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Abstract:
When governing shared resources, the level and quality of information available to resource users on the actions of others and the state of the environment may have a critical effect on the performance of groups. In the work presented here, we find that lower availability of information does not affect the average performance of the group in terms of their capacity to provide public infrastructure and govern resource use, but it affects the distribution of earnings and the ability to cope with disturbances. We performed behavioral experiments that mimic irrigation dilemmas in which participants need to maintain infrastructure function in order to generate revenue from the use of water. In the experimental design, there is an upstream-downstream asymmetry of access to water that may lead to unequal access to water. We find that inequality of investment in irrigation infrastructure and water appropriation across players is more pronounced in experiments where resource users have limited information about the actions of others. We also find that inequality is linked to the ability of groups to cope with disturbances. Hence a reduced level of information indirectly reduces the adaptive capacity of groups.

Keywords:
Common pool resource, public infrastructure, experimental economics, inequality, communication, asymmetric commons dilemma

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1. Introduction

It is well known that groups can overcome collective action problems in sharing common pool resources when they can engage in self-governance [1]. This has not only been observed in real-world case studies, but also replicated in laboratory experiments [2]. Communication and the ability to enforce rules have been found to be critical factors that enhance the ability of groups to self-govern shared resources [3,4].

In this paper we focus on the ability of groups to self-govern their resources in the face of disturbances. Moreover, we are interested how capacity for self-governance is affected by constraints on information and communication. The question of the ability of groups to self-organize in the face of disturbances is a critical one because climate change and globalization are increasingly challenging the capacity of small-scale social-ecological systems (SESs) to function [5]. A particularly critical group of such challenged SESs is small-scale irrigation systems that supply 40% of the world's food supply which are the focus of this paper.

The work presented here represents the latest stage in a sequence of lab experiments that systematically add biophysical complexity to better understand governance of social dilemmas in irrigation systems – what we will hereafter refer to as "irrigation dilemmas". The irrigation dilemma captures situations in which farmers at the tail-end or head-end can experience differences in their influence on the collective action problems related to the maintenance of the irrigation system and allocation of water [6]. The fundamental problem facing irrigation systems is how to solve two related collective action problems: 1) provisioning for the resource, such as in building and maintaining physical infrastructure, and 2) the asymmetric common-pool resource dilemma, where the relative positions of resource users at the head and tail of the system generate asymmetric access to the resource [6]. If actors act as selfish, rational economic agents, we cannot expect irrigation infrastructure to ever be created. Even if the initial problem of providing the infrastructure were solved and water is made available, the head-end user may not necessarily share water with the tail-ender.

In earlier experiments we have shown that participants are able to overcome the irrigation dilemma in experimental settings [7,8]. A key explanatory factor for these findings is the trust that participants have in other community members, and the reduction of investments by tail-enders to match to unequal allocation of the water consistent with Ostrom's second institutional design principle that requires a good fit between appropriation and provision rules and the local context. These mechanisms have been found in experimental treatments involving farmers as well as university student participants. Anderies et al. [9] extended these earlier treatments by introducing shocks to the infrastructure and variability in water availability. The groups consisting of 5 players who could communicate, were still effective in solving the collective action problems. However, we did find some subtle and interesting differences between the treatments with and without variability (uncertainty). First, the understanding of the action situation (the experimental environment) made no difference in group performance without disturbances but it did after we introduced the disturbances. Second, inequality in earnings during the first 10 rounds without disturbances was a highly significant predictor for the performance of the group when exposed to disturbances in water availability or infrastructure levels in the second 10 rounds.

In this paper we extend the experimental setting once again and vary the social network structure and, as a result, constrain information availability and communication. The original irrigation dilemma experiments were inspired by small-scale irrigation systems where all the individuals could communicate with one another (e.g. a steep, small systems with 100-200 households in mountainous terrain). In such circumstances, the biophysical context has a strong influence on social network structure because individuals work in close proximity (e.g. 100 households on 100 hectares) and can observe each others' actions [10]. Some irrigation systems, on the other hand, are extremely large, e.g. the Kurnool-Cuddapah (KC) canal in state of Andhra Pradesh in India irrigates about 120,000 hectares and is about 300km long [11]. In this case, not all users can communicate with, and see the action of others. As such, the biophysical context strongly influences the social network. In our study presented here, we manipulate in the action situation to mimic this very issue. What if participants are not able to see the actions of all other participants and cannot communicate with all of them? Will groups still be able to self-organize?

