 - w_2$ and restrict the leader's contribution to $0 \leq g_1 \leq w_1$. Both followers contribute when $0 \leq g_1 < h$ (this interval exists only if $h > 0$); only player 2 contributes when $\max\{0, h\} \leq g_1 < w_2$; and both followers contribute zero when $g_1 \geq w_2$. Table 1 gives the corresponding unique subgame equilibrium. The adjacent formulas agree at the switching points.

Table 1. Follower-stage regimes in the sequential game

Regime	Followers' contributions	Total provision
Both followers contribute	$\boldsymbol{B}_2(g_1) = \frac{2w_2 - w_3 - g_1}{3}$ $\boldsymbol{B}_3(g_1) = \frac{2w_3 - w_2 - g_1}{3}$	$G(g_1) = \frac{g_1 + w_2 + w_3}{3}$
Only player 2 contributes	$\boldsymbol{B}_2(g_1) = \frac{w_2 - g_1}{2}$ $\boldsymbol{B}_3(g_1) = 0$	$G(g_1) = \frac{g_1 + w_2}{2}$
No follower contributes	$\boldsymbol{B}_2(g_1) = 0 \qquad \boldsymbol{B}_3(g_1) = 0$	$G(g_1) = g_1$

These regimes capture the main strategic difference between the sequential and simultaneous games. The leader's contribution increases the public good, but it may also crowd out subsequent contributions by the followers. When both followers contribute, an additional unit of leader contribution is partly offset by reductions in both followers' contributions. When only player 2 contributes, the offset operates only through player 2. When neither follower contributes, the leader's contribution fully translates into public-good provision.

Leader's problem. Anticipating the followers' responses, the leader solves

$$\max_{0 \leq g_1 \leq w_1} [g_1 + B_2(g_1) + B_3(g_1)]^{1/2} (w_1 - g_1)^{1/2} \tag{6}$$

where $B_2(g_1)$ and $B_3(g_1)$ are the Nash equilibrium functions of the two followers. Both B_2 and B_3 are piecewise, so is the leader's induced feasible frontier. Consequently, several equilibrium regimes can arise depending on the endowment distribution. The full classification of these regimes is reported in Appendix B.

Illustrative example. To illustrate the backward-induction procedure, consider the endowment profile (w_1, w_2, w_3) = (25,13,10). In this case, both followers contribute in equilibrium. Using the first regime in Table 1, total public-good provision is $G(g_1) = (g_1 + w_2 + w_3)/3$. Substituting this into the leader's utility gives $U_1(g_1) = \big((g_1 + w_2 + w_3)/3\big)^{1/2}(w_1 - g_1)^{1/2}$. Maximizing this expression yields $g_1^* = (w_1 -$

$w_2 - w_3)/2$. For the present endowment profile, $g_1^* = (25 - 13 - 10)/2 = 1$. Substituting $g_1^* = 1$ into the followers' Nash equilibrium functions gives $z_2^* = B_2(g_1^*) = (2 \times 13 - 10 - 1)/3 = 5$, $z_3^* = B_3(g_1^*) = (2 \times 10 - 13 - 1)/3 = 2$. Therefore, $G^* = g_1^* + z_2^* + z_3^* = 8$.

The regime-specific maxima of V_1 over the feasible intervals are 192, 180, and 156, respectively. Thus, $g_1^* = 1$ is the leader's global optimum, rather than merely a stationary point of the first branch.

This example shows how the Stackelberg equilibrium is obtained by backward induction. The followers' equilibrium responses are first derived for a given leader contribution, and the leader then chooses her contribution while taking those responses into account.

The sequential game provides a benchmark for evaluating how timing affects public-good provision. Given the followers' equilibrium responses, a higher leader contribution strictly increases aggregate provision: the slope is $1/3$ while both followers contribute, $1/2$ while only player 2 contributes, and 1 when neither follower contributes. Active followers therefore partially offset an increase in the leader's contribution. Appendix B derives the complete global equilibrium conditions, including ties and boundary cases.

2.3 Direct Theoretical Predictions for the Experiment

Table 2 summarizes the endowment structures used in the experiment and the corresponding theoretical predictions for both the simultaneous and sequential contribution games. In all treatments, the total endowment is held constant at 48 points, while the distribution of endowments across the three players varies. The endowments are strictly ordered, so that player 1 has the highest endowment, player 2 has the intermediate endowment, and player 3 has the lowest endowment. This design allows us to compare behavior across different degrees of endowment inequality while keeping the total resources available to the group unchanged.

For each treatment, the table reports the predicted individual contribution of each player, the resulting aggregate contribution to the public good, and the corresponding payoff. In the simultaneous game, four endowment structures are considered. Although the distribution of endowments differs across treatments, the theoretical benchmark predicts the same aggregate contribution of 12 points in all four cases. In the sequential game, player 1 moves first, and players 2 and 3 choose their contributions after observing player 1's contribution. The reported predictions for the sequential game are obtained by solving the game backward: we first determine the followers' optimal responses and then determine player 1's optimal initial contribution. These predictions serve as the benchmark against which the experimental results are evaluated. In addition, it should be noted that S1 and T1, as well as S2 and T2, share the same endowment structure across all three players; therefore, the experimental results from these treatment pairs allow us to compare behavior between the simultaneous and sequential games.

As shown in Table 2, it is theoretically predicted that the aggregate contribution levels of public goods in the simultaneous games are higher than those in the sequential games. This is consistent with the two-person games investigated by Varian (1994).

Table 2: Theoretical predictions of the simultaneous and sequential games for the experiment

Game	Treatment	Role	Endowment	Individual contribution	Aggregate contribution	Payoff V
Simultaneous	S1	Player1	21	9	12	144
		Player2	14	2		144
		Player3	13	1		144
	S2	Player1	18	6	12	144
		Player2	16	4		144
		Player3	14	2		144
	S3	Player1	23	11	12	144
		Player2	13	1		144
		Player3	12	0		144
	S4	Player1	19	7	12	144
		Player2	17	5		144
		Player3	12	0		144
Sequential	T1	Player1	21	0	9	189
		Player2	14	5		81
		Player3	13	4		81
	T2	Player1	18	0	10	180
		Player2	16	6		100
		Player3	14	4		100
	T3	Player1	25	1	8	192
		Player2	13	5		64
		Player3	10	2		64
	T4	Player1	27	3	8	192
		Player2	11	3		64
		Player3	10	2		64

Note: Payoff entries are the squared-utility index $V_{\mathrm{i}} = (w_{\mathrm{i}} - z_{\mathrm{i}})G$, rather than $U_{\mathrm{i}} = \sqrt{V_{\mathrm{i}}}$. In T2, each follower consumes 10 and total provision is 10, so $V_2 = V_3 = 100$ and $U_2 = U_3 = 10$. The S3 and S4 profiles satisfy $3w_3 = w_1 + w_2$; their zero contribution by player 3 is a boundary outcome.

3. Experimental Design and Procedure

3.1 Experimental Design

Our experiment involves a non-linear three-player public goods game. We designed eight experimental treatments: four for simultaneous games (S1–S4) and four for sequential games (T1–T4). Each subject participated in only one experimental session, and each session combined two different treatments with eight rounds per treatment. Table 3 summarizes the eight experimental sessions. As shown in the table, the treatment combinations in sessions S12 and S21, S34 and S43, T12 and T21, and T34 and T43 are the same but implemented in reverse order, which is intended to control for possible order effects in a within-subjects design.

Table 3. Summary of the experimental sessions

Session	Description	No. of subjects	No. of groups
S12	treatment S1 (8 rounds)→treatment S2 (8 rounds)	27	9
S21	treatment S2 (8 rounds)→treatment S1 (8 rounds)	24	8
S34	treatment S3 (8 rounds)→treatment S4 (8 rounds)	18	6
S43	treatment S4 (8 rounds)→treatment S3 (8 rounds)	27	9
T12	treatment T1 (8 rounds)→treatment T2 (8 rounds)	27	9
T21	treatment T2 (8 rounds)→treatment T1 (8 rounds)	24	8
T34	treatment T3 (8 rounds)→treatment T4 (8 rounds)	27	9
T43	treatment T4 (8 rounds)→treatment T3 (8 rounds)	24	8

The endowments of the three subjects within each group differ in every treatment, with the player-1 subject always receiving the highest endowment and the player-3 subject always receiving the lowest. Although the individual endowment levels vary across treatments, the total group endowment (i.e., the sum of the three subjects' endowments) is fixed at 48 points throughout all treatments.

3.2 The Procedure of Treatments S1 – S4

The detailed experimental instructions for treatments S1–S4 are provided in Appendix C. The procedures are summarized as follows.

Step 1. Upon arrival at the laboratory, subjects were seated in the order in which they entered and were asked to complete consent forms. Once all subjects were seated, the experimental instructions and three practice payoff tables (i.e., one each for player-1, player-2, and player-3 subjects) were distributed.

Step 2. Each subject read the instruction while listening to a pre-recorded explanation by a native Japanese-speaking co-author.

Step 3. Before starting the first part of the experiment (i.e., the first treatment of a session), subjects answered two quiz questions about the payoff tables. After all

subjects provided correct answers, two practice rounds were conducted using the practice payoff tables. Once the practice rounds were completed, we collected the practice payoff tables and distributed new payoff tables for the first half of the experiment.

Step 4. The first part of the experiment began with group formation and role assignment (players 1–3), both of which were randomly determined. This information was displayed on each subject's screen. Subjects were informed that their roles and group memberships would remain fixed throughout both parts of the experiment (i.e., both treatments of a session).

Step 5. At the beginning of Round 1 of the first half, each subject could see their own endowment and those of the other two group members, depending on their assigned role. They were then asked to choose an investment amount based on their endowment and enter it into the computer.

Step 6. Once all members of a group entered their investment amounts, the investment decisions of all three members and the resulting payoffs were displayed on the screen. Each subject's payoff was determined according to their own investment and the sum of the investments of the other two group members, as specified in the payoff table. This completed Round 1 of the first half of the experiment.

Step 7. The procedures in *Steps 5* and *6* were repeated for Rounds 2–8 of the first half. Note that each subject's endowment remained constant across all rounds. After the first half was completed, we collected the payoff tables and distributed new payoff tables for the second half.

Step 8. The procedures in the second half of the experiment were almost identical to those in the first half, except that subjects' endowments and the payoff tables differed.

Step 9. After the experiment, one round from each half was randomly selected, and each subject's payoff for these two rounds was summed. Subjects were then paid in cash at a rate of 0.8 JPY per 1 point of total payoff.

3.3 The Procedure of Treatments T1 – T4

The procedures for treatments T1–T4 are similar to those for treatments S1–S4, except for *Step 5* described above. In *Step 5* of treatments T1–T4, the player-1 subject, who received the highest endowment, first determined an investment amount from his/her endowment and entered it into the computer. After this amount was entered, it was displayed on the computer screens of the player-2 and player-3 subjects in the same group. Then, the player-2 and player-3 subjects entered their own investment amounts into the computer.

3.4 Conduction of the Experiment

The experiment was conducted at the Research Institute for Socionetwork Strategies (RISS) of Kansai University from October 25 to 27, 2023, using the z-Tree software (Fischbacher, 2007). We recruited a total of 198 subjects (107 females and 91 males) from various majors through the online recruitment system ORSEE (Greiner, 2015), and all participants signed consent forms prior to taking part in the experiment.

Subjects were informed that the experiment consisted of two parts (i.e., two treatments), each comprising eight rounds. Communication among subjects was strictly prohibited; they were clearly instructed that the experiment would be terminated immediately if any communication occurred. Each experimental session lasted approximately 90 minutes, and subjects earned an average of 1,902 JPY (about 12.68 USD, using an exchange rate of 1 USD = 150 JPY).

