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Coordination and free-riding problems in the provision of multiple public goods[1]

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Abstract
This study considers the twin problems of free riding and coordination failure prevailing in the provision of multiple public goods with diminishing marginal returns in which the payoff-sum maximising Pareto optimal outcome requires less-than-full contributions by group members. We examine theoretically and experimentally whether the provision of information on the demand for public goods helps overcome these problems and improves efficiency. We construct a game of two public goods, each with an upper bound on effective contributions. Theoretical analysis predicts that this information improves efficiency as it prompts efficiency concerned individuals to match the upper bound of each public good in equilibrium. The experimental results show countervailing effects of demand information, i.e., it improves coordination but deteriorates the free-riding problem. (JEL: C72, C91, C92, H41)

Keywords: Charity, Free riding, Coordination, Multiple public goods, Laboratory experiment, Information.

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1. Introduction

This study considers the twin problems of free riding and coordination failure prevailing in the provision of multiple public goods with diminishing marginal returns. We examine theoretically and experimentally whether the provision of information on the demand for public goods helps overcome these problems and enhances efficiency. Most studies on voluntary contribution mechanisms (VCM) have examined the free-riding problem of a single linear public good (see, e.g., Ledyard, 1995 and Croson, 2010 for survey). However, many social services share characteristics of multiple public goods with diminishing marginal returns in which the payoff-sum maximising Pareto optimal outcome requires less-than-full contributions by group members. The feature of non-linearity makes them vulnerable not only to the free-riding problem but also to coordination failure.[1] In our study, we give two motivating examples of charitable giving.[2]

Blood banks, for example, are an important public health service based primarily on human blood donated by volunteers. For an effective operation of blood banks it is essential to match supply and demand in any season of the year, say the summer and winter seasons. Accordingly, the operations of blood banks in each seasons can be considered as a different public goods, thus making this situation a game of multiple public goods game. Blood components are perishable and donors must observe an interval period between consecutive blood donations (between 4 to 16 weeks). [3] Because of these aspects, an excess supply of blood at a given period preempts supply in the subsequent period, causing wastage in the previous period and a shortage of donated blood in the latter.

Charitable action, such as post-disaster volunteering, is another example of public services requiring a coordination among volunteers. Often multiple locations are in need of volunteer support that can be considered as multiple public goods provided by on-site volunteers. Coordination problems arise when some popular locations attract too many volunteers, causing an oversupply in those communities, while other

1. Compared to the large experimental literatures on the linear public goods game, experiments on public goods with diminishing returns are limited (see Laury and Holt, 2008 for literature in Economics and Kameda, Tsukasaki, Hastie, and Berg, 2011 for literature in Social Psychology). Experiments on multiple public goods are few but increasing. Corazzini, Cotton, and Valbonesi (2015) study a case involving multiple threshold public goods. Blackwell and McKee (2003) and Fellner and Lünser (2014) analyze a case involving local and global public goods. Bernasconi, Corazzini, Kube, and Maréchal (2009) and Engl, Riedl, and Weber (2017) analyze a case involving two identical public goods with one receiving institutional support to promote contributions. Except for Corazzini et al. (2015), these studies adopted linear public goods models and did not address coordination problems.

2. In conformity with the existing experimental literature on donations, we use the public goods game to model charitable giving. Vesterlund (2015), in her survey on experimental literature on charitable giving, explains the relevance of the public goods game for examining charitable giving.

3. Blood products are manufactured for each blood type and have different shelf lives—4 days for platelets, 21 days for red blood cells and whole blood, and 1 year for plasma (Ministry of Health, Labour and Welfare, 2019). In the case of excess supply, there is always a risk of some blood components reaching their expiration dates before use.

locations are left with few or no volunteers. Such misallocation of volunteers hampers efficient provision of a much needed support for the disaster affected residents. Similar coordination issues may also arise in connection with charitable donations on crowdfunding websites: Some projects attract funding far in excess of their operational capacities, while other projects are left underfunded, compelling them to remain below their minimum operational levels (Corazzini et al., 2015).

The above examples share two common features. First, the efficient provision of multiple public goods requires the coordination of contributors. Second, a lack of information about the required amount of contributions, i.e., the demand for them, makes coordination difficult. For instance, the absence of information about a seasonally varying scarceness of blood makes it difficult for potential donors to coordinate the timing of their donations with the demand across time periods. Without sufficient information about the availability of alternative volunteers, some of them may become redundant.

To overcome coordination and free-riding problems and thereby improve the efficiency of social service provision, it is essential to ensure that the necessary information is available. Providing information about the demand for blood donations across time and the needs of volunteers across locations may solve these twin problems. In view of fast-progressing information technologies, such as smartphone apps and data streaming, the forecasting of intertemporal demand for blood donations across the seasons and the provision of real-time information about alternative locations in need of volunteers can be made readily available. Thus, our focus is on answering the following question: Does the provision of information about the relative need of contributions (i.e., demand for each public good) promote coordination, reduce free riding, and thus improve the efficient provision of multiple public goods?

In general, the following features permeating the social services give rise to social dilemma situations with free riding and coordination failure: i) the contribution to each public good exhibits diminishing marginal returns, ii) there are multiple public goods, and iii) the contributions, once made, are not transferable between the public goods. When these three features coexist, as in the motivating examples, the efficiency loss of over-contribution to one public good has a larger consequence in the sense that an over-contribution to one leads to an insufficient contribution to the other. It may therefore be advantageous for society to make efficient use of the altruistic/pro-social behavior of individuals, coordinating them to allocate their contributions to different public goods. In this study, we investigate whether provision of *fuller* information on the demand for each public good facilitates coordination of contributions to multiple public goods, enabling potential contributors to respond to relative scarcities and thereby improving efficiency. [4]

4. In a similar vein, Slonim, Wang, and Garbarino (2014) propose a donor registry as a central clearinghouse system. The registry collects information about past blood donors, including their convenient donation times and locations. The call center contacts registered people for blood donations. A field experiment with the Australian Red Cross Blood Service reveals that registered past donors are more likely to donate in response to calls for donation and that the registry system helps blood banks to facilitate

To incorporate the above mentioned three features underlying a social dilemma with coordination and a free-riding problem, we construct a game of two public goods, each with an upper bound on effective contributions. The upper bound implies that the marginal return of a contribution to a public good becomes zero when the sum of contributions to this public good goes beyond its upper bound. This is a special case of a public goods model with a diminishing marginal return of contributions. Instead of the marginal return gradually decreasing, it remains constant up to the threshold, dropping to zero beyond it. This specification has three advantages. First, this game is simple and much easier for subjects to understand when compared to other specifications of diminishing marginal returns, such as quadratic or Cobb-Douglas type utility functions used in the experimental literature (e.g., Laury and Holt, 2008). Second, it has an interior payoff-sum maximising Pareto Optimal outcome as intended but maintains the property of free riding as a dominant strategy. This allows us to compare our results against the existing literature on the linear public goods game. Finally, the specification of multiple public goods with upper bounds fits well with the example of blood banks with growing concerns over coordination issues.[5]

Two alternative information regimes are considered. In the *partial information* condition, demands are probabilistically determined and ex ante players only know the probability distribution of demands for each public good. In the *full information* condition, demands are deterministic and players know the exact demands before making contributions.