Besides the biophysical context, community structures are also changing through their increased integration with the globalizing economy. Information exchange within communities is affected by those developments. On the one hand, farmers have less information due to the increasing number of absent farmers who work in wage labor jobs in urban centers, or spend time on the pleasures of modern entertainment (TV). On the other hand, mobile phone and other telecommunication technologies enable people to communicate at low cost between more distance places. How will these changes impact the capacity for self-governance of shared resources by small communities?

We use behavioral experiments to address the question of the effect of information. This enables us to look at fundamental drivers of decision making in typical conditions that many small scale irrigation communities face. Results from earlier social dilemma – not irrigation dilemma - experiments suggest that limiting the information will affect the experimental outcomes [12, 13, 14]. Since the majority of participants act in experiments as if they are conditional cooperators, information availability affects the expectations participants have and therefore their tendency to cooperate [15]. Hence we don't know for sure what the expected results will be.

In the next section we will present the experimental design and hypothesis to be tested. In Section 3, we discuss the results of the experiments and present the statistical analysis used to test our hypotheses. Section 4 closes the paper with a discussion of our findings and their broader implications for persistence of small-scale irrigation systems in a globalizing world.

2. Experimental design

The experimental design is a variation of the design discussed in [9] (See Supplementary Data for the experimental protocol and the exact language in the current experiment). Five participants are randomly allocated to different positions, A, B, C, D and E, related to the position along an irrigation canal (A= upstream, E= downstream). Participants play 20 rounds (i.e. growing seasons) in each of which they receive an endowment of 10 tokens (where one token is worth 10 cents), which they can keep or invest in the public infrastructure (i.e. the irrigation system). The investment in infrastructure is necessary to maintain its capacity to deliver water. In each round the infrastructure declines with 25 units, so each participant needs to invest 5 tokens on average if the group is to prevent the performance of the infrastructure from declining.

After the infrastructure level is determined, participants will make decisions regarding when to open and close their irrigation gate during a 50 second period as is shown in Figure 1. A player’s earnings from water delivery depend on the total amount of water applied to their field during this period (Figure 1). If more than 549 units of water is applied, the earnings will decline as the crops get flooded. Before participants make the decisions to invest and open or close their gates, they can chat via text messages for 40 seconds.

In the experiment of Anderies et al. [9] participants could communicate with and see the decisions regarding the opening and closing of gates by all other participants. Here, we will compare those results with new experiments in which participants are constrained in their ability to communicate with and information they have about other players. Participants can only communicate with nearest neighbors in stage 1 of each round. For example, player A can communicate to player B only. Player B can communicate directly with players A and C, but not D. In stage 3, participants only see the actions of the nearest players. For example in Figure 1, player C’s gate is open. Player C can see that Player B’s and D’s gates are closed but has no information about what Player A and E are doing.

Within each of these different types of information treatments, we compare four cases of environmental variation. In both treatments, the first 10 rounds are deterministic. In the second 10 rounds, one of four cases was run: 1) variation in water supply, high and low (i.e. monsoonal rainfall varies from year to year), 2) variation in the depreciation rate of public infrastructure (washouts of canals and diversion structures from floods) (Table 1 and Figure 2).