4. Results

4.1 Order Effect

Because each treatment was conducted twice in different orders, we first examine whether order effects exist in either the aggregate contribution (i.e., the sum of the three players' contributions) or in each player's individual contribution. To avoid potential within-treatment round-to-round dependence, we used the round-mean contribution of each group or each player in the statistical tests.[2]

The results of both the Wilcoxon rank-sum test and the *t* test indicate that aggregate contributions differ significantly between orders in treatments S2 and T4 (rank-sum test: $p = 0.0012$ in S2 and $p = 0.0097$ in T4; *t* test: $p = 0.006$ in S2 and $p = 0.0154$ in T4). Individual contributions differ significantly only for player-1 subjects in treatment T4 (rank-sum test: $p = 0.0222$; *t* test: $p = 0.0197$). These findings suggest the presence of order effects in treatments S2 and T4 at the aggregate level, and for player-1 contributions in treatment T4. Therefore, in the subsequent analysis, we pool the data for treatments in which no order effect is detected, and we analyze each session separately for treatments in which an order effect is observed.

4.2 Experimental Behavior vs. Theoretical Prediction

4.2.1 Aggregate Contribution

Table 4 presents the summary statistics of the aggregate contributions in each treatment.[3] As shown in the table, the mean aggregate contribution levels in all simultaneous-contribution treatments (i.e., treatments S1–S4) are close to their corresponding theoretical prediction (i.e., 12). The results of both the sign test and the *t* test statistically support this consistency, as all *p*-values in the rightmost two columns exceed 0.10.

In contrast, with the exception of treatment T4 in the T34 session, the mean aggregate contribution levels in most sequential-contribution treatments (i.e., treatments T1–T4) exceed their corresponding theoretical predictions, and these differences are statistically significant according to both the sign test and the *t* test (all *p*-values are below 0.05 except for T4 in T34).

[2] Not limited to this analysis, we also use the round-mean contribution of each group or each player in the other statistical tests described in the following subsections.

[3] Appendix D presents the graphs of mean aggregate contributions by round for each treatment.

Taken together, the statistical evidence above yields our first main result:

RESULT 1: *The theoretical predictions match the observed aggregate contributions more closely in the simultaneous-move setting than in the sequential-move setting.*

Table 4. Summary of the aggregate contributions

Treatment	Mean	Theoretical prediction	Tests on theoretical consistency (*p*-values)	
			Sign test	*t* test
S1	12.06	12	1.0000	0.8576
S2 in S12	11.00	12	0.5078	0.1329
S2 in S21	13.63	12	0.7266	0.2198
S3	12.79	12	0.7905	0.2458
S4	12.23	12	0.7905	0.6556
T1	11.33	9	0.0003	0.0001
T2	11.49	10	0.0490	0.0067
T3	11.12	8	0.0127	0.0055
T4 in T34	8.54	8	0.1797	0.1962
T4 in T43	12.61	8	0.0156	0.0088

4.2.2 Individual Contribution

Table 5 presents the summary of the individual contribution in each treatment.[4] As shown in the top four rows of the table, the contributions of both player-1 and player-3 subjects significantly deviate from their theoretical predictions in all simultaneous-contribution treatments (i.e., treatments S1–S4). Specifically, on average, player-1 subjects (i.e., those endowed with the highest amount) contribute 0.99–3 points less, whereas player-3 subjects (i.e., those endowed with the lowest amount) contribute 1.04–1.90 points more than the corresponding theoretical predictions when contributing simultaneously. In addition, player-2 subjects contribute significantly more than the predicted values in treatments S1 and S3, while their contributions are statistically indistinguishable from the theoretical predictions in treatments S2 and S4.

Turning to the sequential-contribution treatments (i.e., treatments T1–T4), the bottom four rows of Table 5 show that player-1 subjects (i.e., those endowed with the highest amount), acting as leaders, contribute significantly more than the theoretical predictions in all treatments. In contrast, player-2 and player-3 subjects (i.e., those with lower endowments), acting as followers, contribute significantly less than their corresponding theoretical predictions in most treatments, except for treatments T3 and T4 for player-3 subjects.

Based on the statistical evidence above, we derive our second main result along with two sub-results.

[4] Appendix E presents the graphs of mean individual contributions by round for each treatment.

RESULT 2: *The theoretical predictions for individual contributions in our three-person non-linear public goods game with heterogeneous endowments do not accurately capture subjects' actual contribution behavior.*

RESULT 2a: *In simultaneous-contribution settings, subjects endowed with the highest amount contribute less than the theoretical predictions, whereas subjects endowed with lower amounts contribute more than predicted.*

RESULT 2b: *In sequential-contribution settings, the highest-endowed subjects, acting as leaders, contribute more than the theoretical predictions, while the lower-endowed subjects, acting as followers, contribute less than predicted.*

In addition, in the sequential-contribution treatments, our theoretical predictions for players 2 and 3 are derived by backward induction. It should be noted that, in the experiment, players 2 and 3 make their decisions after observing player 1's contribution. Therefore, it is natural to construct predictions conditional on player 1's actual contributions. Using the formulas for the both-followers-contribute regime in Table 1, we calculated these predictions and compared them with the actual contributions of players 2 and 3. Based on the results of two-sided sign test and *t* test, we find no significant differences between the predicted and actual contributions for either type of player, except for player-3 subjects in Treatment T4 (all other *p* values are larger than 0.10). This is because the predictions conditional on player 1's actual contributions, which are lower than those derived by backward induction, are closer to the actual contributions of players 2 and 3. This implies that followers' decisions are well explained by the model conditional on the leader's contribution, and that the deviations from the backward-induction predictions arise mainly from player 1's higher-than-predicted contributions.

Table 5. Summary of the individual contributions

Treatment	Player 1			Player 2			Player 3		
	Mean	Prediction	*t* test[b]	Mean	Prediction	*t* test	Mean	Prediction	*t* test[b]
S1	6.76	9	0.0000	3.12	2	0.0010	2.18	1	0.0012
S2	5.01	6	0.0003	4.19	4	0.3440	3.04	2	0.0002
S3	8.00	11	0.0006	3.23	1	0.0000	1.56	0	0.0003
S4	5.63	7	0.0041	4.71	5	0.4596	1.90	0	0.0000
T1	5.93	0	0.0000	3.39	5	0.0004	2.01	4	0.0000
T2	3.79	0	0.0000	4.72	6	0.0023	2.97	4	0.0118
T3	6.41	1	0.0003	3.24	5	0.0005	1.46	2	0.0654
T4[a]	6.41	3	0.0008	2.21	3	0.0174	1.84	2	0.5513

Notes: [a] The mean contributions of player-1 subjects in treatment T4 are 4.54 and 8.52 in sessions T34 and T43, respectively, and the *p*-values of *t* test are 0.0220 and 0.0039, respectively. [b] The reported figures are *p*-values of the two-tailed *t* test examining whether the mean individual contribution is equal to the theoretical prediction. The sign test results are similar to these ones and are omitted for the sake of saving spaces.

4.2.3 Subjects' Payoff

The mean ratios of subjects' payoffs to the theoretically predicted payoffs in each treatment are presented in Table 6. As shown in the table, the mean ratios for player-2 and player-3 subjects are less than 1 in the simultaneous treatments and greater than 1 in the sequential treatments. This indicates that subjects endowed with lower amounts earned payoffs below the theoretical predictions in the simultaneous treatments but above the predictions in the sequential treatments. Both the two-tailed *t* test and the sign test confirm that these differences are statistically significant in almost all treatments, except for player-2 subjects in S2 and S4.

In contrast, player-1 subjects, who were endowed with the highest amount, tend to earn payoffs above the theoretical predictions in the simultaneous treatments but below the predictions in the sequential treatments, although these differences are not statistically significant in several treatments.

The statistical evidence above leads to our third main result along with two sub-results.

RESULT 3: *The theoretical predictions for subjects' payoffs in our three-person non-linear public goods game with heterogeneous endowments do not accurately capture the actual payoffs obtained by subjects.*

RESULT 3a: *When subjects contribute simultaneously, those endowed with the highest amount earn higher payoffs than the theoretical predictions, whereas those endowed with lower amounts earn lower payoffs than predicted.*

RESULT 3b: *When subjects contribute sequentially, the highest-endowed subjects, acting as leaders, earn payoffs below the theoretical predictions, while the lower-endowed subjects, acting as followers, earn payoffs above the predicted levels.*

Table 6. Summary of the mean ratios of subjects' payoff to theoretically predicted payoff

Treatment	Player 1	Player 2	Player 3
S1	1.076**	0.940**	0.938**
S2	1.031	0.979	0.948*
S3	1.129**	0.907**	0.944*
S4	1.031	0.985	0.889**
T1	0.927**	1.191**	1.222**
T2	0.930*	1.114**	1.102**
T3	0.962	1.249**	1.168*
T4[a]	1.005	1.166**	1.116**

Notes: * and ** indicate that the ratio is significant different from 1 at 5% and 1% level by both the two-tailed *t* test and sign test, respectively. [a] The mean ratios of player-1 subjects in

treatment T4 are 0.967 and 1.048 in sessions T34 and T43, respectively, and neither ratio differs significantly from 1 at the 5% level based on both the two-tailed *t* test and the sign test.

4.3 Simultaneous Contribution vs. Sequential Contribution

To compare subjects' experimental behavior between the simultaneous and sequential treatments, we use the data from treatments S1, S2, T1, and T2. Recall that the endowments of the three subjects in each group and their corresponding payoff tables were identical in treatments S1 (resp. S2) and T1 (resp. T2). The only difference was that the player-1 subject determined his/her contribution simultaneously with the other two subjects in S1 (resp. S2), whereas in T1 (resp. T2) the player-1 subject made the contribution decision first.

4.3.1 Aggregate Contribution

RESULT 1 indicates that the theoretical predictions for aggregate contributions fit the data better when subjects contribute simultaneously in S1 and S2 than when they contribute sequentially in T1 and T2, respectively. Because the theoretical predictions differ between S1 (resp. S2) and T1 (resp. T2), it is necessary to compare the actual aggregate contributions of each group across these treatments to examine whether the aggregate contribution itself differs. Both the rank-sum test and *t* test suggest that aggregate contributions are significantly higher in S2 of S21 than in T2 (p<0,05 in both tests), while there are no significant differences in the comparisons of S1 vs. T1 and S2 of S12 vs. T2 (all *p*-values of both tests exceed 0.10).

4.3.2 Individual Contribution

RESULT 2a and RESULT 2b indicate that there are significant differences between S1 (resp. S2) and T1 (resp. T2) in how each type of subject's individual contribution deviates from its corresponding theoretical prediction. However, both the rank-sum test and the *t* test show that there are no significant differences in the individual contribution levels themselves across these treatments. For all subject types, the *p*-values in both tests exceed 0.10.

4.3.3 Subjects' Payoff

Similar to the results on individual contributions, both the rank-sum test and the *t* test indicate that there are no significant differences in the payoffs themselves for any type of subject between S1 (resp. S2) and T1 (resp. T2).[5] This holds despite RESULT 3a and RESULT 3b showing significant differences between these treatments in terms of how each subject type's payoff deviates from its corresponding theoretical prediction.

Summing up the above statistical evidence, we present our fourth result.

[5] All the *p*-values for any type of subjects are larger than 0.05 in both tests.