Theoretical analysis predicts that information conditions affect the provision of public goods differently, depending on the assumption of individual preferences. If each subject aims to maximise own payoff, information conditions will not affect individual behavior. The underlying reason is that the demands for contributing to each public good do not alter the essential property of the standard public goods game in which free riding is a dominant strategy. If, by contrast, each player aims to maximise the payoff-sum of all players, information provision will increase efficiency since full information on the demand prompts the payoff-sum maximising players to match the demand for each public good in equilibrium. However, when only partial information on the demand is available, it will become impossible to match the demand for each public good. Particularly, when demand follows a uniform distribution, contributions

donor coordination. Slonim et al. (2014) compared the donation behaviors of registered and unregistered past donors and found that among those contacted 9.7% of registered members came to the donation venues, while only 5.9% of control subjects came to the venues 4 weeks after receiving the call. Contrary to their *centralized* clearinghouse system, we consider a *decentralized* system that enables independent decision makers to better coordinate their individual actions, based on additional common information on the demands met by the blood bank.

5. The model's applicability may differ between examples. The case of blood donations closely resembles the model: The marginal benefit is constant until the demand is satisfied and drops to about zero for contributions beyond because the shelf life of many blood products is short. On the contrary, for the case of post-disaster volunteers, the change in the marginal benefit from contributions may be smoother and could even become negative (because of congestion due to too many volunteers.

to each public good will be about equal. This could cause over or under contributions, depending on the realized value of the upper bounds, thereby lowering efficiency.

To test whether and how information provision affects individual's behavior, we conducted a laboratory experiment. Based on theoretical analysis, we hypothesize that, if there are subjects who are efficiency-concerned, providing full information on the demand structure will increase efficiency.

The results of our laboratory experiment do not support our hypothesis but reveal countervailing effects of demand information. We find that *full information* improves the coordination of contributions but worsens the free-riding problem, which more than offsets the positive effects of improved coordination. On the one hand, demand information directs more contributions to the public good in case of relatively high demand. On the other hand, demand information tends to lower subjects' contributions to the public good in case of low demand. The latter effect can be explained by strategic uncertainty, making subjects withhold contributions to avoid potential wastage in view of possibile over-contribution.

The paper is organized as follows. Section 2 presents the model and theoretical predictions, followed by Section 3, describing the experimental design and hypotheses. The subsequent sections, 4 and 5, compare the contribution rates and efficiency under the two information conditions and discuss the possible interpretations of subjects' behavior under the *full information* condition. The final section, 6, concludes the paper. The Appendix includes full proofs of propositions.

2. The Model

2.1. Basic setup

We consider a model of an n-person society with two public goods, denoted as A and B. Each member $i \in \{1,\dots,n\}$ has a semi-binary choice of whether to contribute to either public good, A or B, at a cost of $c > 0$ or not to contribute.[6] Thus, the strategy set of each individual is $x_i = (x_i^A, x_i^B) \in \{(1,0),(0,1),(0,0)\}$.

In this model, considering scenarios in which excessive contributions to a public good lower efficiency, we assume that each public good $k \in \{A,B\}$ requires a certain level of contribution $d^k \in \mathbb{N}$, and any excessive contribution would be wasted.[7] In other words, each contribution to a public goods yields a constant marginal return β until the sum of contributions to public good k reaches d^k, but, any contribution beyond d^k yields a marginal return of zero. The benefit from public good k for each individual at

6. This reflects the infeasibility of individuals to contribute to both public goods at the same time. For example, regarding blood donations, to donate blood during consecutive periods is prohibited in many developed countries. As for volunteers, it is not possible for one volunteer to be at two different locations at the same time.

7. In the blood donation example, d^k corresponds to the demand for blood donations in period k. In the post-disaster volunteer example, d^k corresponds to the number of volunteers needed in location k.

a strategy profile $x = (x_1, x_2, ..., x_n)$ can thus be written as

$$B^k(x) = \beta \times \min\{\sum_{j=1}^{n} x_j^k, d^k\}, \qquad k \in \{A, B\}.$$

The payoffs of individuals are defined, using the marginal cost of contribution c and the benefit from the public goods. Individual i's payoff at a strategy profile x is

$$\pi_i(x) = -c \times (x_i^A + x_i^B) + B^A(x) + B^B(x). \tag{1}$$

We have the following assumptions on the size of the parameters. First, we assume that $d^A + d^B \leq n$, which implies that there are sufficient individuals to satisfy the demand for contributions. Second, as in the standard linear public goods game, we assume that $\beta < c$ and $n\beta > c$. $\beta < c$ reflects the fact that an individual's marginal benefit from an individual contribution is less than an individual's marginal cost. $n\beta > c$ reflects the fact that society's marginal benefit from an individual's contribution is larger than an individual's marginal cost. The latter implies that it is efficient to contribute until the upper bound of the effective contribution d^k is reached. Due to these assumptions, this game presents a social dilemma situation, in which individuals have an incentive to free ride, although it is advantageous for society to have the players coordinate and contribute to the upper bounds.

2.2. Different information conditions

This study investigates whether efficiency can be increased by providing information about the demand for contributions. To investigate the effects of the change in information provision, we model the baseline situation with less or no information provision as a game of imperfect information, in which the upper bounds are initially determined by nature (*partial information* condition). None of the players know the realized value of the upper bounds, but they know the probability distribution in which each combination of the upper bound may occur. In contrast, as a result of being provided with more information, players will have a better understanding of the needs for each public good. This baseline situation with information provision is modeled as a game of perfect information, in which the values of the upper bounds are exogenously given (*full information* condition).

More precisely, the model of the latter case, the *full information* condition, refers to the game explained in Section 2.1 above. The model of the former case, the *partial information* condition, shares all basic aspects of the *full information* condition models except that we assume that d^A and d^B are endogenous variables determined by nature. For simplicity, we assume that each combination of d^A and d^B would occur with equal probability.[8]

8. Let $D(n)$ be the set of all possible combinations of (d^A, d^B) for a given number of players n. This condition on probability would impose a discrete probability distribution over $D(n)$ because we assume that $d^A, d^B \in \mathbb{N}$ and $d^A + d^B \leq n$. For example, when $n = 3$, $D(3) = \{(1,1), (1,2), (2,1)\}$, thus each element would occur with a probability of $1/3$.

2.3. *Theoretical prediction*

In this section, we analyze the game under the standard assumption of payoff maximising players. We find that different information conditions do not affect players' behavior because in both conditions players'dominant strategy is to free ride. However, in laboratory experiments on the public goods game, subjects often choose contribution levels that yield higher efficiency than that of no contributions, at least in the first few periods of the game (see, e.g., Ledyard, 1995 and Croson, 2010). As a reference point, we also analyze the game with an alternative assumption of payoff-sum maximising players. In this case, we find it is possible to achieve higher efficiency in equilibrium under the *full information* condition than under the *partial information* condition.

2.3.1. Payoff maximising players. We start our analysis with the assumption of payoff maximising players. As stated above, with the assumption of $\beta < c$ and $n\beta > c$, the decision to contribute or not to each public good has a feature similar to that of the prisoner's dilemma game. This gives us the first proposition wherein the players' dominant strategy is not to contribute to either public good under the *full information* condition.

PROPOSITION 1. *Let $i \in \{1,\ldots,n\}$. In the full information condition, for any (d^A, d^B), $x_i = (0,0)$ is the strictly dominant strategy for player i.*

Changing the information condition from *full* to *partial* does not significantly change Proposition 1. It changes the calculation of the expected benefit from contributing. However, since this is going to be less than or equal to β, it will be lower than cost c. Thus, it is also a dominant strategy to not contribute in the *partial information* condition.

PROPOSITION 2. *Let $i \in \{1,\ldots,n\}$. In the partial information condition, $x_i = (0,0)$ is the strictly dominant strategy for player i.*

Propositions 1 and 2 imply that if the players maximise own payoffs, then differences in information provision would not affect the equilibrium strategies. All players decide to completely free ride, and no public good is provided.