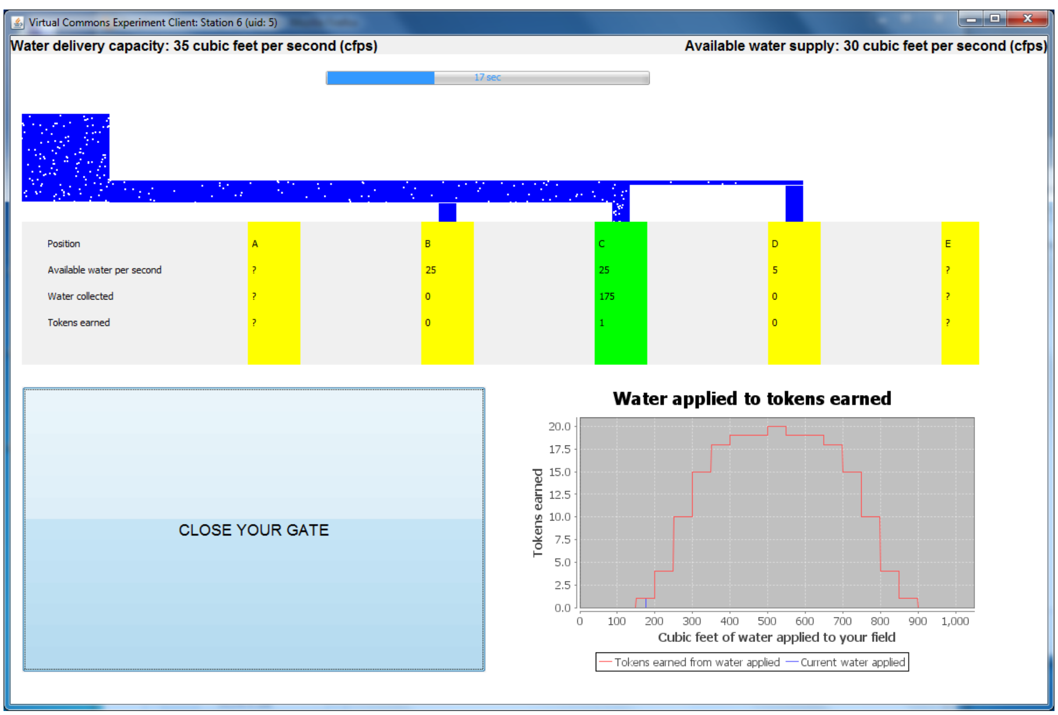
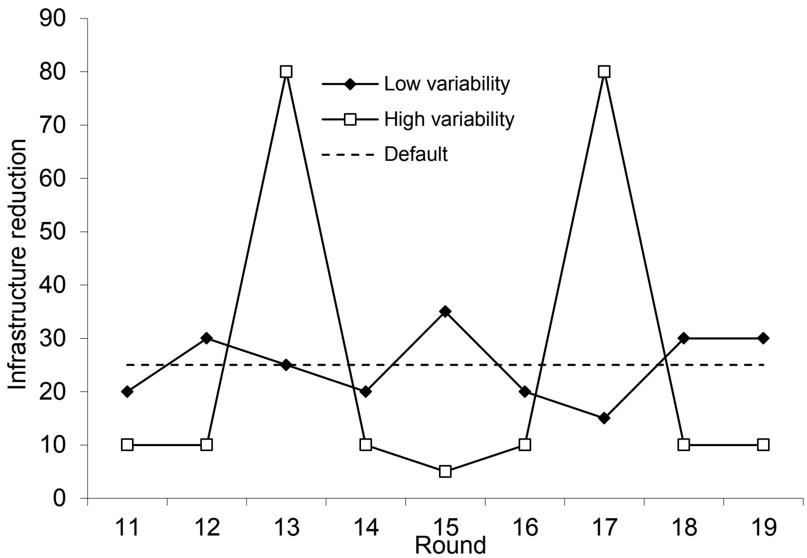


Figure 1. Screenshot of the experiment. Participants located in positions A, B, C, D and E need to make decisions whether to open or close their gate. The water is coming from the left of the screen. This screenshot is for player C, and therefore the scoreboard of player C is green. The other players’ positions are indicated in yellow. In this screenshot, player C’s gate is open, indicated by the flow of white dots into player C's scoreboard. Player C can see that Player B’s and D’s gates are closed but has no

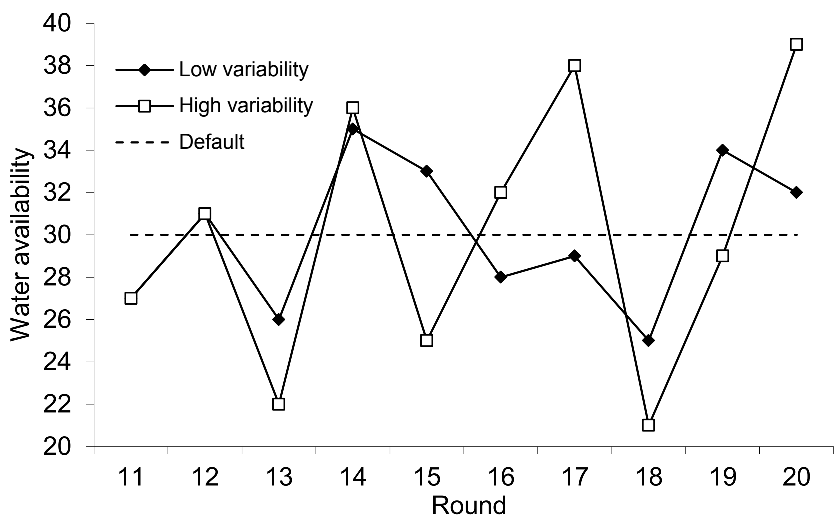
information about what Player A and E are doing (although C can infer what A has done and what is available for E).