RESULT 4: *The aggregate contribution to the public goods is significantly higher in the simultaneous treatment than in the sequential treatment in one case, but not in the other two cases. In addition, no significant differences are found between the two treatments in individual contributions or payoffs for any subject type.*

4.4 Regressions on Each Type of Subjects' Individual Contribution

Tables 7 - 9 report panel regression results on the player-1, player-2, and player-3 subjects' individual contribution, respectively. In all regressions, the dependent variable is the subject's contribution in each round. In the simultaneous treatments, the main independent variables are the previous round contributions of all three subject types within the same group—that is, the variables *Previous own contribution* and *Previous contribution of players 1, 2,* or *3*. In the sequential treatments, the relevant independent variables differ across player types. For player-1 subjects, the key regressors are the previous-round contributions of themselves and the other two group members (i.e., *Previous own contribution*, *Previous contribution of player 2*, and *Previous contribution of player 3*). For player-2 (resp. player-3) subjects, the main regressors include the current-round contribution of the player-1 subject and the previous-round contributions of themselves and player-3 (resp. player-2) subjects (i.e., *Current contribution of player 1*, *Previous own contribution*, and *Previous contribution of player 3* (resp. *Previous contribution of player 2*)). In all specifications, we also include the variable *Round* to control for potential round effects.[6]

For player-1 subjects, who were endowed with the highest amount, the results in Table 7 indicate that their contributions are positively correlated with their own contributions in the previous round in both the simultaneous and sequential treatments, although the estimated coefficients are not statistically significant in T2 and in T4 of session T34. The effects of the other two subjects' previous-round contributions on player-1 subjects' contributions are mixed. In several treatments (S2, S3, and T4 in T34), neither coefficient is statistically significant. In contrast, in some treatments (S1, S4, T1, and T2), the previous-round contribution of at least one of the two other players significantly and negatively affects player-1 subjects' contribution. Interestingly, in T3 and in T4 of session T43, the coefficients on *Previous contribution of player 3* and *Previous contribution of player 2*, respectively, are positive and significant at the 10% level. This suggests that in these treatments, player 1 subjects may be inclined to reciprocate the generosity of the less endowed players.

Turning to the determinants of player-2 and player-3 subjects' contributions, the results in Tables 8 and 9 suggest that in the simultaneous treatments they generally do not respond to the contributions of other players, as most of the estimated coefficients on others' previous-round contributions are statistically insignificant. In contrast, in the sequential treatments, both follower types appear to react strategically to the leader's behavior: the estimated coefficients on *Current contribution of player 1* are negative and significant in most cases, indicating that followers tend to reduce their contributions

[6] Regressions using the ratio of each player's contribution to his/her endowment were also conducted. The results are consistent with those reported in Tables 7 - 9.

when the leader contributes more. Interestingly, player 2 subjects positively respond to player 3 subjects' previous-round contributions in three of the four sequential treatments (T1, T3, and T4), with the estimated coefficients statistically significant in two of them (T3 and T4).[7] Regarding *Previous own contribution*, both player 2 and player 3 subjects exhibit positive persistence in their contribution behavior, similar to player 1 subjects. Their current contributions are positively correlated with their own previous-round contributions, and the corresponding coefficients are significant in most treatments.

Finally, the variable *Round* is insignificant in most specifications, indicating that round effects are negligible in our experiment.

Based on the above regression results, we generate our fifth and sixth results.

RESULT 5: *In our three-person non-linear public goods game with heterogeneous endowments, all subjects exhibit positive persistence in their contribution behavior: they consistently respond to their own previous contributions in both the simultaneous and sequential treatments, regardless of their endowment level.*

RESULT 6: *When contributions are made simultaneously, subjects generally do not condition their decisions on the past contributions of others, irrespective of their endowment level. In contrast, when contributions are made sequentially, behavioral patterns diverge by role: the highest-endowed subjects, acting as leaders, occasionally reciprocate the generosity of the less-endowed followers, whereas the lower-endowed subjects, acting as followers, tend to free-ride on the higher contributions of the leader.*

Table 7. Panel regressions on the player-1 subjects' individual contributions

Player 1	S1	S2	S3	S4	
Previous own contribution	0.301**	0.340***	0.642***	0.291**	
Previous contribution of player 2	-0.139	-0.098	0.030	-0.259***	
Previous contribution of player 3	-0.428***	-0.125	-0.255	-0.014	
Round	0.017	-0.118	-0.053	0.043	
Constant	6.094***	4.662***	3.465***	5.083***	
R-squared (overall)	0.281	0.156	0.494	0.156	
Observations	119	119	105	105	
	T1	T2	T3	T4 in T34	T4 in T43
Previous own contribution	0.537***	0.222	0.731***	0.254	0.651***
Previous contribution of player 2	0.057	-0.279*	-0.360*	-0.220	0.784*
Previous contribution of player 3	-0.429***	-0.034	0.511*	-0.280	-1.144***
Round	0.096	-0.001	0.059	-0.112	-0.110
Constant	2.962***	4.172**	1.472	4.791**	4.505**

[7] The player-3 subjects also positively respond to the player-2 subjects' previous-round contributions in two of the four sequential treatments (T3 and T4), with the estimated coefficient reaching statistical significance in one of them (T3).

R-squared (overall)	0.416	0.151	0.580	0.151	0.464
Observations	119	119	119	63	56

Notes: *z* values and robust standard errors are omitted for saving space. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Table 8. Panel regressions on the player-2 subjects' individual contributions

Player 2	S1	S2	S3	S4
Previous own contribution	0.311***	0.380*	0.136	0.426***
Previous contribution of player 1	-0.017	0.003	-0.096	-0.076
Previous contribution of player 3	-0.082	-0.067	0.490***	0.046
Round	-0.079	-0.143*	-0.260***	-0.137
Constant	2.660***	3.450**	3.866***	3.596***
R-squared (overall)	0.166	0.187	0.404	0.187
Observations	119	119	105	105
	T1	T2	T3	T4
Previous own contribution	0.147	0.049	0.291***	0.356***
Current contribution of player 1	-0.286***	-0.373***	-0.119***	-0.108***
Previous contribution of player 3	0.192	-0.033	0.208***	0.259**
Round	-0.047	-0.010	0.101	-0.028
Constant	4.277***	5.949***	2.200***	1.746***
R-squared (overall)	0.392	0.282	0.322	0.480
Observations	119	119	119	119

Notes: *z* values and robust standard errors are omitted for saving space. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Table 9. Panel regressions on the player-3 subjects' individual contributions

Player 3	S1	S2	S3	S4
Previous own contribution	0.505***	0.567***	0.253	0.252**
Previous contribution of player 1	-0.155**	-0.079	-0.087*	0.116
Previous contribution of player 2	-0.010	-0.098*	0.182	-0.058
Round	-0.063	0.023	0.020	-0.164**
Constant	2.323***	1.986***	0.995	1.767**
R-squared (overall)	0.374	0.348	0.314	0.348
Observations	119	119	105	105
	T1	T2	T3	T4
Previous own contribution	0.300**	0.438***	0.046	0.406***
Current contribution of player 1	-0.230***	-0.228***	-0.072*	-0.055
Previous contribution of player 2	-0.021	-0.053	0.160**	0.030
Round	0.034	-0.121*	-0.146**	0.009
Constant	2.697***	3.363***	2.058***	1.324

R-squared (overall)	0.434	0.374	0.172	0.246
Observations	119	119	119	119

Notes: z values and robust standard errors are omitted for saving space. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

5. Discussion and Conclusion

This study theoretically and experimentally investigates contribution behavior in a three-person non-linear public goods game with heterogeneous endowments under both simultaneous- and sequential-move institutions. Several important findings emerge regarding the extent to which standard theoretical predictions capture actual behavior, how contribution patterns differ across institutional settings, and what behavioral mechanisms may underlie these differences.

First, our results show that theoretical predictions track aggregate contribution levels more closely in simultaneous-move treatments than in sequential-move treatments (RESULT 1). However, when examining decisions at the individual level, theoretical predictions systematically fail to describe subjects' actual contribution behavior (RESULT 2). In the simultaneous treatments, the highest-endowed subjects contribute less than predicted, while the lower-endowed subjects contribute more (RESULT 2a). A contrasting pattern arises in the sequential treatments: leaders—who are endowed with the highest amount—contribute more than predicted, whereas followers contribute less (RESULT 2b). These behavioral deviations from theory also manifest in payoffs. Subjects' realized earnings differ substantially from theoretical predictions (RESULT 3). In simultaneous settings, the highest-endowed subjects earn more than predicted and the lower-endowed subjects earn less (RESULT 3a). In sequential settings, leaders earn less than predicted, while followers earn more (RESULT 3b). Together, these results suggest that the combination of endowment heterogeneity and institutional structure induces systematic deviations from standard equilibrium predictions.

Second, we find the aggregate contribution to the public good is significantly higher in the simultaneous treatment than in the sequential treatment in one of the three cases, while no significant differences arise in individual contributions or payoffs across subject types between the two treatments (RESULT 4). This suggests that institutional structure may affect group-level efficiency but not necessarily the relative standing of individuals within groups, despite large differences in endowments and theoretical incentives.

Third, our regression analysis provides insight into the behavioral mechanisms underlying these deviations from theory. Across both institutional settings, all subjects exhibit strong positive persistence in their contribution behavior: they respond consistently to their own previous decisions regardless of endowment level (RESULT 5). This suggests that contribution behavior is strongly path-dependent and may reflect individual heuristics or learning rules rather than forward-looking optimization. The responsiveness to others' contributions, by contrast, differs sharply across institutions.

In simultaneous treatments, subjects generally do not condition their behavior on others' previous contributions (RESULT 6), consistent with the notion that simultaneous moves provide limited opportunities for strategic signaling. In sequential treatments, however, behavioral patterns diverge across roles. Leaders occasionally reciprocate the generosity of less-endowed followers, while followers tend to exploit—rather than reward—the higher contributions of leaders (RESULT 6). This combination of reciprocal and free-riding tendencies likely contributes to the aggregate divergence from theoretical predictions observed in sequential settings.

Despite these novel findings, the study has several limitations. The experimental design focuses on a specific non-linear public goods environment with fixed aggregate endowments and a small group size, which may limit external validity. The sequential treatments also impose a strict leader–follower structure that may not fully capture more complex real-world institutional arrangements where leadership may be endogenous or rotate over time. Moreover, the number of rounds is limited, thus, common knowledge of finite repetition may influence dynamic behavior, potentially dampening or enhancing reciprocity patterns. Finally, while our regressions document behavioral correlations, they cannot fully disentangle the underlying psychological motivations—such as fairness concerns, reciprocity, or strategic reasoning—without complementary elicitation methods.

In conclusion, our study contributes to the literature by demonstrating that in a three-person non-linear public goods game with heterogeneous endowments, actual contribution behavior systematically deviates from standard theoretical predictions, with the nature of the deviation depending crucially on the institutional environment. Simultaneous moves generate more theory-consistent aggregate outcomes, whereas sequential moves induce richer behavioral dynamics involving reciprocity and strategic exploitation. These findings highlight the importance of institutional design and role asymmetries when predicting contribution behavior in heterogeneous groups. Future research may extend this analysis by allowing endogenous leadership, or exploring alternative dynamic environments to better understand the robustness of the behavioral patterns identified in this study. In addition, it would be interesting to reverse the leadership role in the sequential setting by assigning the least-endowed or mid-endowed subjects to act as the leader, as doing so may generate behavioral patterns that differ from those observed in the present study.

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Appendix

Appendix A. Simultaneous Game: Calculations and Graphical Illustration

A.1. The Model

We consider a three-player public-good game with players indexed by $i \in \{1, 2, 3\}$. Player i is endowed with private good $w_i > 0$ and chooses a contribution $0 \leq z_i \leq w_i$ to the public good production. Let $x_i \geq 0$ denote the consumption of private good by player i. The budget constraints of players re:

$$x_1 = w_1 - z_1,\ x_2 = w_2 - z_2,\ x_3 = w_3 - z_3$$

and the public good is produced by the sum of individual contributions:

$$G = z_1 + z_2 + z_3$$

The players have Cobb-Douglas preferences over (x_i, G), $u_i(x_i, G) = x_i^{\alpha} G^{1-\alpha}$, and throughout the appendix we set α = 1/2. Then,

$$u_i(x_i, G) = x_i^{1/2} G^{1/2}$$

We assume that endowments satisfy $w_1 > w_2 > w_3$.