2.3.2. Payoff-sum maximising players. Next, we analyze the two information conditions in the case of payoff-sum maximising players. The payoff of player i at strategy profile x is:

$$\begin{aligned}\Pi_i(x) &= \sum_{j=1}^{n} \pi_j(x)\\ &= -c \times \sum_{j=1}^{n} (x_j^A + x_j^B) + n\beta \times (\min\{\sum_{j=1}^{n} x_j^A, d^A\} + \min\{\sum_{j=1}^{n} x_j^B, d^B\}).\end{aligned}$$

This equation shows that if the sum of contributions to public good k is less than demand d^k, then the marginal benefit from contributing to public good k is $n\beta$, which is larger than cost c. Thus, while the contribution is effective, additional contributions will increase the payoff sum. However, unlike in the standard linear public goods game where the payoff-sum is maximised when all players contribute their whole endowment, the social optimum is obtained when the demand for contributions is just met in both public goods. The reason is that any contribution beyond the upper bound yields a marginal benefit of zero. This implies the next proposition for the *full information* condition.

PROPOSITION 3. *Under the full information condition, when all players maximise their payoff-sum, the strategy profile x^* is a Nash equilibrium if and only if the sum of contributions to each public good k is equal to its upper bounds d^k.*

Proposition 3 implies that, under the *full information* condition when all players are maximising the payoff-sum of the n players, the Nash equilibrium will be efficient and the payoff-sum will be maximised. This game has multiple equilibria, and hence there may be a coordination problem as to which equilibrium to play. However, within each equilibrium the coordination problem associated with the choice of public good is resolved.

For the *partial information* condition, however, a similarly efficient result will not hold because the information about the upper bound is ex ante unknown to players. Thus, they cannot adjust contributions to match the upper bounds even in equilibrium. To prove the inefficiency in the *partial information* condition, we show that the amount contributed to each public good is going to be almost equal in equilibrium.

LEMMA 1. *Let x^* be a Nash equilibrium of the game under the partial information condition when all players are maximising the payoff-sum. Then, $|\sum_{j=1}^{n} x_j^{*A} - \sum_{j=1}^{n} x_j^{*B}| \in \{0,1\}$.*

The main point of this lemma is that the group's total contribution to each public good would be about the same in equilibrium. One reason is that the expected marginal payoff from contributing to public good k decreases with the number of other players contributing to that public good. Another reason is that all combinations of (d^A, d^B) have an equal likelihood of occurrence and the expected upper bounds of the two public goods are ex ante symmetric to the players. Consequently, in equilibrium almost the same number of players contributes to each public good.[9]

9. There are two possible cases when the difference would equal 1. The first is a boundary case in which the marginal expected payoff from contributing to public good k and k' is exactly equal when $|\sum_{j=1}^{n} x_j^{*k} - \sum_{j=1}^{n} x_j^{*k'}| = 1$. The second is a special case in which the expected marginal payoff from contribution is positive even when everyone has contributed. In this case, if n is an odd number, the difference equals 1.

Finally, we show that under the *partial information* condition, depending on the size of the parameters of n relative to c and β, the set of Nash equilibria would be one of two types: In one type of the equilibrium only a subset of players contribute, and in the other type all players contribute. The former type arises when the relative cost of contribution c/β is sufficiently large because it is not beneficial for all players to contribute due to probable waste. Let us state this result more precisely in the next proposition.

PROPOSITION 4. *Let x^* be a Nash equilibrium of the game under the partial information condition, in which all players maximise the payoff-sum.*[10]

- *When $n < 4c/\beta - 1$, $\sum_{j=1}^{n} x_j^{*k} \in \{\lfloor t_* \rfloor + 1, \lceil t_* \rceil\}$ for $k \in \{A,B\}$, where*

$$t_* := \frac{1}{2}\left\{(2n-1) - \sqrt{\frac{4c(n-1)}{\beta} + 1}\right\} < (n-1)/2.$$

- *When $n \geq 4c/\beta - 1$, $\sum_{j=1}^{n} x_j^{*k} = \lceil n/2 \rceil$ and $\sum_{j=1}^{n} x_j^{*k'} = \lfloor n/2 \rfloor$ for $k, k' \in \{A,B\}$.*

Proposition 4 implies that even if the players maximise the payoff-sum, there may still be ex post inefficiencies in equilibrium under the *partial information* condition. There may be over and under contributions with respect to the upper bounds, depending on the realized values of d^A and d^B because the players cannot adjust their contributions due to lack of information.

In reality, not all individuals are payoff maximisers or payoff-sum maximisers. Nonetheless, if there are some payoff-sum maximisers believing there are similar players, then providing more information on the upper bounds may improve overall efficiency. Both, Propositions 3 and 4, imply that players would respond to the demand information under the *full information* condition but not under the *partial information* condition. In order to investigate whether an increase in information provision increases efficiency and people's responsiveness to the demand, we examine the two information conditions in a laboratory experiment.

3. Experimental Design

The experiment was conducted in January and February 2017 at the experimental room CHOCOLA in Ritsumeikan University, Japan. One hundred and twelve subjects were recruited via posters and leaflets distributed on campus. The proportion of undergraduate was 92% and the female students accounted for 25.9% of the subjects. Although we recruited subjects from all departments on campus, about half of them were from the Economics department. To the best of our knowledge, the last economic

10. Here, we use $\lceil \cdot \rceil$ and $\lfloor \cdot \rfloor$ to represent operations rounding up and down the decimals to the nearest whole numbers. For instance, $\lceil 5/2 \rceil = 3$ and $\lfloor 5/2 \rfloor = 2$.

experiment conducted at Ritsumeikan University took place four years prior to our experiments. Hence, for most subjects this was their first economic experiment.[11]

3.1. Experimental treatments and theoretical predictions

In the experiment, subjects repeatedly played a four-person multiple public goods game with upper bounds for 10 periods in the same group. The cost of contribution c was 500 points, and the utility from the effective contribution β was 250 points. We also gave an endowment of 500 points to remove the possibility of negative payoffs. Thus, subject i's payoffs in the experiment were

$$\pi_i(x) = 500 - 500 \times (x_i^A + x_i^B) + 250 \times (\min\{\sum_{j=1}^{n} x_j^A, d^A\} + \min\{\sum_{j=1}^{n} x_j^B, d^B\}).$$

The main treatment variable in this experiment was the availability of the information on the upper bounds (i.e., demands). With $n = 4$, the possible combinations for the demands (d^A, d^B) were $\{(1,1)$, $(2,1)$, $(1,2)$, $(2,2)$, $(3,1)$, and $(1,3)\}$. In each period of the game, and separately for each group, one of the six combinations were randomly chosen by the computer with equal probability. In the *full information* treatment, subjects were informed of the realized values of the demands before making their contribution decision, whereas in the *partial information* treatment, subjects made their decision without knowledge of the realized values. A treatment comparison was conducted in the between-subject design. Table 1 shows the summary of the treatments and the distribution of realized values of the demands.

With these parameters, the theoretical prediction of payoff-sum maximising players for the *partial information* treatment (based on Proposition 4) is that either 1 or 2 subjects would contribute to each treatment. In other words, any strategy profile x in which $(\sum_{j=1}^{n} x_j^A, \sum_{j=1}^{n} x_j^B) \in \{(1,1),(1,2),(2,1),\ (2,2)\}$ would be a Nash equilibrium.[12]

3.2. Experimental procedures

When subjects entered the experimental room, they were randomly assigned a seat with a network-connected computer terminal. To ensure anonymity among subjects, seats were partitioned so that the computer monitors of the other subjects were unobservable. At the start of the experiment, the experimenter read out the consent forms, and subjects were given sufficient time to read the forms before signing. Subsequently, subjects were shown written instruction on their individual computer

11. We conducted a pre-experiment in January 2017 to test the procedures and the program. Twenty subjects participated in the pre-experiment but not in the actual experiment.