Table 1: Experimental design, where *I* stands for infrastructure, *W* for water supply, *LV* for low variability and *HV* for high variability.

Label	Infrastructure decline (%)	Water supply (cp/s)	Number of groups
I-LV	15-35	30	5
I-HV	10-80	30	6
W-LV	25	25-35	5
W-HV	25	20-40	5



(A)



(B)

Figure 2: A: Values of infrastructure decline after the round. B: Values of the water availability over the rounds.

The group starts in round 1 with a public infrastructure stock of 75 (75% efficiency), and the decline is 25 for each round during the first 10 rounds of the experiment. We can calculate the Nash and social equilibria for this experimental design by assuming that participants have zero reaction time and attempt in the opening and closing of their gates to maximize their number of tokens. Anderies et al. [9] show that the Nash equilibrium for selfish rational actors leads to investments only during the first 3 rounds by the upstream participants. The earnings for 10 rounds vary from 131 (A) to 100 (E) (equivalent to $13.10 and $10.00, respectively).

3. Results

The experiments with the full information were performed in Spring 2010 [9], and those with the constrained communication and limited information were performed in Spring 2012. The participants were recruited from a database of undergraduate students at Arizona State University who had indicated that they were willing to take part in experiments with human subjects. This database consists of students from all majors and invitations were sent out to a random sample of the whole population when an experiment was scheduled. Based on exit surveys, of the 220 persons that participated in the experiments reported in this paper, half of the participants were female and the average age was 19.5 years. Average earnings were $22 including a show up bonus of $5 plus payments for their play (made in private) for experiments with an average duration of 70 minutes. The individual minimum and maximum earnings were $12.20 and $34.70, respectively.

Figure 3 shows the average investment levels in the infrastructure for the first 10 rounds across the 44 groups split among groups who have full and limited information. Based on the public infrastructure provision schedule (see supplementary materials for details), the socially optimal infrastructure efficiency level is 66%. The average group level of infrastructure efficiency converges to about 75%, which is above the socially optimal level. Although the investment levels are similar for both information treatments, we see major differences in the distribution of contributions and appropriation. When participants have full information, the experimental results suggest that the upstream participants invest slightly more than participants downstream (Figure 4). When information is limited and participants cannot communicate with everyone else, the differences between upstream and downstream become substantial. The downstream participants, on average, decrease their investment after the first round (compare the average investment of players in positions A, B, and C of 5-6 tokens to that of players in positions D and E of 3-4 and 2-3 tokens, respectively).

As we would expect, in the appropriation phase participants upstream earn more than those downstream, but here a major impact of limited information (Figure 5) becomes clear. If communication is constrained, downstream participants, especially those in E, often do not receive any water. The results suggest that players in position D, perhaps through communication with upstream players via players in position C, are able to convince them to share more water (e.g. while participants in position B take markedly less) and thus receive more water over time during the first 10 rounds. This result suggests that even though they couldn't communicate directly, the communication between B and D, through C, was reasonably effective. However, the constraints on communication channels between players seem to diminish the effectiveness of communication in overcoming social dilemmas. This is clear in how the appropriation of players in positions A and E change much less than those in positions B and D, respectively.

Another key difference between treatments is the level of inequality in earnings between the full and limited information treatments as Figure 6 makes clear. Participants upstream earn considerably more than those downstream due to asymmetric access. Downstream participants compensate with lower investments in the public fund while upstream participants compensate with a higher investment level. These differences are exacerbated by limited information ahs shown by the difference in the white and black bars in Figure 6.