A.2. Nash equilibrium for the simultaneous game

In the simultaneous game, every player chooses a contribution $z_i \geq 0$ at the same time. It is convenient to describe equilibrium using a cumulative response function that depends on the total provision G. (The standard response function of player i is defined as a function of the strategies of the other players, but the cumulative response function of player i depends on the aggregated strategy. For details, see Okuno-Fujiwara and Suzumura (1993), P.52, ll.5-7.)

Write $C_i = \sum_{j \neq i} z_j$. Maximizing $(w_i - z_i)(z_i + C_i)$ gives the unique best response $BR_i(C_i) = max\{0, (w_i - C_i)/2\}$. At equilibrium, the cumulative response as a function of total provision is therefore

$$r_i(G) = max\{w_i - G, 0\}$$

The Nash equilibrium $(z_1^*, z_2^*, z_3^*, G^*)$ is thus characterized by

$$z_i^* = r_i(G^*) \text{ for } i = 1, 2, 3, \text{ and } G^* = r_1(G^*) + r_2(G^*) + r_3(G^*).$$

The function $F(G) = \sum_{i=1}^{3} max\{w_i - G, 0\} - G$ is continuous and strictly decreasing, with $F(0) > 0$ and $F(w_1) < 0$ It has a unique zero, which determines the unique Nash equilibrium. The non-negativity constraints give the three exhaustive regimes in Table A1.

Depending on the endowment distribution, there are three types of Nash equilibrium. Table A1 summarizes the equilibrium contributions and total provision across the relevant ranges of endowment inequality.

Table A1. Summary of the three types of Nash equilibria in the simultaneous game

Endowment distribution	z_1	z_2	z_3	$\boldsymbol{G}$
$w_3 > \frac{1}{3}(w_1 + w_2)$	$\frac{3w_1 - (w_2 + w_3)}{4}$	$\frac{3w_2 - (w_1 + w_3)}{4}$	$\frac{3w_3 - (w_1 + w_3)}{4}$	$\frac{(w_1 + w_2 + w_3)}{4}$
$w_3 \leq \frac{w_1 + w_2}{3}$ and $w_2 > \frac{1}{2}w_1$	$\frac{2w_1 - w_2}{3}$	$\frac{2w_2 - w_1}{3}$	0	$\frac{(w_1 + w_2)}{3}$
$w_2 \leq \frac{1}{2}w_1$	$\frac{w_1}{2}$	0	0	$\frac{w_1}{2}$

The three rows correspond to equilibria with (i) all three players contributing, (ii) only the poorest player not contributing, and (iii) only the richest player contributing. In particular, when player 3's endowment is sufficiently large (the first row), all players make positive contributions and the total provision is $G = (w_1 + w_2 + w_3)/4$. When the inequality gap is so large that player 3 cannot afford to contribute anything (the second row), the equilibrium features $z_3^* = 0$, and the equilibrium is determined by the two richer players. Finally, when the middle player's endowment is not greater than one-half of the richest player's endowment (the third row), only the richest player contributes.

At $3w_3 = w_1 + w_2$, player 3 contributes zero and the second row applies; at $2w_2 = w_1$, player 2 also contributes zero and the third row applies. Adjacent formulas agree at these boundaries, so uniqueness is preserved.

A.3. Cumulative reaction function and graphical solution (Figure A1)

To describe how endowment inequality affects equilibrium outcomes more intuitively, we construct the aggregate cumulative response function (See Okuno-Fujiwara and Suzumura (1993), P.52, ll.13-14.). Summing individual reactions across players yields:

$$R(G) = r_1(G) + r_2(G) + r_3(G) .$$

Case-a1. All three players contribute.

First, consider the situation where all three individuals contribute (see Figure A1). The total endowment of the three players is fixed at $w_1 + w_2 + w_3$. On the red segment, we know from the functional form that its intercept on the vertical axis and the slope are respectively $(w_1 + w_2 + w_3)$ and -3, which remains constant regardless of changes in the allocation of w_1, w_2 and w_3 (as long as the total remains fixed). Therefore, if not constrained by the value of w_3, the graph of this function would continue to extend downward to the right until it intersects with the horizontal axis.

From the above analysis, we can conclude that the equilibrium point will always lie on the 45-degree line. As long as the value of w_3 is greater than the horizontal-axis value at the intersection of the function $R(G)$ and the 45-degree line, the total income

remains constant and the equilibrium point will remain unchanged. This holds true as long as the rule is followed that player 1 is the wealthiest and player 3 is the poorest, with reasonable adjustments to their respective incomes.

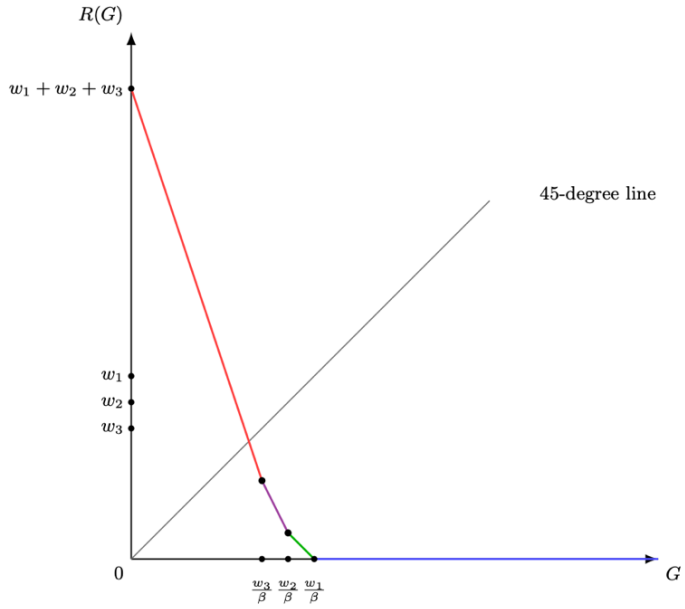


Figure A1. Cumulative reaction function and the 45-degree line.

A.4. A second graphical case (Figure A2)

Case-a2. Players 1 and 2 contribute and player 3 does not.

Similarly, analyzing the case where only player 3 does not contribute (see Figure A2), which corresponds to the purple segment of the graph, we can observe the following. According to the function $R(G)$, when the value of w_3 remains unchanged, the total endowments for players 1 and 2 also remain constant under redistributions between them. Because the intercept of the function $R(G)$ remains unchanged, when the equilibrium exists with only player 3 not contributing, the equilibrium point will always be within the range of the purple segment. It will remain unchanged as long as the incomes of players 1 and 2 are adjusted reasonably.

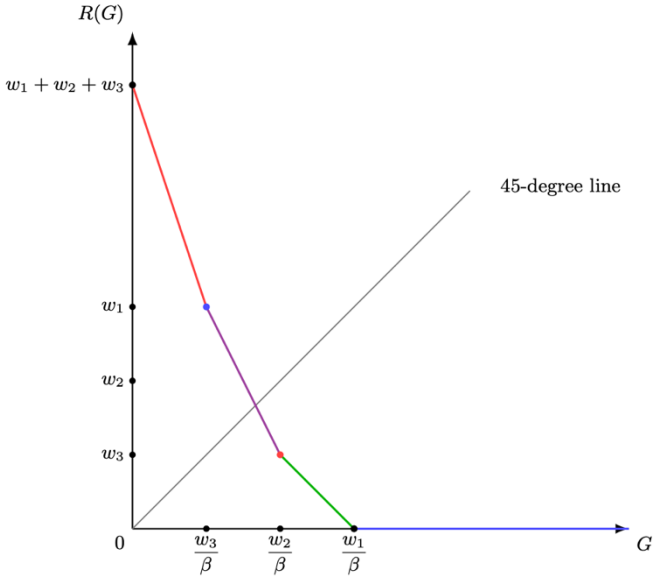


Figure A2. Cumulative reaction function and the 45-degree line.

Appendix B. Sequential Game: Calculations and Graphical Illustration

B.1. Sequential Game

We consider a sequential public-good game with three players. Player 1 moves first and acts as the leader, while players 2 and 3 move after observing the leader's contribution and then choose their contributions simultaneously. Namely, players 2 and 3 act as the followers. Throughout this appendix, we assume that the endowment distribution satisfies $w_1 > w_2 > w_3$, so that player 1 is the richest and player 3 is the poorest. To distinguish the leader's decision from those of the followers, let g_1 denote the contribution made by player 1, and let z_2 and z_3 denote the contributions made by players 2 and 3, respectively. Let x_i denote the consumption of private good by player i, and let the total amount of the public good be

$$G = g_1 + z_2 + z_3$$

Private consumption satisfies the following budget constraints:

$$x_1 = w_1 - g_1,\ x_2 = w_2 - z_2,\ x_3 = w_3 - z_3$$

The players have Cobb-Douglas preferences over private consumption and the public good. For each follower i = 2, 3, the utility function is given by

$$U_i(x_i, G) = G^{\frac{1}{2}} x_i^{\frac{1}{2}}$$

Because this is a sequential game, the *subgame-perfect equilibrium* is solved by backward induction. The leader chooses her contribution anticipating the followers' reactions. Therefore, the first step is to characterize the followers' subgame for a given g_1. Once the followers' Nash equilibrium functions for the subgame has been derived as functions of action by the leader, it can be substituted into the leader's problem to

determine the subgame-perfect equilibrium of the sequential game, which consists of the action by the leader and the Nash equilibrium functions of the two followers. The Stackelberg equilibrium is obtained by substituting the action by the leader into the Nash equilibrium functions and computing the associated provision of the public good.

Accordingly, this appendix proceeds as follows. We first derive the followers' Nash equilibrium functions and identify the possible outcomes of the followers' subgame. We then solve the leader's optimization problem under each relevant regime to find the Stackelberg equilibrium. Finally, based on these derivations, we classify the cases of Stackelberg equilibria and provide graphical illustrations for each case.

B.2. Followers' subgame

Given the leader's contribution g_1, players 2 and 3 simultaneously choose their contributions in the follower stage. We therefore first characterize the followers' subgame conditional on g_1.

For each follower i = 2, 3, the optimization problem is

$$\max_{x_i, z_i} U_i(x_i, G) = G^{\frac{1}{2}} x_i^{\frac{1}{2}}$$

subject to

$$w_i = z_i + x_i, \quad G = g_1 + z_2 + z_3.$$

Substituting the budget constraint into the utility function, the problem can be written as

$$\max_{0 \le z_i \le w_i} (g_1 + z_2 + z_3)^{\frac{1}{2}} (w_i - z_i)^{\frac{1}{2}}, \quad i = 2, 3.$$

Taking logarithms, which preserves the maximizer, yields

$$\log U_i(g_1, z_2, z_3) = \frac{1}{2}\log(g_1 + z_2 + z_3) + \frac{1}{2}\log(w_i - z_i)$$

Hence, for an interior solution,

$$\frac{\partial \log U_i}{\partial z_i} = \frac{1}{2(g_1 + z_2 + z_3)} - \frac{1}{2(w_i - z_i)} = 0$$

which implies $g_1 + z_2 + z_3 = w_i - z_i$.