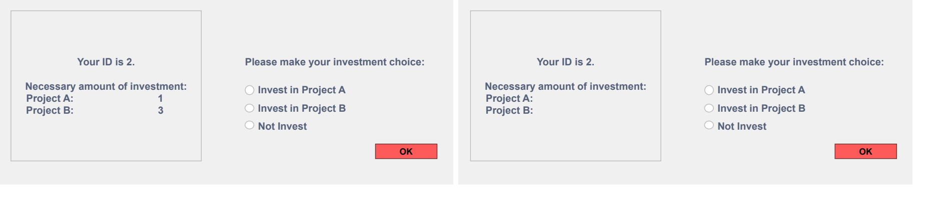
12. With our parameter values of $c = 500$ and $\beta = 250$, $4c/\beta - 1 = 7$ is larger than $n = 4$. According to Proposition 4, in the equilibrium the sum of contributions to each public good should equal $\lfloor t_* \rfloor + 1$ or $\lceil t_* \rceil$. Here, $t_* = 1$, and hence the former is equal to 2 and the latter equal to 1.

TABLE 1. Summary of treatments and realized values of demands

	Full information	*Partial information*
Number of subjects	48	64
Number of subjects by session		
Sessions (1,3,5)	(12,20,16)	
Sessions (2,4,6,7)		(16,20,16,20)
Frequencies of demand pairs		
(1,1)	16	28
(1,2) or (2,1)	43	46
(2,2)	23	34
(1,3) or (3,1)	38	52

Note: Since the values of the demands were drawn randomly for each group in each period, the realized frequency of the demands was counted in terms of the number of groups. The total adds up to the (number of groups) × (number of periods), which is 120 in *full information* and 160 in *partial information* treatments.

screen, which they were allowed to read at their own pace. After reading them, subjects solved a quiz to ensure they had understood the rules of the game. Subjects' answers to the quiz questions were checked individually by the experimenters.[13] The experimental program started after all subjects had answered all quiz questions correctly. This ensured that all subjects understood the rules of the experiment. We also read the answers aloud to assure subjects that they had all received the same instructions and that the rules of the game were common knowledge. All the materials, including instruction, quiz, program, and the questionnaire, are available as supplementary material. Throughout the experiment, no deception were used.



(A) Full Information (B) Partial Information

FIGURE 1. Decision making screens

At the beginning of the instruction, subjects were warned about general rules of the experiment such as the use of cell phones, or private conversations with other participants. They were then given detailed information on the rules of the game, matching protocols, how to use the computer interface, and the payment method. Since

13. As a result of this procedure, we do not know exactly how much time it took subjects to read the instruction. We do know, though, that in each session, it took subjects about 30 minutes from the start of reading the instructions to the end of making corrections to the quiz. Please note that there was a large individual heterogeneity regarding the length of time it took subjects to complete reading the instruction and solving the quiz. We report the average of the longest time taken by subjects in each session.

they read the instructions at their own pace, they were told that all participants in the room had received the same instructions and quiz. All materials used in the experiment were in neutral frames.

The experiment was programmed and conducted using z-tree (Fischbacher, 2007). The main and only difference in the program between the two treatments lay in the design of the decision-making screen. In the *full information* treatment (see Figure 1(A)), subjects received information about the necessary amount of investment for each project, whereas in the *partial information* treatment (see Figure 1(B)), the space for realized values was left blank. Except for this difference, all screen interfaces of the two treatments were identical.[14]

In both treatments, the program proceeded as follows. At the beginning of the first period, subjects were randomly matched into groups of four and stayed in their group throughout the experiment (partner matching protocol). Each period started with a decision-making screen as shown in Figure 1, informing subjects about their identification number, which changed in every period to reduce the reputation effect. On the same screen, they subsequently made their decision by choosing one of the following three options: "invest in project A," "invest in project B," and "not invest." After all subjects had made their choice, they proceeded to the end-of-period feedback information, which was identical in both treatments. The subjects received information on the following: the choices made by all four group members, the necessary amount of investment for each project, the total amount of investment in each project, the points gained from each project, the total points gained from the two projects, the points kept by the subject, and the points gained in that period. After the last period ended, there was a final screen enabling subjects to confirm the results in each period.

After the 10 periods, subjects answered a questionnaire. Most of the questions were administered using z-tree except for the social value orientations (SVOs) questions, which were administered on paper due to programming difficulties. [15]

Subjects were paid for the points they had earned in the two randomly selected periods. After completion of the 10 periods, the experimenter rolled two 10-sided dices to determine the payment period.[16] Subjects received payment of 1 yen for each point earned in the experiment. The show-up fee was 500 yen. The average payment was 1795 yen (which amounted to about $16 at the time of the experiment) for an experiment that lasted less than 1.25 hours.

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14. For the *partial information* treatment, we maintain the statement "The necessary amount of investment for this period was as follows…" This was to make subjects aware that the values of the demands for that period were unknown but already determined.

15. In social psychology, SVOs comprise a measure developed to distinguish individuals by a preference regarding their respective payoffs relative to the payoff of others. Based on subjects' responses to the questions on primary slider measures developed by Murphy, Ackermann, and Handgraaf (2011), we obtained parameters of SVOs and used them in the analysis in the next section.

16. When two rolled numbers turned out to be the same, we re-rolled one of the dices again to obtain another number.

3.3. Experimental Hypothesis

As mentioned in Section 2.3, if there are some payoff-sum maximising players, they would try to match the demands in the *full information* treatment. Since behavior in the *partial information* treatment does not vary with demands, there could be over- or under-contributions with respect to the demands, likely to cause inefficiency. These theoretical results lead to the following two hypotheses tested in the next section.

HYPOTHESIS 1. *In the full information treatment, average contribution rates to a public good increase with an increase in its demand.*

HYPOTHESIS 2. *Efficiency is higher in the full information treatment than in the partial information condition.*

4. Results

4.1. Effects of demand information on the aggregate contribution rates

We examine the aggregate propensity to contribute (average contribution rate) to either public good. Recall that each subject can contribute at most once to one of the two public goods in each period. Hence, the proportion of subjects'contributions to either public good in each period yields the per-period aggregate contribution rate. Figure 2 shows the trend of contribution rates observed in *full* and *partial information* treatments. In both treatments, over 50% of subjects contributed in the first period, with contribution rates declining over the periods. Averaging across the 10 periods, the mean contribution rate of the *full information* treatment (0.348) and that of the *partial information* treatment (0.375) were not statistically different.[17] Thus, we can state the following:

RESULT 1. *The provision of information on the demand for each public good has no effect on the aggregate propensities to contribute.*

4.2. Effects of demand levels on contribution rates in the full information treatment

Result 1 implies that the "availability of information" on the demand does not have a significant impact on the aggregate contribution rates. With reference to *Hypothesis*

17. Using the decision of individuals to contribute or not in each period as a unit of observation (480 observations for the *full information* treatment and 640 observations for the *partial information* treatment), the p-value of the two-sample test of proportions is 0.351. The Wilcoxon rank-sum test of the comparison of a group's average contribution rates across 10 periods also supports no difference between the treatments ($p = 0.66$).