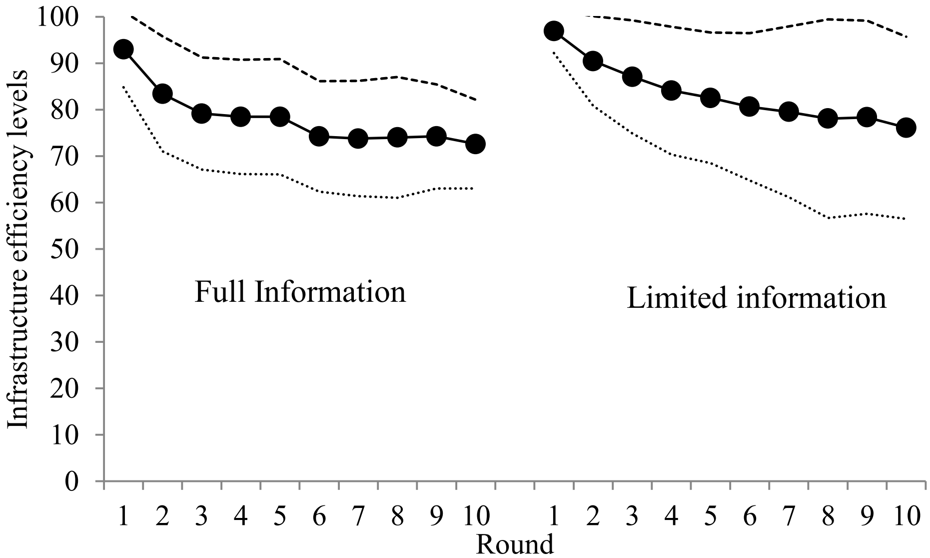


Figure 3: The average infrastructure efficiency levels of groups in the four different treatments. The dotted lines are the average +/- one standard deviation of the efficiency levels.

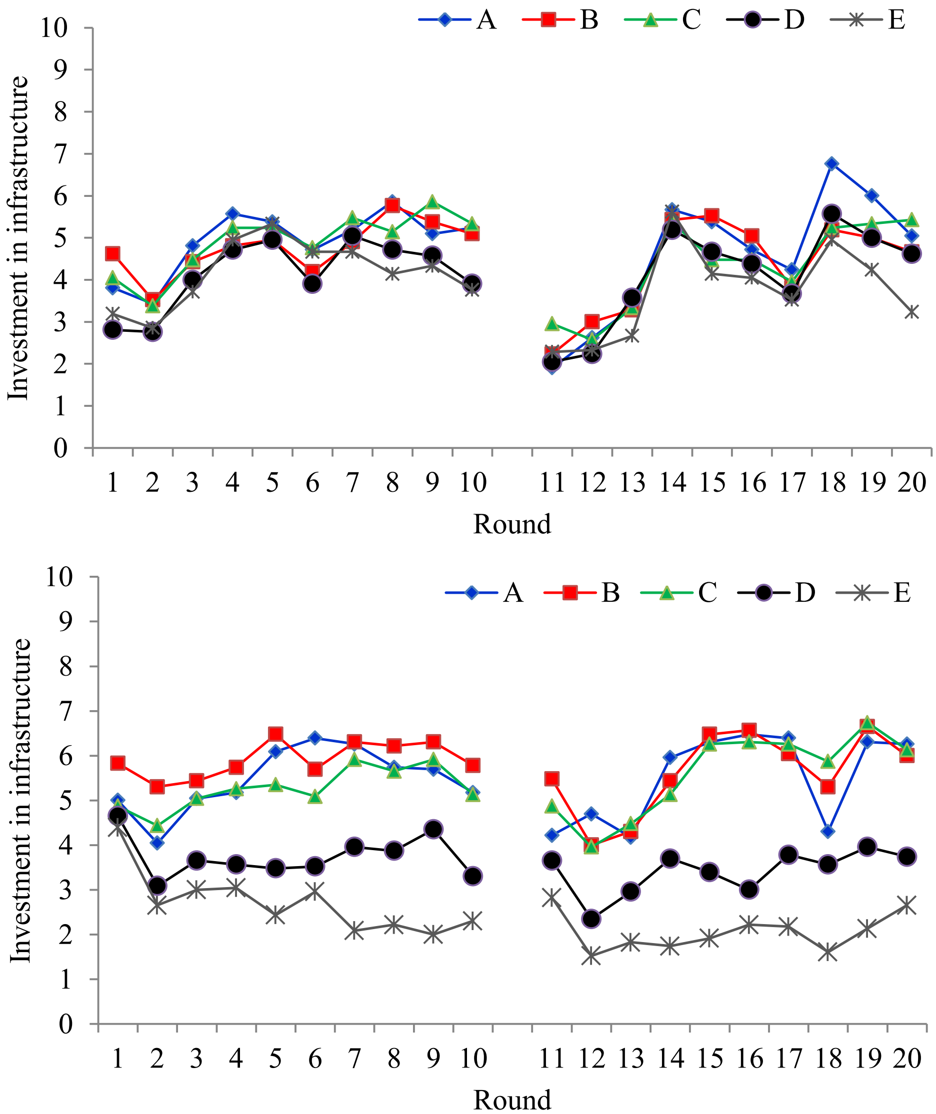


Figure 4: The average number of tokens invested per position and round for treatment with full (top) and limited (bottom) information.