Combining the first-order condition with the non-negativity constraint $z_i \ge 0$, the maximization condition for each follower i is:

$$\begin{cases} g_1 + z_2 + z_3 \ge w_i - z_i & \text{if } z_i = 0 \\ g_1 + z_2 + z_3 = w_i - z_i & \text{if } z_i > 0 \end{cases}$$

Accordingly, the unique best responses to a given contribution by the other follower are

$$BR_2(g_1, z_3) = max\{0, (w_2 - g_1 - z_3)/2\}$$

and

$$BR_3(g_1, z_2) = max\{0, (w_3 - g_1 - z_2)/2\}$$

Solving these conditions jointly gives the following unique subgame equilibrium for every $g_1 \in [0, w_1]$. Write $h = 2w_3 - w_2$; the first interval is absent if $h \leq 0$.

$$B_2(g_1) = \begin{cases} \dfrac{2w_2 - w_3 - g_1}{3} & 0 \leq g_1 < h \\ \dfrac{w_2 - g_1}{2} & \max\{0, h\} \leq g_1 < w_2 \\ 0 & w_2 \leq g_1 \leq w_1 \end{cases}$$

$$B_3(g_1) = \begin{cases} \dfrac{2w_3 - w_2 - g_1}{3} & 0 \leq g_1 < h \\ 0 & \max\{0, h\} \leq g_1 \leq w_1 \end{cases}$$

These functions are continuous at $g_1 = h$ when $h > 0$ and at $g_1 = w_2$. The three possible follower outcomes are illustrated below.

B.2.1. Graphical illustration of the followers' subgame

The Nash equilibrium for the follower-stage given g_1 can be illustrated in the (z_2, z_3)-plane. The three relevant cases are shown below.

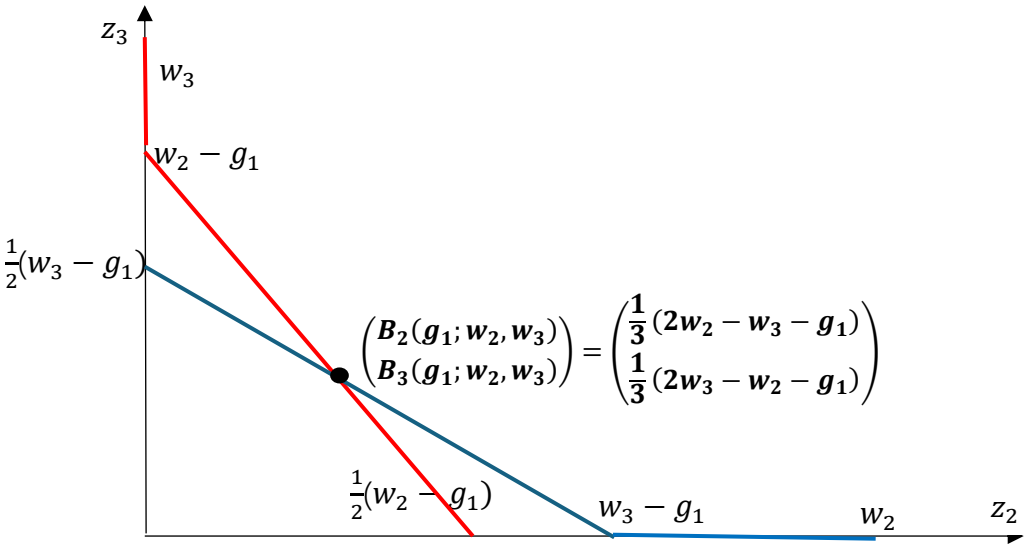


Figure B-1: Case A: $\mathbf{0 \leq g_1 < 2w_3 - w_2}$. Both followers contribute, and the intersection of the constrained best responses is strictly inside the first quadrant.

Figure B-1 shows the case in which both followers make strictly positive contributions. This occurs when the intersection of the two reaction lines lies in the interior of the first quadrant.

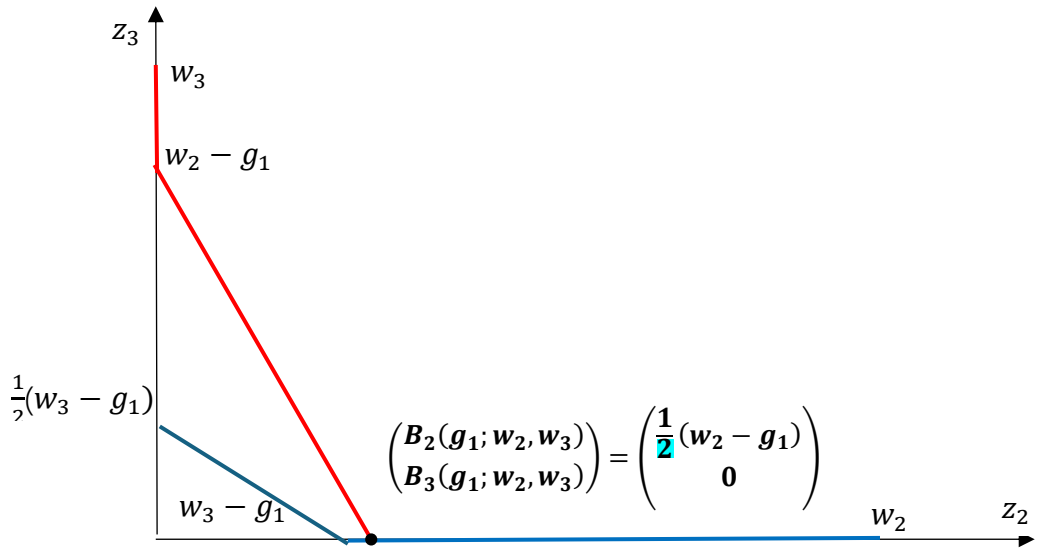


Figure B-2: Case B: $\max\{0, 2w_3 - w_2\} \leq g_1 < w_2$. The equilibrium is on the horizontal axis at $z_2 = (w_2 - g_1)/2$, with $z_3 = 0$. The value $z_2 = w_2 - w_3$ occurs only at $g_1 = 2w_3 - w_2$ when that boundary is feasible.

Figure B-2 illustrates the regime in which player 2 contributes positively while player 3 contributes zero. The equilibrium is on the horizontal axis throughout this regime.

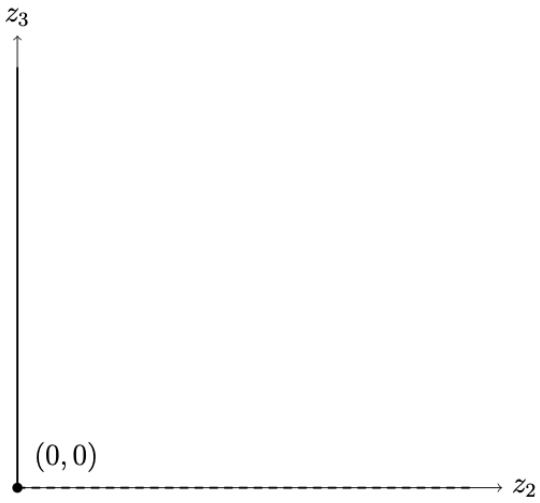


Figure B-3: Case C: $g_1 \geq w_2$. Both followers choose zero, and the follower-stage Nash equilibrium is at the origin.

Figure B-3 shows the case in which the leader's contribution is so large that neither follower contributes. The follower-stage Nash equilibrium is therefore located at the origin. These three cases fully characterize the possible outcomes of the followers'

subgame and will be used in the next section to derive the leader's optimal contribution under each regime.

B.3. Leader's maximization under each followers' regime

Using the followers' Nash equilibrium functions derived in Section B.2, player 1 chooses g_1 to maximize

$$U_1 = (g_1 + max\{B_2(g_1; w_2, w_3), 0\} + max\{B_3(g_1; w_2, w_3), 0\})^{\frac{1}{2}}(w_1 - g_1)^{\frac{1}{2}}$$

Each regime yields a strictly concave quadratic for $V_1 = U_1^2$, but the full objective need not be concave. Its derivative jumps upward when a follower exits. We first identify branch candidates and their feasible intervals, and then compare all branches globally in Section B.3.4.

B.3.1. Case-b1: both followers contribute

Suppose that both followers make strictly positive contributions, that is,

$$z_2 > 0,\ z_3 > 0.$$

From the Nash equilibrium functions of players 2 and 3, this requires

$$g_1 < 2w_2 - w_3 \quad \text{and} \quad g_1 < 2w_3 - w_2.$$

Since $w_2 > w_3$, the latter condition is the binding one, and hence the relevant regime is $g_1 < 2w_3 - w_2$.Under this condition, the aggregate amount of the public good is

$$G = g_1 + z_2 + z_3 = \frac{g_1 + w_2 + w_3}{3}$$

Substituting this into the leader's utility function gives

$$U_1 = \left(\frac{g_1 + w_2 + w_3}{3}\right)^{\frac{1}{2}} (w_1 - g_1)^{\frac{1}{2}}$$

The unconstrained A-branch maximizer, with the non-negativity constraint imposed, is

$$g_1^* = \begin{cases} \frac{1}{2}(w_1 - w_2 - w_3), & \text{if} \quad w_1 > w_2 + w_3 \\ 0, & \text{if} \quad w_1 \le w_2 + w_3 \end{cases}$$

This is a branch candidate, not yet a global optimum. When $h = 2w_3 - w_2 > 0$, the maximum over the actual closed A interval $[0, h]$ is attained at $\min\{h, \max\{0, (w_1 - w_2 - w_3)/2\}\}$.

B.3.2. Case-b2: player 2 contributes and player 3 does not.

Next, suppose that the contribution by player 2 is positive while that of player 3 is zero:

$$z_2 > 0,\ z_3 = 0.$$

Using the followers' maximization conditions, the existence of this regime requires

$$\max\{0, 2w_3 - w_2\} \le g_1 < w_2.$$

Because player 3 does not contribute, player 2's Nash equilibrium function reduces to

$$B_2(g_1; w_2) = \begin{cases} \frac{1}{2}(w_2 - g_1), & \text{if } g_1 < w_2, \\ 0, & \text{if } g_1 \geq w_2, \end{cases}$$

Thus, only player 2 contributes for $\max\{0, 2w_3 - w_2\} \leq g_1 < w_2$. Total provision is

$$G = g_1 + z_2 = \frac{w_2 + g_1}{2}$$

Hence the leader's utility becomes

$$U_1 = \left(\frac{w_2 + g_1}{2}\right)^{\frac{1}{2}} (w_1 - g_1)^{\frac{1}{2}}$$

The unconstrained B-branch candidate is

$$g_B = \frac{w_1 - w_2}{2}.$$

Since $w_1 > w_2$, this candidate is positive. Over the actual closed B interval, the maximizer is $\min\{w_2, \max\{0, 2w_3 - w_2, (w_1 - w_2)/2\}\}$.

B.3.3. Case-b3: neither follower contributes

Finally, suppose that neither follower contributes: $z_2 = 0$, $z_3 = 0$.
From the condition in Case B, this regime arises when $g_1 \geq w_2$.In this case, the total amount of the public good equals the leader's own contribution: $G = g_1$.
Therefore, the leader's utility function is

$$U_1 = g_1^{\frac{1}{2}}(w_1 - g_1)^{\frac{1}{2}}$$

Maximizing this function gives

$$g_1^* = \frac{w_1}{2}.$$

Given the endowment ordering, this candidate is consistent with the regime only when $w_1/2 \geq w_2$. Over the closed C interval $[w_2, w_1]$, the maximizer is $\max\{w_2, w_1/2\}$. Branch feasibility alone does not establish global optimality.