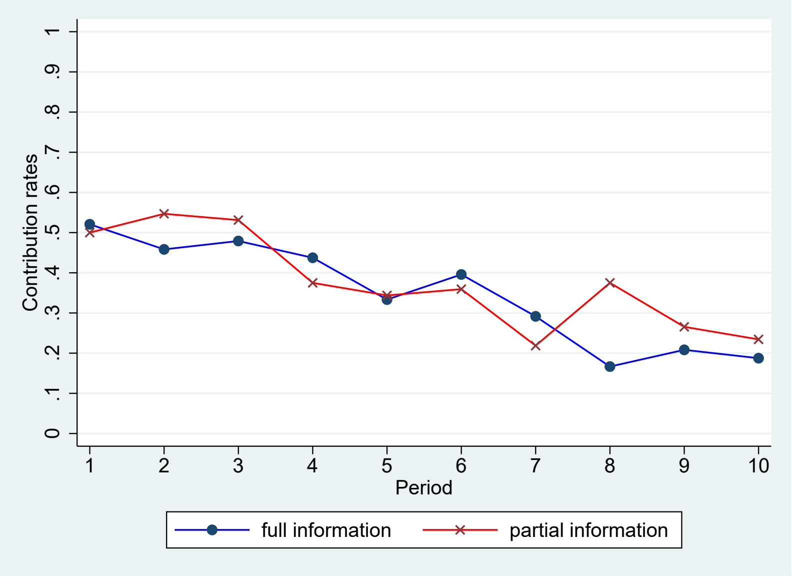

FIGURE 2. Average contribution rates by treatment

1, we focus on the observations made in the *full information* treatment and examine whether and how demand levels affect the average contribution rates.

First, we test whether contribution rates differ with the sum of demands by evaluating 480 observations in the *full information* treatment. The first column of Table 2 reports contribution rates, i.e., the share of individual decisions to contribute to either public good in each period. We note that the greater the summed demand of the two public goods, the higher is individuals' propensity to contribute. Odds ratios confirm this observation: Compared to the baseline case where the total demand is two, subjects are about 6.5 times more likely to contribute than not when the total demand is 3, and 8.3 times more likely to contribute than not when the total demand is 4.[18] The contribution rates increase with the sum of upper bounds, i.e., the total demand.

Next, we examine the relations between individual choices regarding which public good to contribute and demand sizes. Recall that, under the *full information* treatment, subjects are informed of the demand in each of the two public goods and decide whether and to which public good to contribute. Figure 3 visualizes the propensity to contribute to the public good by demand. When demand pairs are asymmetric, that is, (2,1), (1,2), (3,1), or (1,3), contribution rates to the public good, for which there is a greater demand, tend to be higher than contribution rates to the public good, for which there is a smaller demand. Concerning the demand pairs (2,1) and (1,2), the average contribution rate to the public good for which there is a larger demand is 0.279,

18. Pairwise Bonferroni adjusted multiple comparisons of differences in odds ratios between total demands equaling 2 and 3, and 2 and 4 yield z values that are statistically significant ($p < 0.01$) but not between total demands of 3 and 4 ($p = 0.222$).

TABLE 2. Odd ratios of contributions by the sum of upper bounds

Summed upper bound (Contribution Rates)	Odds ratio	Standard error	Z (p-value)
2 (0.078)	1	-	-
3 (0.355)	6.485	3.192	3.80 (0.000)
4 (0.414)	8.334	4.030	4.38 (0.000)
constant	0.085	0.040	-5.30 (0.000)

Notes: Logistic regression with contribution to either public good as dependent variables (=1 if contribution is made to either public good, =0 otherwise). The odds of contributions indicate how often an individual contributes relative to how often an individual does not contribute, that is, $Pr(contribute|summed\ upper\ bounds)/Pr(not\ contribute|summed\ upper\ bounds)$. Logistic regression takes the log of the odds and yields the odds ratios using the summed upper bound = 2 as a base.

with a 95% confidence interval [0.212, 0.346], while the average contribution rate to the public good for which there is a smaller demand is 0.076, with 95% confidence interval [0.036, 0.115]. Similarly, for the demand pairs (3,1) and (1,3), the contribution rates to the public good, for which there is a larger and a smaller demand, are 0.303 with a confidence interval [0.229, 0.376] and 0.092 with a confidence interval [0.046, 0.138], respectively. Facing asymmetric demands, contributors tend to direct their contributions to a public good with a larger demand. Result 2 summarizes the above two findings.

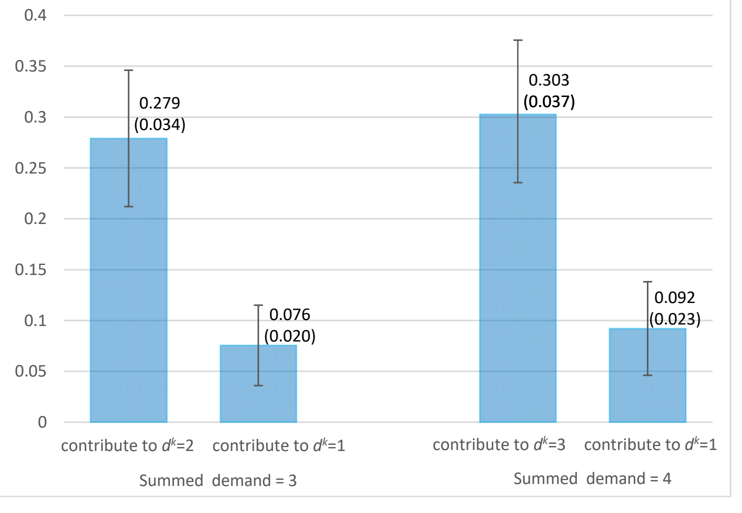

FIGURE 3. Propensities to contribute when demands are asymmetric: mean contribution rates (standard errors in parenthesis) and 95% confidence intervals

RESULT 2. *Contribution rates increase with demand: In the full information treatment, the contribution rate increases, on average, with an increase in the sum of demands. Moreover, subjects direct more contributions to the public good with a relatively high demand than to the public good with a low demand.*

4.3. Effects of demand information on individual decisions to contribute

Until now, Result 1 has indicated that the provision of information on demands has no significant impact on the aggregate contribution rates. However, Result 2 indicates that, with information on demands, the average individual contribution rates increase with demand such that more contributions are directed to the public good with a larger demand. Based on these observations, we investigate whether and how the provision of information on the demands in the *full information* treatment affects decisions to contribute at an individual level.

We regress an individual's contribution choices against the informational treatment dummy, its interaction with the sum of demands for the two public goods, and some characteristics of the individual. Columns (1), (2), and (3) of Table 3 report the results of the ordinary least squares (OLS) specification. The coefficient on *information* (dummy for the *full information* treatment) is not significantly different from zero in specification (1), which echoes Result 1. In specification (2), the coefficient on the interaction term between *information* and the sum of demands is positive and significant, while the coefficient on *information* is negative and significant. These coefficients imply countervailing effects of information; information on the summed demand increases individuals' propensities to contribute, while the provision of information on the demand structure itself depresses contribution rates. As a result of these effects offsetting each other, there is no effect of information provision on average (Result 1). At the expected value of the summed demand (3.33), the point estimate of the predicted contribution rate is 0.302, in the *full information* treatment which is marginally lower than in the *partial information* treatment (0.329). Specification (3) includes additional control for subjects' SVOs. For the range of SVOs corresponding to the "prosocial" orientation, which is above 22.45 according to Murphy et al. (2011), the observed association between the prosocial value orientation and individual contribution rates is positive. However, for the "individualistic" and "competitive" ranges, the association is negative. Specifications (4), (5), and (6) use Probit models. Although it is known that probit specifications are likely to introduce bias in the estimates of the interaction terms, the probit models produce qualitatively the same results as those with linear specifications. Thus, we state the following.