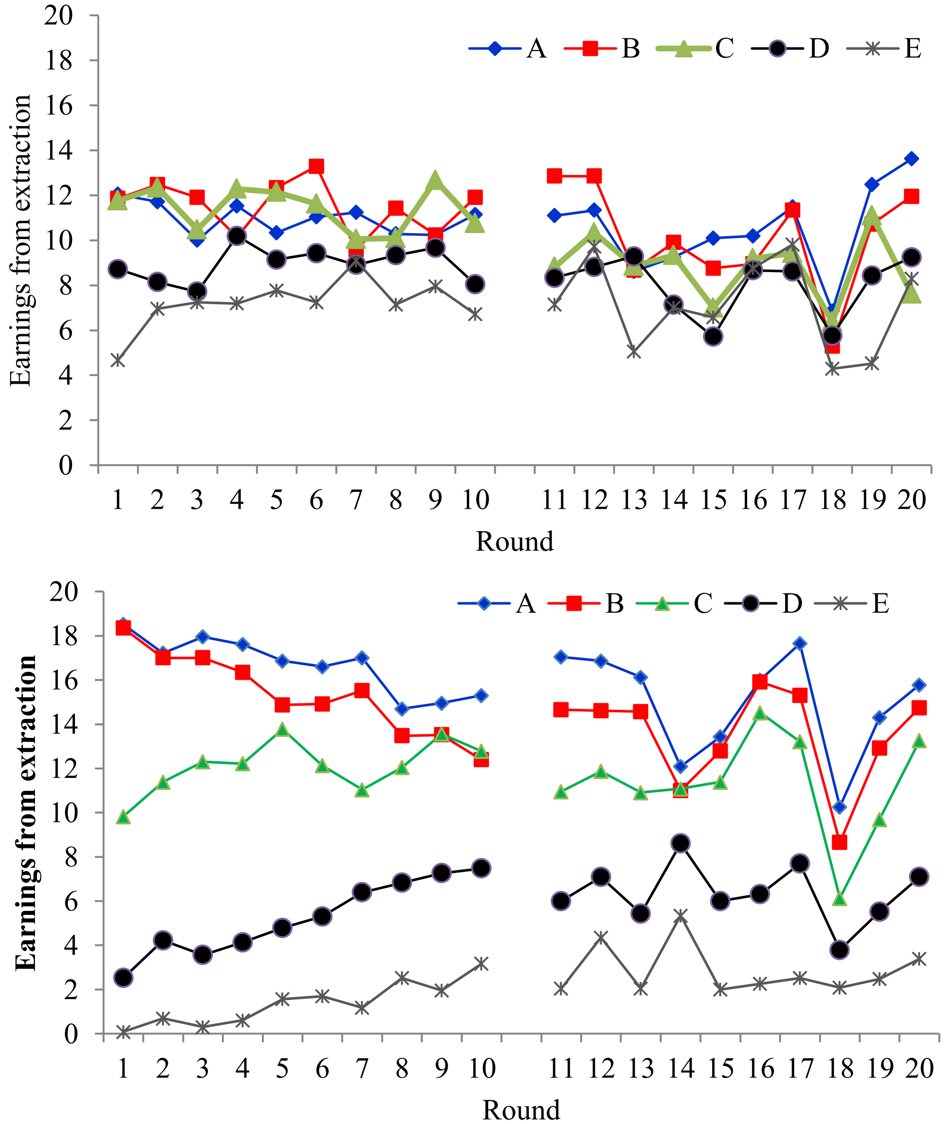


Figure 5: The average earnings resulting from water appropriation per position and round for treatment with full (top) and limited (bottom) information.