B.3.4. Complete global solution and ties

Let $a = w_1 > b = w_2 > c = w_3 > 0$, $W = a + b + c$, and $g = g_1$. The follower equilibrium implies $G(g) = \max\{(g + b + c)/3, (g + b)/2, g\}$. Since $a - g \geq 0$, the leader's squared utility is the upper envelope of three auxiliary quadratics:

$$V_1(g) = \max\{q_A(g), q_B(g), q_C(g)\},$$

$$q_A(g) = \frac{(a - g)(g + b + c)}{3}, \qquad q_B(g) = \frac{(a - g)(g + b)}{2},$$

$$q_C(g) = (a - g)g.$$

Extend each auxiliary quadratic to $[0, a]$. Their unique maximizers are $g_A = \max\{0, (a - b - c)/2\}$, $g_B = (a - b)/2$, and $g_C = a/2$. Their maximum values are

$$M_{\mathrm{A}} = \begin{cases} \dfrac{a(b+c)}{3} & a \le b + c \\ \dfrac{W^2}{12} & a > b + c \end{cases}$$

$$M_{\mathrm{B}} = \frac{(a+b)^2}{8}, \qquad M_{\mathrm{C}} = \frac{a^2}{4}.$$

For every feasible g, $V_1(g) \le \max\{M_{\mathrm{A}}, M_{\mathrm{B}}, M_{\mathrm{C}}\}$. If a branch k attains the largest maximum at g_{k}, then $V_1(g_{\mathrm{k}}) \ge q_{\mathrm{k}}(g_{\mathrm{k}}) = \max\{M_{\mathrm{A}}, M_{\mathrm{B}}, M_{\mathrm{C}}\}$, so equality holds. Conversely, any global optimum must maximize one of the auxiliary quadratics. Thus, all equilibrium leader actions are exactly

$$\{g_{\mathrm{k}} : M_{\mathrm{k}} = \max\{M_{\mathrm{A}}, M_{\mathrm{B}}, M_{\mathrm{C}}\}, k \in \{A, B, C\}\}.$$

A winning candidate automatically lies in the regime represented by its branch. Combining each winning action with the complete follower functions in Section B.2 gives every pure-strategy subgame-perfect equilibrium. Non-winning auxiliary maxima need not be payoffs attainable within their named follower regime.

The following sections express the maximum comparisons as necessary and sufficient conditions. Weak inequalities retain all ties. When two or three branches tie for the global maximum, each associated leader action is a distinct equilibrium; only one action need be chosen in any pure-strategy equilibrium. A triple tie occurs at $(a, b, c) = t(1, \sqrt{2} - 1, \sqrt{3} - \sqrt{2})$, $t > 0$. The internal switching points $g = h$ and $g = b$ cannot be leader optima, because the derivative jumps upward there.

For example, the profile $(a, b, c) = (23.5,16,8.5)$ has a locally optimal A-branch endpoint $g = 0$, but deviating to $g = 3.75$ raises V_1 from $2303/12$ to $6241/32$. Also, at $(28,12,8)$, the B outcome $(8,2,0)$ gives $V_1 = 200$, exceeding the C candidate's value of 196. These comparisons show why cross-regime maximization is essential.

B.4. Conditions and graphical illustrations of the equilibrium cases

B.4.1. Case I: Equilibrium 1 (corner solution with only followers contributing)

We first consider Equilibrium 1 under Case I. Recall that Case I is defined by $w_2 < 2w_3$. In Equilibrium 1, the leader free-rides while both followers contribute:

$$g_1^* = 0, \quad z_2^* > 0, \quad z_3^* > 0.$$

Using the notation in Section B.3.4, Equilibrium 1 exists if and only if

$$a \le b + c, \qquad 8a(b+c) \ge 3(a+b)^2.$$

These conditions imply $b < 2c$ and positive contributions by both followers. The outcome is

$$(g_1^*, z_2^*, z_3^*) = (0, (2b - c)/3, (2c - b)/3), \qquad G^* = (b + c)/3.$$

To illustrate this equilibrium, consider the endowment profile $(w_1,\ w_2,\ w_3)$ = (20, 16, 12). This profile satisfies:

$$w_1 > w_2 > w_3 > 0,\quad 2w_3 - w_2 = 8 > 0,$$
$$a = 20 \le b + c = 28,$$
$$8a(b+c) = 4480 > 3(a+b)^2 = 3888.$$

Hence, $(w_1,\ w_2,\ w_3)$ = (20, 16, 12) lies in the parameter region for Equilibrium 1. Figure B-4 illustrates this equilibrium in the (x_1, G)-plane. The horizontal axis measures player 1's private consumption x_1, and the vertical axis measures the total public good G. The feasible frontier is piecewise linear and is given by

$$G = w_1 - x_1, G = \frac{w_1 + w_2}{2} - \frac{x_1}{2}, G = \frac{w_1 + w_2 + w_3}{3} - \frac{x_1}{3}$$

For $(w_1,\ w_2,\ w_3)$ = (20, 16, 12), the breakpoints occur at

$$x_1 = w_1 - w_2 = 4,\quad x_1 = w_1 - (2w_3 - w_2) = 12,\quad x_1 = w_1 = 20.$$

The equilibrium point is the right endpoint of the third segment, where the leader chooses $g_1^* = 0$, while both followers contribute positively.

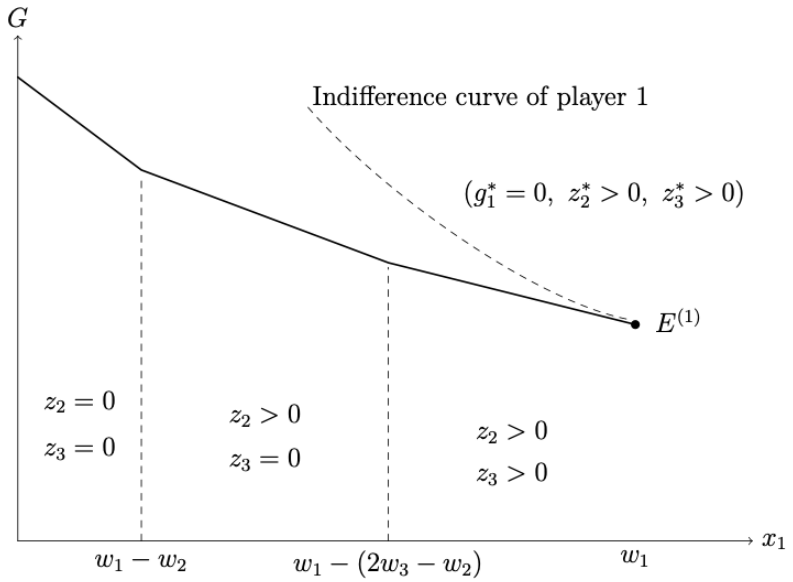


Figure B-4: Illustration of Equilibrium 1 in the $(\boldsymbol{x_1}, \boldsymbol{G})$-plane for $(\boldsymbol{w_1},\ \boldsymbol{w_2},\ \boldsymbol{w_3})$ = (20, 16, 12).

The figure can be read from left to right. In the leftmost segment, neither follower contributes, so the feasible frontier is given by $G = w_1 - x_1$. In the middle segment, player 2 contributes while player 3 does not, and the frontier is therefore

$$G = \frac{w_1 + w_2}{2} - \frac{x_1}{2}$$

In the rightmost segment, both followers contribute, so the frontier becomes

$$G = \frac{w_1 + w_2 + w_3}{3} - \frac{x_1}{3}$$

The frontier becomes flatter as additional followers become active when moving from left to right. The point $E^{(1)}$ is the right endpoint of the third segment, where $x_1 = w_1$ and $g_1^* = 0$, while both followers contribute positively. This is an endpoint

optimum, rather than a tangency. Global optimality follows from $M_A = 560/3 > M_B = 162 > M_C = 100$.

B.4.2. Case I: Equilibrium 2 (interior solution with all three players contributing)

We next consider Equilibrium 2 under Case I. Recall that Case I is defined by

$$2w_3 - w_2 > 0 \Leftrightarrow w_2 < 2w_3$$

In this equilibrium, all three players contribute to the public good:

$$g_1^* > 0, \quad z_2^* > 0, \quad z_3^* > 0$$

In our experimental design, the total income is fixed at $w_1 + w_2 + w_3 = 48$.

For Case I, Equilibrium 2 exists if and only if the following conditions hold jointly:

$$a > b + c, \qquad \sqrt{2}c \geq (\sqrt{3} - \sqrt{2})(a + b),$$

$$b + c \geq (\sqrt{3} - 1)a.$$

To illustrate this Stackelberg equilibrium, consider the endowment profile $(w_1, w_2, w_3) = (25, 13, 10)$, for which $w_1 + w_2 + w_3 = 48$.This triple satisfies

$$w_1 > w_2 > w_3 > 0, \quad 2w_3 - w_2 = 7 > 0$$

so that we are indeed in Case I.

$$a = 25 > b + c = 23, \qquad b + c = 23 > (\sqrt{3} - 1)25 \approx 18.30,$$

and

$$\sqrt{2}c = 10\sqrt{2} \approx 14.14 > (\sqrt{3} - \sqrt{2})(a + b) \approx 12.08.$$

Hence, $(w_1, w_2, w_3) = (25, 13, 10)$ lies in the parameter region for Case I, Equilibrium 2. When both followers contribute, their best-response functions are

$$z_2 = \frac{2w_2 - w_3 - g_1}{3}, \; z_3 = \frac{2w_3 - w_2 - g_1}{3},$$

and the aggregate public good is $G(g_1) = g_1 + z_2 + z_3 = \frac{g_1 + w_2 + w_3}{3}$.

Substituting this into player 1's Cobb-Douglas utility,

$$U_1(x_1, G) = x_1^{\frac{1}{2}} G^{\frac{1}{2}}, \qquad x_1 = w_1 - g_1$$

the first-order condition for an interior solution yield $g_1^* = \frac{w_1 - w_2 - w_3}{2}$.

For $(w_1, w_2, w_3) = (25, 13, 10)$, this gives

$$g_1^* = \frac{25 - 13 - 10}{2} = 1$$

Substituting $g_1^* = 1$ back into the followers' best responses,

$$z_2^* = \frac{2w_2 - w_3 - g_1^*}{3} = \frac{26 - 10 - 1}{3} = 5, \; z_3^* = \frac{2w_3 - w_2 - g_1^*}{3} = \frac{20 - 13 - 1}{3} = 2$$

Thus, $x_1^* = w_1 - g_1^* = 24$, $G^* = g_1^* + z_2^* + z_3^* = 8$.

These values are strictly interior and consistent with $g_1^* > 0, \quad z_2^* > 0, \quad z_3^* > 0$.
In general, the equilibrium contributions are $((a-b-c)/2, (5b-c-a)/6, (5c-b-a)/6)$ and $G^* = W/6$. Equality in a global payoff comparison also admits the tied branch's distinct equilibrium.

Figure B-5 illustrates this equilibrium in the (x_1, G)-plane. The solid frontier is piecewise linear. Moving from left to right, the relevant regime changes from ($z_2 = 0$, $z_3 = 0$), to ($z_2 > 0$, $z_3 = 0$), and finally to ($z_2 > 0$, $z_3 > 0$). The dashed curve is player 1's indifference curve, and the equilibrium point $E^{(2)}$ is located in the interior of the third segment.

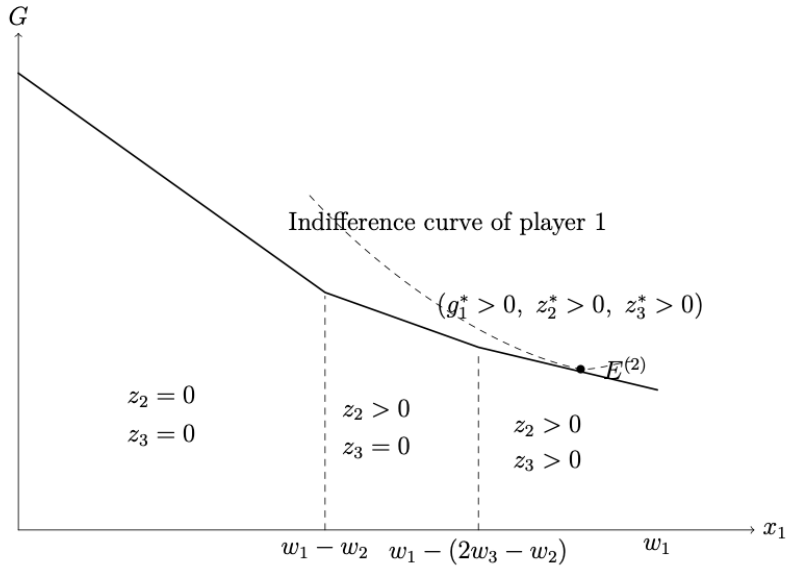


Figure B-5: Illustration of Case I, Equilibrium 2 in the (x_1, G)-plane for (w_1, w_2, w_3) = (25, 13, 10).