RESULT 3. *Countervailing effects of information about the demand structure on contribution rates: On the one hand, the baseline effect of information about the demand structure on contribution rates is negative—the provision of information alone lowers the contribution rate. On the other hand, the provision of a demand structure directs the subject's contribution toward the public good with a higher demand.*

TABLE 3. Individual decision to contribute by information on the demand structure (Random effect panel data analysis: Dependent variable is subject's contribution decision to either public good)

	Linear specification			Probit specification		
	(1)	(2)	(3)	(4)	(5)	(6)
Information	-0.036	-0.463***	-0.484***	-0.108	-1.744***	-1.828***
	(0.053)	(0.094)	(0.094)	(0.195)	(0.410)	(0.406)
Information $\times$ $(d^A + d^B)$		0.127***	0.126***		0.478***	0.475***
		(0.027)	(0.027)		(0.107)	(0.106)
Female	0.144**	0.154**	0.145**	0.506**	0.543**	0.514**
	(0.061)	(0.060)	(0.060)	(0.218)	(0.220)	(0.216)
Economic major	-0.001	0.000	0.007	0.034	-0.023	-0.060
	(0.055)	(0.055)	(0.054)	(0.205)	(0.206)	(0.200)
SVO			-0.006			-0.023*
			(0.004)			(0.014)
SVO^2			0.0003***			0.001***
			(0.001)			(0.004)
Constant	0.345***	0.342***	0.291***	-0.530***	-0.546***	-0.725***
	(0.046)	(0.046)	(0.057)	(0.170)	(0.171)	(0.202)
Observations	1110	1110	1110	1110	1110	1110
R-sq	0.0184	0.0389	0.0731			
Log likelihood				-635.9109	-625.0010	-618.7843

Notes: Figures between brackets are robust standard errors clustered by subjects. Information represents the treatment dummy, which equals 1 for the *full-information* treatment. *** Significant at a 1% level, ** 5% level, and * 10% level.

4.4. Effects of demand information on the efficiency of group outcomes

According to Result 2, in the *full information* treatment the average contribution rate increases with an increase in demand, supporting *Hypothesis* 1. The countervailing effects of information about demand structures on an individual's contribution decision presented in Result 3 are likely to exert ambiguous impacts on the efficiencies of group outcomes. We turn to examine *Hypothesis* 2, i.e., the relationship between the provision of information on the demands and efficiencies of outcomes at group level. Figure 4 plots the average efficiency of group outcomes for each treatment. Efficiency is measured here as a ratio of actually attained group profits to the maximum attainable group profit, over and above the minimum attainable group profit.[19] On average, efficiency rates observed in the groups under the *full information*

19. For example, consider a case where the demand structure is $(d^A, d^B) = (1, 1)$. The maximum payoff-sum occurs when one member contributes to one and another member to the other public good. The minimum payoff-sum is reached when all four subjects contribute to the same public good. Suppose the total actual group payoff is 2000. Using the parameter settings of the experiment, the maximum and the minimum attainable group payoff are 3000 and 1000, respectively. The resulting efficiency measure amounts to $(2000 - 1000)/(3000 - 1000) = 0.5$.

and *partial information* treatments are 0.569 and 0.526, respectively. The overall efficiency appears to be only marginally higher in the *full information* treatment.[20]

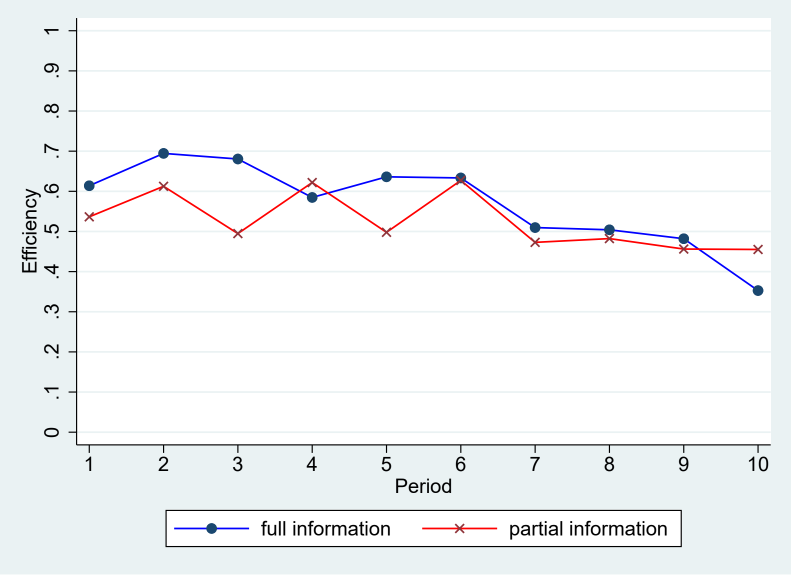

FIGURE 4. Average efficiency of group outcomes by treatment

In this game, there are two sources of inefficiency—one caused by insufficient contributions, the other by excessive contributions. We try to visualize the difference in these sources by classifying each group outcome into one of the following four categories: "Efficient," "Free riding," "Coordination failure," or "Free riding and coordination failure." "Efficient (EF)" refers to the case in which the summed contribution by group members exactly satisfies the demands of both public goods. "Free riding (FR)" occurs when the summed contribution to each public good is less than or equal to demand and strictly less for at least one public good. "Coordination failure (CF)" refers to the case in which the summed contribution to at least one public good exceeds demand, and the excess is sufficient to cover any shortage of contributions directed to another public good. "FR and CF" occur when the summed contribution to only one public good exceeds demand and the excess contribution to one public good is not sufficient to offset the shortage of the other. As an example, Figure 5 demonstrates the classification of these categories of outcomes when the demand structure is (2,1).

Eyeballing the frequency distribution of group outcomes in terms of the efficiency categories in Table 4, we notice that the provision of information tends to improve

20. Using each group's data in each period as a unit of observation, a Wilcoxon Rank Sum test of the equality of distribution of unmatched data was performed; the test yields a Mann-Whitney statistic of 1.512 (p=0.1306).

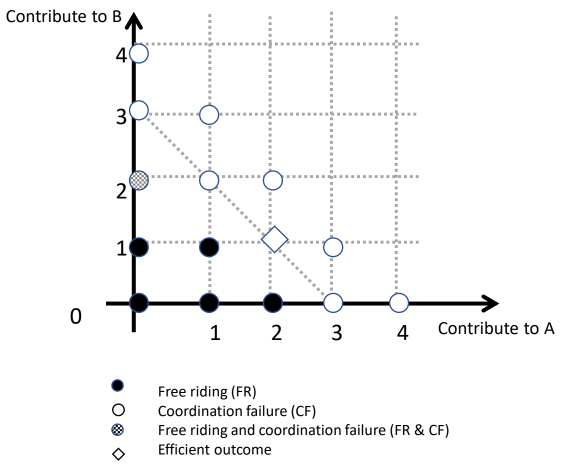

FIGURE 5. Efficiency categories of group outcomes when the demand structure is $(d^A, d^B) = (2, 1)$

TABLE 4. Frequencies and proportions (in parentheses) of group outcomes by efficiency categories

	No. of observations	Efficient (EF)	Free riding (FR)	Coordination failure (CF)	FR and CF
full information	120	7 (0.058)	105 (0.875)	4 (0.033)	4 (0.033)
partial information	160	9 (0.056)	122 (0.762)	13 (0.081)	16 (0.3)

outcome efficiencies mainly by reducing coordination failures. Under the *full information* treatment, groups' outcomes are much less likely to be characterized as CF with a ratio of 0.033 than under the *partial information* treatment with a ratio of 0.081. It is worth noting that the outcomes of FR and CF are extremely rare under the *full information* treatment with a ratio of 0.033, compared to the *partial information* treatment case with a ratio of 0.3. FR outcomes occur more frequently under the *full information* treatment than under the *partial information* treatment, and the frequencies of efficient (EF) outcomes do not differ between the treatments.

RESULT 4. *The coordination-enhancing effect of information on upper bounds: Provision of information on the upper bounds of effective contribution improves efficiency by reducing excessive contribution and coordination failures. However, such efficiency gains are not sufficiently robust to offset the efficiency losses arising from a persistent majority of free-riding outcomes.*

5. Discussion

At the aggregate level, the result of our experiment shows the neutral effect of information about the demand (Result 1). At an individual level, the core effect of information provision on the contribution rate is even negative (Result 3). Recasting these findings on our theoretical predictions put forward in the Experimental Design section it seems reasonable to conclude that individuals are monetary payoff maximisers. Thus, the provision of information on the upper bounds does not lead to differences in individual contribution behavior (Propositions 1 and 2). A further analysis of individual contributions based on the size of summed demands for both public goods reveals the effects of information, driving a higher demand to induce a higher contribution. Moreover, larger contributions are made to the public good with a higher demand, when subjects are informed of asymmetric demands between the two public goods (Result 2).

Our result further shows that the provision of information on the demand of multiple public goods tends to depress subjects' average contribution rates, while demand information directs more contributions to the public good, given a relatively high demand. In a first attempt to explain the puzzling effects of demand information on individual contribution behavior, we propose a hypothesis about strategic uncertainty and avoidance of potential wastage generated from excessive contributions. In our theory discussed in section 3, Experimental Design, we state that if all individuals are payoff-sum maximisers and are informed of the upper bounds, they would contribute efficiently in equilibrium. Since there are a number of equilibria, an issue might arise over selecting an equilibrium on which individuals can coordinate their contributions. Uncertainty about each group member's action complicates coordination of such equilibria. In view of the underlying strategic uncertainty and difficulties of coordination, payoff-sum maximisers may end up withholding contributions to avoid potential wastage.

Particularly, when demand is low, strategic uncertainty may additionally lower the contribution of an efficiency-concerned individual, the reason being that this individual might perceive the futility of own contributions and hence avoid them. Under the *full information* treatment, when the demand structure is $(d^A, d^B) = (1, 1)$, almost all outcomes (15 out of 16, 93.7%, of group outcomes) are categorized as free riding. When the demand structure is $(d^A, d^B) = (2, 2)$, free-riding outcomes occur less often (20 out of 23, 86.9%). By comparison, under the *partial information* treatment, corresponding frequencies of free-riding outcomes occur 16 out of 28 times (57.1%) when $(d^A, d^B) = (1, 1)$, and 24 out of 29 times (85.2%) when $(d^A, d^B) = (2, 2)$. With reference to outcomes under the *partial information* treatment, the free-riding outcomes are observed more frequently under the *full information* treatment, particularly, when demands are low. This evidence corroborates our result that the apparent negative effect of demand information on individual contribution is, at least partly, associated with strategic uncertainty.

6. Conclusion

Efficient provisions of multiple public goods with upper bound demands require overcoming the twin problems of coordination failure and free riding. We investigate the role of information in solving these problems and improving efficiency. According to standard theory, stating that players maximise their payoffs, information conditions do not affect an individual's contribution behavior: The dominant strategy of players is to withhold contributions regardless of information conditions. On the contrary, if players maximise the payoff-sum of all players, then information provision would increase efficiency. The reason for this is that when information on demands is made available, payoff-sum maximising players will in equilibrium match the upper bound in each public good. However, when such information is not available, contributions to each public good will be about the same in equilibrium. This could cause over- and underachievement of the realized upper bounds, thereby lowering overall efficiency. Thus, we hypothesize that if there are efficiency-concerned individuals, providing full demand information will increase efficiency.

Based on the laboratory experiment, we find that information provision about the demand structure promotes individual contributions to the public good. However, at the aggregate level, information does not increase average contribution rates or efficiency. The reason is that the difficulty of interpersonal coordination offsets the efficiency-enhancing effect of information as individuals tend to withhold contributions to avoid contribution wastage.

In conclusion, we offer some reflections on the example of a blood bank. The provision of information on the seasonal demand for blood may not solely improve the overall efficiency of blood banks. This may be attributable to the countervailing effects of information on an efficient provision of blood banks. In other words, information on demand helps blood banks to overcome the inter-seasonal coordination problem. However, such information provision may worsen the free-riding problem when potential donors fear over donation. Information provision for comprehensively improving efficiency may become practicable when it is complemented by mechanisms to reduce strategic uncertainty and manage aversion to wasteful donations. Future studies should address these issues, for example, by using the framework of a sequential voluntary contribution mechanism. Some experimental evidences associated with a real-time voluntary contribution mechanism show that providing information about others' contributions and allowing subjects to adjust contributions upward increases the provision of public goods (Dorsey, 1992; Kurzban, McCabe, Smith, and Wilson, 2001). As Kurzban et al. (2001) point out, the real-time public goods game closely mirrors the mechanism discussed in Schelling (1960) (pp.45-46)—dividing a contribution into smaller contributions lowers the risk of the initial contribution, thereby boosting contributions. Similar mechanisms, such as providing real-time information on donations with a prediction on demand, may improve the efficiency of blood donations.

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Appendix

Proof of Proposition 1

Proof. Let $t^k(x_{-i}) := \sum_{j \neq i} x_j^k$ denote the sum of contributions to public good k by players other than i. The marginal benefit from contributing to public good k is zero when $t^k(x_{-i}) \geq d^k$, and is β when $t^k(x_{-i}) < d^k$. In either case, it is lower than the cost of contribution c. Hence, independent of whether the contribution is ineffective or effective, $x_i^k = 0$ is a best response to any x_{-i} for $k \in \{A, B\}$. Thus, $x_i = (0, 0)$ is a strictly dominant strategy for all $i \in N$.

□

Proof of Proposition 2

Proof. Let $P(t^k(x_{-i}) < d^k)$ denote the probability in which the sum of contributions by players, other than i, is less than d^k. This is also the probability in which i's contribution in public good k would be effective. Since both $t^k(x_{-i})$ and d^k are integers,

$$\begin{aligned} P(t^k(x_{-i}) < d^k) &= \frac{(n - t^k(x_{-i}) - 1) + (n - t^k(x_{-i}) - 2) + \cdots + 1}{(n-1) + (n-2) + \cdots + 1} \\ &= \frac{(n - t^k(x_{-i}) - 1)(n - t^k(x_{-i}))}{n(n-1)}, \end{aligned} \tag{A.1}$$

where the numerator in the first equation counts the possible combinations of $(d^k, d^{k'})$, given that $t^k(x_{-i}) < d^k$, and the denominator counts the number of all possible combinations of $(d^k, d^{k'})$. Using this probability, we can calculate the expected marginal payoff for player i from contributing in public good k as

$$P(t^k(x_{-i}) < d^k) \times (\beta - c) + \big(1 - P(t^k(x_{-i}) < d^k)\big) \times (-c).$$

Since $\beta < c$, this is clearly negative for any $t^k(x_{-i}) \leq n$, which is lower than the marginal payoff from not donating in either public good. Thus, strategy $(0, 0)$ strictly dominates $(1, 0)$ and $(0, 1)$. □

Proof of Proposition 3

Proof.
First, given x_{-i}, when compared to the case of not contributing to either public good, the marginal payoff for player i from contributing to public good k is $n\beta - c$ when

the contribution is effective, and it is $-c$ when it is ineffective. When the contribution is effective, i's contribution increases the monetary payoff of all players by β. Since there are n players, it increases the utility of payoff-sum maximiser i by $n\beta$ at a cost of c. When the contribution is ineffective, it creates no extra benefit but still costs c. To summarize, for payoff-sum maximising player, it is better to contribute if the contribution is effective, and it is better not to contribute if it is ineffective.