B.4.3. Case I: Equilibrium 3 (The leader and player 2 contribute, player 3 exits)

We next consider Equilibrium 3 under Case I. Recall that Case I is defined by

$$2w_3 - w_2 > 0 \Leftrightarrow \quad w_2 < 2w_3.$$

In Equilibrium 3, the leader and player 2 contribute and player 3 does not. In the notation of Section B.3.4, this equilibrium exists if and only if $M_B \geq M_A$ and $M_B \geq M_C$. Equivalently, one of the following two sets of conditions holds:

$$a \leq b + c, \qquad 3(a+b)^2 \geq 8a(b+c);$$

or $a > b + c$, $\sqrt{2}c \leq (\sqrt{3} - \sqrt{2})(a+b)$, $b \geq (\sqrt{2} - 1)a$.

The equilibrium is $((a-b)/2, (3b-a)/4, 0)$, with $G^* = (a+b)/4$.
To illustrate this Stackelberg equilibrium, consider the endowment profile (w_1, w_2, w_3) = (27, 13, 8), for which $w_1 + w_2 + w_3 = 48$. This triple satisfies

$$w_1 > w_2 > w_3 > 0, \ 2w_3 - w_2 = 16 - 13 = 3 > 0,$$

The global comparisons can be verified directly:

$$M_{\mathrm{A}} = 192, \qquad M_{\mathrm{B}} = 200, \qquad M_{\mathrm{C}} = 182.25.$$

Thus, the B candidate is uniquely optimal, and $g_{\mathrm{B}} = (27 - 13)/2 = 7$.
It lies strictly inside the B interval, because $h = 3 < 7 < b = 13$.

Hence, $(w_1,\ w_2,\ w_3) = (27,\ 13,\ 8)$ is an admissible example for Case I, Equilibrium 3. When player 3 exits while player 2 still contributes, the relevant middle regime is characterized by $z_2 > 0,\ z_3 = 0$.In this regime, the feasible frontier in the (x_1, G)-plane is piecewise linear: left segment: $z_2 = 0,\ \ z_3 = 0$, middle segment: $z_2 > 0,\ z_3 = 0$, right segment: $z_2 > 0,\ z_3 > 0$.
For $(w_1,\ w_2,\ w_3) = (27, 13, 8)$, the breakpoints occur at

$$x_1 = w_1 - w_2 = 14, \quad x_1 = w_1 - (2w_3 - w_2) = 24, \quad x_1 = w_1 = 27.$$

The middle segment is

$$G = \frac{w_1 + w_2}{2} - \frac{x_1}{2} = 20 - \frac{x_1}{2}$$

Under Cobb-Douglas preferences,

$$U_1(x_1, G) = x_1^{\frac{1}{2}} G^{\frac{1}{2}}$$

the indifference curves are downward sloping and convex to the origin. In Equilibrium 3, the relevant indifference curve is tangent to the middle segment of the feasible frontier at $E^{(3)}$. Thus, in this equilibrium, $g_1^* > 0,\ z_2^* > 0,\ z_3^* = 0$.The tangency condition yields the point

$$E^{(3)} = (20, 10).$$

Thus, in this equilibrium,

$$g_1^* = w_1 - x_1^* = 27 - 20 = 7,\ z_2^* > 0,\ z_3^* = 0.$$

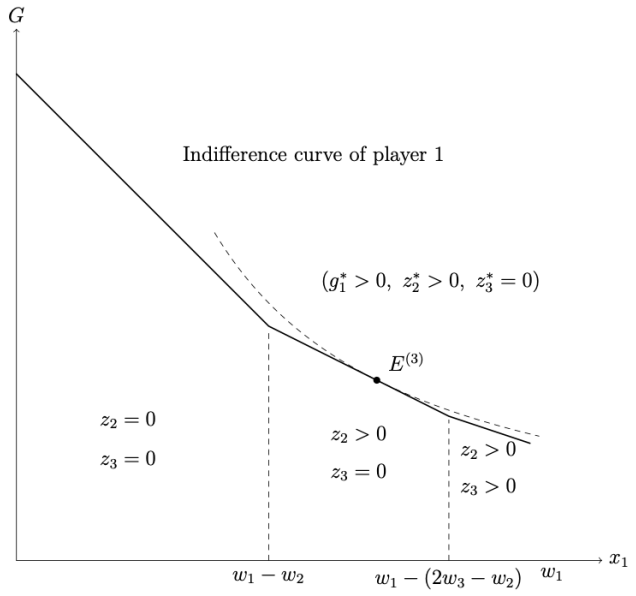


Figure B-6: Illustration of Case I, Equilibrium 3 in the $(\boldsymbol{x_1}, \boldsymbol{G})$-plane for $(\boldsymbol{w_1},\ \boldsymbol{w_2},\ \boldsymbol{w_3})$ = (27, 13, 8).

B.4.4. Case I: Equilibrium 4 (only the leader contributes)

We finally consider Equilibrium 4 under Case I. Recall that Case I is defined by

$$2w_3 - w_2 > 0 \Leftrightarrow w_2 < 2w_3.$$

In this equilibrium, only the leader contributes to the public good, while both followers exit: $g_1^* > 0,\ z_2^* = 0,\ z_3^* = 0$.In our experimental design, the total income is fixed at $w_1 + w_2 + w_3 = 48$. The necessary and sufficient conditions for this equilibrium are

$$b \le (\sqrt{2} - 1)a, \qquad b + c \le (\sqrt{3} - 1)a.$$

Both comparisons are required: the first compares the C and B maxima, and the second compares C and A. The equilibrium is $(a/2,0,0)$, with $G^* = a/2$.

To illustrate this Stackelberg equilibrium, consider the endowment profile $(w_1,\ w_2,\ w_3) = (35, 8, 5)$, for which $w_1 + w_2 + w_3 = 48$. This triple satisfies

$$w_1 > w_2 > w_3 > 0, 2w_3 - w_2 = 10 - 8 = 2 > 0$$

The auxiliary maxima are $M_{\mathrm{A}} = 192,\ M_{\mathrm{B}} = 231.125$, and $M_{\mathrm{C}} = 306.25$, so C is uniquely optimal.

Hence, $(w_1, w_2, w_3) = (35,8,5)$ is an example of Case I, Equilibrium 4. Both followers contribute zero, total provision equals g_1, and the equilibrium leader contribution is 17.5. Since $x_1 = w_1 - g_1$, the relevant frontier is the leftmost segment

$$G = w_1 - x_1$$

For $(w_1,\ w_2,\ w_3) = (35, 8, 5)$, the breakpoints occur at

$$x_1 = w_1 - w_2 = 27, x_1 = w_1 - (2w_3 - w_2) = 33,\ x_1 = w_1 = 35.$$

Under Cobb-Douglas preferences,

$$U_1(x_1, G) = x_1^{\frac{1}{2}} G^{\frac{1}{2}}$$

the indifference curves are bowed toward the origin. In Equilibrium 4, the relevant indifference curve is tangent to the leftmost segment of the feasible frontier. The tangency point is denoted by $E^{(4)}$and satisfies $g_1^* > 0,\ z_2^* = 0,\ z_3^* = 0$.

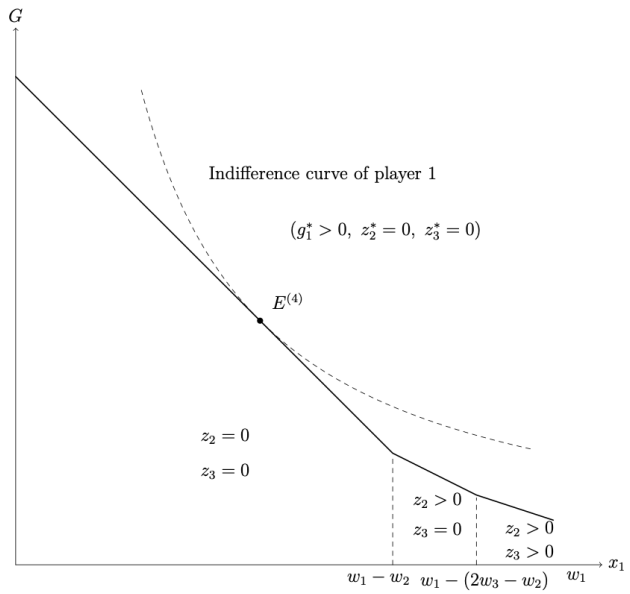


Figure B-7: Illustration of Case I, Equilibrium 4 in the $(\boldsymbol{x_1}, \boldsymbol{G})$-plane for $(\boldsymbol{w_1},\ \boldsymbol{w_2},\ \boldsymbol{w_3})$ = (35, 8, 5).

B.5. Conditions and graphical illustrations of the equilibrium cases under Case II

Case II includes $w_2 \geq 2w_3$, so $h \leq 0$. The A branch is never strictly dominant and its auxiliary maximum is strictly below M_B. Only the B and C outcomes can be equilibria. B is uniquely optimal if $a < (1+\sqrt{2})b$, C is uniquely optimal if $a > (1+\sqrt{2})b$, and both distinct outcomes are equilibria at equality. This also covers the boundary $w_2 = 2w_3$.

B.5.1. Equilibrium L&1F (leader and player 2 contribute, player 3 does not)

Under Case II, Equilibrium a (L&1F) has positive contributions by the leader and player 2, while player 3 contributes zero:

$$g_1^* > 0,\ z_2^* > 0,\ z_3^* = 0$$

The necessary and sufficient condition for Equilibrium L&1F under Case II is

$$a \leq (1+\sqrt{2})b.$$

At equality, the C outcome also exists; below the threshold, the B outcome is unique.

To illustrate this Stackelberg equilibrium, consider the endowment profile $(w_1,\ w_2,\ w_3) = (24, 17, 7)$, for which $w_1 + w_2 + w_3 = 48$. This triple satisfies

$$w_1 > w_2 > w_3 > 0,\quad 2w_3 - w_2 = 14 - 17 = -3 < 0$$

so that we are indeed in Case II. Moreover, $w_1 = 24 \leq 2w_2 = 34$.