Second, we show by contradiction that $t^k(x^*) = d^k$ for $k \in \{A,B\}$ is a necessary condition for x^* to be a Nash equilibrium. Assume that x^* is a Nash equilibrium and that $t^k(x^*) \neq d^k$, for some $k \in \{A,B\}$.
[Case 1: $t^k(x^*) > d^k$ for some public good k] There is over contribution to public good k, so there is at least one player i, who can refrain from contribution and increase their payoff by c. Thus, x_i^* is not a best response to x_{-i}^*.
[Case 2: $t^k(x^*) < d^k$ for some public good k] There are two possible sub-cases to consider: (i) $t^A(x^*) + t^B(x^*) = n$, and (ii) $t^A(x^*) + t^B(x^*) < n$. When (i), then $t^k(x^*) < d^k$ implies that $t^{k'}(x^*) > d^{k'}$. Then, the argument for Case 1 applies. When (ii), there is at least one player i who is not contributing to either public good. Since i's contribution to k will be effective, it is better to contribute to k. Thus, x_i^* is not a best response to x_{-i}^*.

Therefore, if x^* is a Nash equilibrium, $t^k(x^*) = d^k$.

Finally, we show that $t^k(x^*) = d^k$ for $k \in \{A,B\}$ is a sufficient condition for x^* to be a Nash equilibrium. We begin by considering the case where a player i is not contributing at the strategy profile x^*. If player i deviates and contributes to one of the public goods, then the marginal payoff of player i would be $-c$. This is because the upper bound is already met by the contributions of the other players. Thus, $x_i^* = (0,0)$ is a best response to x_{-i}^* for non-contributing players.

Next, we consider the case where a player i is contributing to public good k at strategy profile x^*. If player i deviates and contributes to another public good $k' \neq k$, then the payoff of player i would decrease by $n\beta > 0$. This is because the upper bound for k' is already met through other players' contributions. Finally, if player i deviates and does not contribute to either public good, then i's payoff would decrease by $n\beta - c > 0$. For both deviations, player i's payoff decreases, and hence x_i^* is a best response to x_{-i}^* for contributing players.

□

Proof of Lemma 1

Proof. Using the probability in Equation (A.1), we can calculate the expected marginal payoff of player i from contributing to public good k compared to not contributing as

$$\begin{aligned} &P(t^k(x_{-i}) < d^k) \times (n\beta - c) + P(t^k(x_{-i}) \geq d^k) \times (-c) \\ &= \frac{\beta}{(n-1)} \left\{ t^k(x_{-i})^2 - (2n-1)t^k(x_{-i}) + (n-1)(n - \frac{c}{\beta}) \right\}. \end{aligned} \tag{A.2}$$

For the payoff-sum maximising players, the values of the expected marginal payoff can be positive. Hence, an individual's decision to contribute can be optimal.

One point to note is that because $P(t^k(x_{-i}) < d^k)$ is decreasing in $t^k(x_{-i})$ for $0 \leq t^k(x_{-i}) \leq n-1$, the expected marginal payoff for player i from contributing to public good k also decreases in $t^k(x_{-i})$. Hence, if $t^k(x_{-i}) < t^{k'}(x_{-i})$, then it would be better to contribute to k than to k'.

Suppose that x^* is a Nash equilibrium and $|t^A(x^*) - t^B(x^*)| \geq 2$. We denote the public good with a higher contribution as k and the other as k'. Let i be a contributor to k in x^*. Then,

$$t^k(x^*) - 1 = t^k(x^*_{-i}) > t^{k'}(x^*) = t^{k'}(x^*_{-i}).$$

This implies that i's expected marginal payoff would be higher if i contributes to k'. Thus, x^* is not a Nash equilibrium if the difference in the sum of contribution to each public good is more than two. □

Proof of Proposition 4

Proof. Without the loss of generality, let us assume that $t^k(x^*) \leq t^{k'}(x^*)$. Using Equation (A.2), we solve the condition of the player i, under which it is better to contribute to public good k than not contribute. This is equivalent to solving for $t^k(x^*_{-i})$, satisfying Equation (A.2) ≥ 0. Since Equation (A.2) is a quadratic function of $t^k(x^*_{-i})$, this condition is satisfied when:

$$t^k(x^*_{-i}) \leq t_* := \frac{1}{2}\left\{(2n-1) - \sqrt{\frac{4c(n-1)}{\beta} + 1}\right\}$$

or

$$t^k(x^*_{-i}) \geq t^* := \frac{1}{2}\left\{(2n-1) + \sqrt{\frac{4c(n-1)}{\beta} + 1}\right\}$$

where t^* and t_* are the two solutions for Equation (A.2) = 0.

Given our restrictions on the parameters that $c, \beta > 0$ and $n \geq 2$, t_* and t^* take real values. Additionally, t^* turns out to be larger than $n/2$, as

$$\begin{aligned} t^* - \frac{n}{2} &= \frac{1}{2}\left\{(2n-1) - n + \sqrt{\frac{4c(n-1)}{\beta} + 1}\right\} \\ &= \frac{1}{2}\left\{(n-1) + \sqrt{\frac{4c(n-1)}{\beta} + 1}\right\} \\ &> 0. \end{aligned}$$

Therefore, in what follows, we consider the conditions for t_* only.

First, we check the possibility of $t_* < 0$. This is a trivial case in which it will never be optimal for the player i to contribute to public good k. It can be verified that if $n\beta > c$, then $t_* > 0$. Hence, $t_* > 0$ in our game.

Next, we examine the condition $t_* \geq (n-1)/2$. If this condition holds, then, because of Lemma 1, all players would be contributing to one of the two public goods in equilibrium.

By rearranging the equations, we find that:

$$
\begin{aligned}
t_* \geq (n-1)/2 \quad &\Longleftrightarrow \quad \frac{1}{2}\left\{(2n-1) - \sqrt{\frac{4c(n-1)}{\beta}+1}\right\} \geq \frac{n-1}{2} \\
&\Longleftrightarrow \quad n \geq \sqrt{\frac{4c(n-1)}{\beta}+1} \\
&\Longleftrightarrow \quad n^2 - 4cn/\beta + 4c/\beta - 1 \geq 0.
\end{aligned}
$$

This inequality holds when $n \leq 1$ or when $n \geq 4c/\beta - 1$.[21] Since we assume that $n \geq 2$, only the second condition needs to be considered.

We can summarize our results depending on whether the second condition is satisfied.

When $n \geq 4c/\beta - 1$, $t_* \geq (n-1)/2$, and hence player i chooses to contribute to public good k. This contribution would continue up to the point where half of the population contributes to k. Since the number of contributors to k is less than or equal to that of the other, in the equilibrium, every player would be contributing to one of the two public goods. Thus, $t^k(x^*) = \lfloor n/2 \rfloor$ and $t^{k'}(x^*) = \lceil n/2 \rceil$.

When $n < 4c/\beta - 1$, $t_* < (n-1)/2$. Hence, except for the boundary cases, only a subset of players would be contributing. In this case, player i would contribute if $t^k(x^*_{-i}) \leq t_*$. Since the players are symmetric, the total number of contributors in each public good would be $\lfloor t_* \rfloor + 1 = \lceil t_* \rceil$ in both public goods if t_* is not a whole number. If t_* is a whole number, then player i would be indifferent between contributing and not contributing when $t^k(x^*_{-i}) = t_*$. In this case, the total number of contributors to each public good would be either $\lceil t_* \rceil$ or $\lfloor t_* \rfloor + 1$. Thus, $t^k(x^*) \in \{\lceil t_* \rceil, \lfloor t_* \rfloor + 1\}$ for $k \in \{A, B\}$.

□

21. It can be verified that $1 < 4c/\beta - 1$ when $2c > \beta$, which is satisfied under our assumption that $c > \beta$.