Hence, $(24,17,7)$ lies in the parameter region for Equilibrium L&1F. The leader contributes 3.5, player 2 contributes 6.75, and player 3 contributes zero. The relevant follower regime is

$$z_2 > 0,\ z_3 = 0.$$

The feasible frontier in the (x_1, G)-plane is therefore piecewise linear:

left segment: $z_2 = 0,\ z_3 = 0$; right segment: $z_2 > 0,\ z_3 = 0$

For $(w_1,\ w_2,\ w_3) = (24, 17, 7)$, the breakpoint occurs at $x_1 = w_1 - w_2 = 7$ and $x_1 = w_1 = 24$. The right segment is given by

$$G = \frac{w_1 + w_2}{2} - \frac{x_1}{2} = \frac{41}{2} - \frac{x_1}{2}$$

Under Cobb-Douglas preferences, namely

$$U_1(x_1, G) = {x_1}^{\frac{1}{2}} G^{\frac{1}{2}}$$

At the optimum, the indifference curve is tangent to the right segment at $E^{(a)}$. Solving the tangency condition yields

$$E^{(a)} = \left(\frac{w_1 + w_2}{2}, \frac{w_1 + w_2}{4}\right) = (20.5, 10.25).$$

Thus, $g_1^* = w_1 - x_1^* = 24 - 20.5 = 3.5,\ z_2^* > 0,\ z_3^* = 0.$

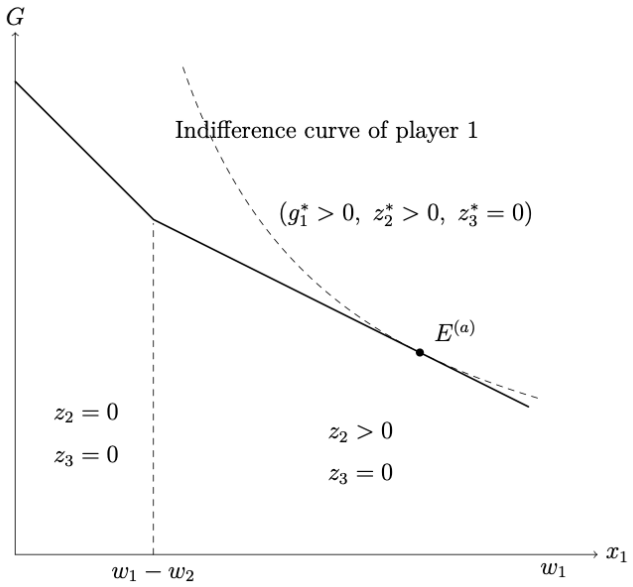


Figure B-8: Illustration of Case II, Equilibrium a in the $(\boldsymbol{x_1}, \boldsymbol{G})$-plane for $(\boldsymbol{w_1},\ \boldsymbol{w_2},\ \boldsymbol{w_3})$ = (24, 17, 7).

B.5.2. Equilibrium L (only the leader contributes)

Under Case II, Equilibrium b (L) has a positive contribution by the leader and zero contributions by both followers:

$$g_1^* > 0,\ z_2^* = 0,\ z_3^* = 0.$$

The necessary and sufficient condition for Equilibrium L under Case II is

$$a \geq (1 + \sqrt{2})b.$$

At equality, the B outcome also exists; above the threshold, the C outcome is unique.

To illustrate this Stackelberg equilibrium, consider the endowment profile $(w_1,\ w_2,\ w_3)$ = (34, 10, 4), for which $w_1 + w_2 + w_3 = 48$. This triple satisfies

$$w_1 > w_2 > w_3 > 0, \quad 2w_3 - w_2 = 8 - 10 = -2 < 0$$

so that we are again in Case II. Moreover, $3w_2 = 30 < w_1 = 34$.

Hence, $(w_1,\ w_2,\ w_3) = (34, 10, 4)$ lies in the parameter region for Equilibrium b. In this equilibrium, both followers choose zero contribution, so the relevant regime is $z_2 = 0,\ z_3 = 0$. Accordingly, the total public good is simply equal to the leader's own contribution, $G = g_1$.

Since $x_1 = w_1 - g_1$, the feasible frontier is the left segment

$$G = w_1 - x_1$$

For $(w_1,\ w_2,\ w_3) = (34, 10, 4)$, the breakpoint occurs at

$$x_1 = w_1 - w_2 = 24, \quad x_1 = w_1 = 34$$

Under Cobb-Douglas preferences, the relevant indifference curve is tangent to the left segment. The tangency point is

$$E^{(b)} = \left(\frac{w_1}{2}, \frac{w_1}{2}\right) = (17,17).$$

Thus, $g_1^* = 17,\ z_2^* = 0,\ z_3^* = 0$.

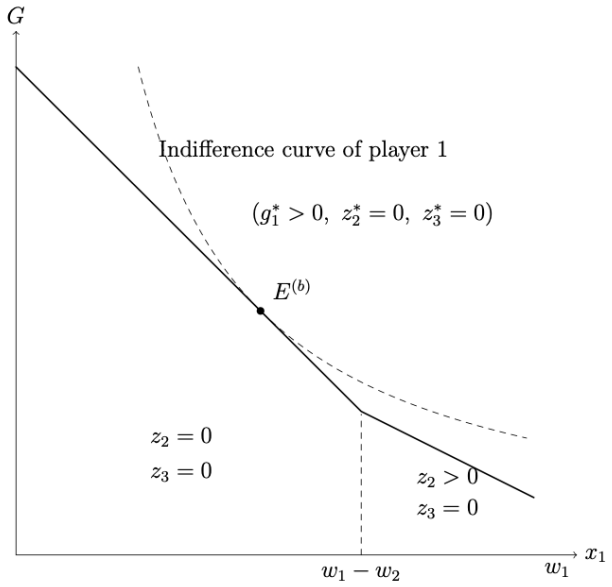


Figure B-9: Illustration of Case II, Equilibrium b in the $(\boldsymbol{x_1}, \boldsymbol{G})$-plane for $(\boldsymbol{w_1},\ \boldsymbol{w_2},\ \boldsymbol{w_3}) = (34, 10, 4)$.

Appendix C: Experimental Instruction for Simultaneous Treatments (originally written in Japanese)

I. Overview

Thank you for participating in today's economic decision-making experiment. Please follow the explanation and the instructions provided by the experimenter throughout the entire session. Communication with other participants is strictly prohibited during the experiment. If this rule is violated, the experiment may be terminated. If you have any questions, please raise your hand and an experimenter will assist you individually.

At the end of the experiment, you will receive a monetary reward. The amount you earn depends on the points you accumulate during the experiment. Please listen carefully to the instructions, understand the rules, and make your decisions thoughtfully. By paying attention to the explanations, you will be able to follow the procedures without difficulty.

The experiment consists of two parts, each containing 8 rounds, for a total of 16 rounds. Before the experiment begins, the computer will randomly assign you to a group of three participants and assign each participant a role: player 1, player 2, or player 3. You will learn your assigned role at that time. Your role will remain the same throughout all 16 rounds. Additionally, at no point in any round of the experiment will you or your group members know the identities of the other participants.

The rules are identical in every round. In each round, you and the other two members of your group will make decisions. The points you earn depend on your own choices and the choices of the other players in your group. At the end of the experiment, one round from the first part and one round from the second part will be randomly selected. Your final score will be based on the sum of the points you earned in these two selected rounds. Your monetary reward will be calculated by converting points into cash at a rate of 0.8 yen per point.

II. Experiment Flow

First Half Procedure

At the beginning of the experiment, the computer will randomly assign groups and determine each participant's role, which will be displayed on your screen.

Procedure for Round 1

1. You will receive an initial endowment based on your assigned role. The initial endowments of the other two members of your group will also be displayed on your screen.
2. Decide how much of your initial endowment you wish to invest, and enter this amount into the computer.
3. After all group members have entered their investment amounts, the results will be displayed on the screen. The results include each participant's investment and the

points earned. Your points are determined by the payoff table, which depends on your own investment and the total investment of the other two group members. If necessary, you may take notes on the points you earned.

This completes Round 1. Rounds 2 through 8 proceed in the same manner.

Second Half Procedure

The initial endowments and payoff tables will be changed, and you will complete 8 rounds in the same manner as in the first half. However, the groups and roles will remain the same as in the first half.

How to Read the Payoff Table

Each role has its own payoff table. In each table, the numbers shown horizontally along the bottom indicate the amount you invest, while the numbers shown vertically on the left indicate the total amount invested by the other two members of your group.

Example

Using the practice payoff table for player 1, suppose the initial endowments are 20, 15, and 13 for players 1, 2, and 3, respectively. Player 1 invests 11 units, player 2 invests 8 units, and player 3 invests 6 units.

In the payoff table, the number "11" in the horizontal row intersects with "14" (8 + 6) in the vertical column. The value at this intersection, "1500," represents the points earned by player 1 in that round.

Confirmation Test

Question 1: Using the practice payoff table for player 2, enter player 2's points into the computer when player 1 invests 11 units, player 2 invests 8 units, and player 3 invests 6 units.

Question 2: Using the practice payoff table for player 3, enter the investment amount player 3 should choose in order to maximize his/her point when player 1 invests 11 units and player 2 invests 6 units.

Note: The payoff table used in this explanation is for practice purposes. Different payoff tables will be used in the actual experiment, and the tables will change between the first and second halves.

Practice Rounds

Before the actual experiment begins, you will participate in two practice rounds using a practice payoff table.

III. Final Results

Your monetary reward will be calculated using the following formula:

(Points earned in one randomly selected round from the first half + points earned in one randomly selected round from the second half) × 0.8 yen

IV. Questionnaire

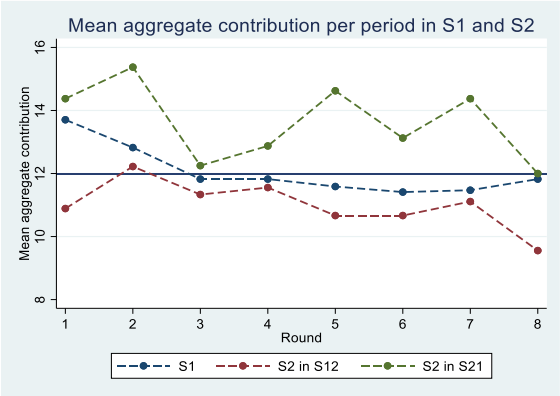
After the experiment, your monetary rewards will be prepared. During this time, you will be asked to complete a questionnaire. Once the screen switches to the questionnaire, please begin answering it.

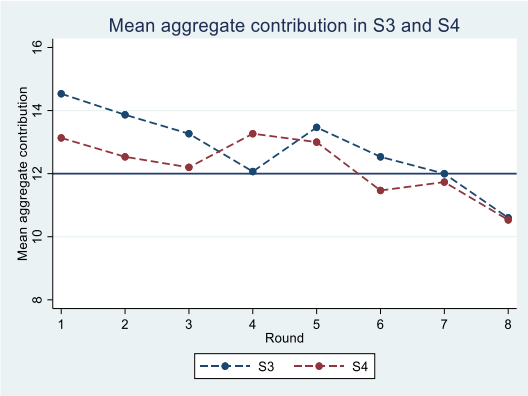
V. Experiment Start

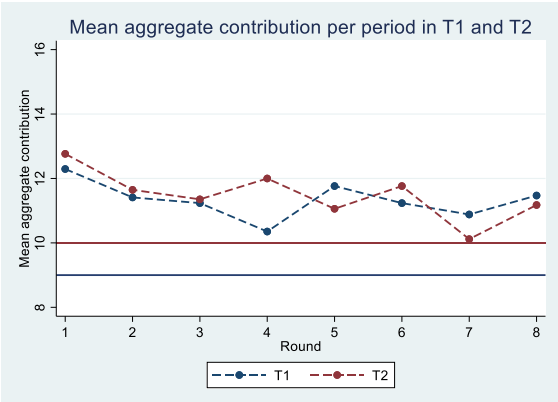
If you have any questions about the instructions, please raise your hand.

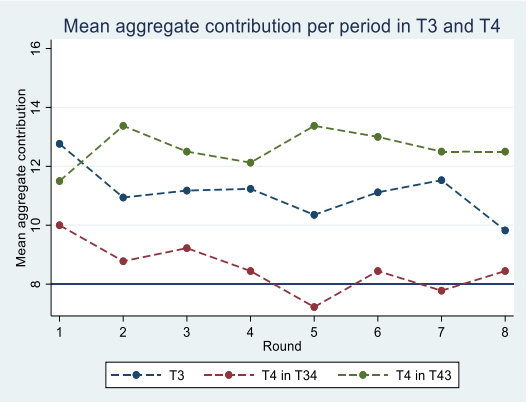
We will now begin the practice rounds. After the practice rounds, the actual experiment will start. The groups and roles will be reassigned, and new payoff tables will be provided. You will have two minutes to review the new payoff tables.

Appendix D: Graphs of Mean Aggregate Contributions by Round for Each Treatment









Appendix E: Graphs of Mean Individual Contributions by Round for Each Treatment