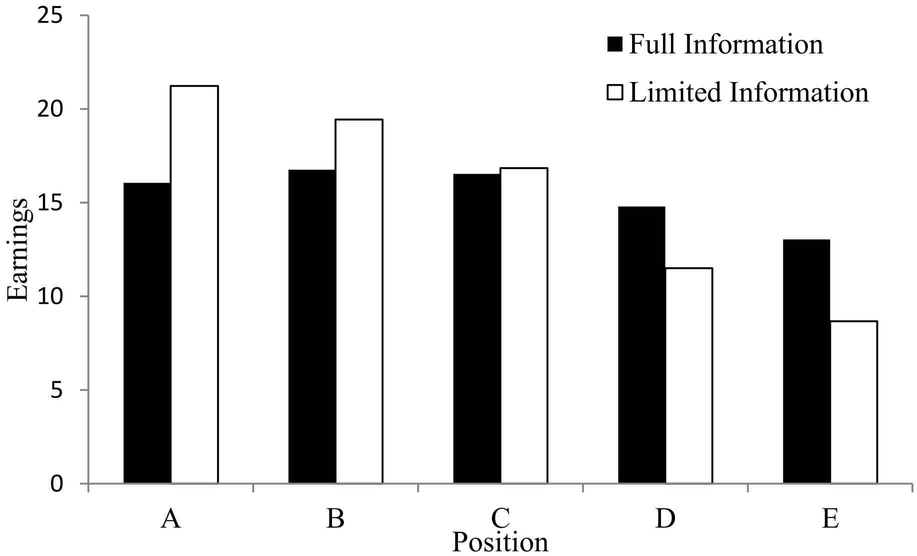


Figure 6. The average earning per position for the two treatments during rounds 1-10.

To explore this issue in more detail, we evaluated the levels of investment and appropriation decisions over the first 10 and second 10 rounds by position. The participants in position D and E invest less and generate less from growing crops when information is limited. Using the two tailed Mann-Whitney test on the average number of tokens invested by the participants over 10 rounds, the difference between the first three positions and the last two is found to be statistically significant (p-value < 0.01). This is also true for the number of tokens earned from growing crops. The differences might be caused by a response of downstream participants to the inequality they experience. Text analysis confirms that most of the discussion within groups is about inequality and fairness (Perez et al., in press). We will investigate the response to inequality further below. Despite the lower investment levels, the total level of earnings for the last two positions is significantly lower than the first three positions. That is, lower investment levels do not offset the reduced income from receiving less water in positions D and E.

In rounds 11- 20, the infrastructure level fluctuates between 0 and 100 for the four different treatments (Figure 7). Interestingly, the infrastructure level is maintained at a higher level with limited information compared to full information, except for the treatment with big infrastructure shocks (I-HV). This may suggest that better communication between participants allows more effective coordination on the optimal investment levels and more rapid response to large shocks (i.e. groups with limited information overinvest, and respond more slowly to shocks). Our data is only suggestive; considerably more work is required to explore this claim further but it is interesting nonetheless.

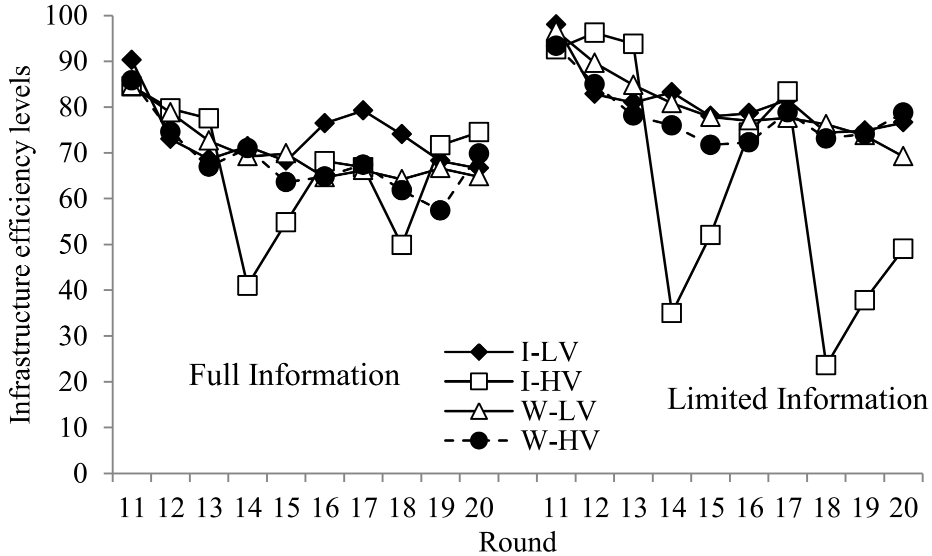


Figure 7: The average investment levels of groups in the four different treatments.

These average statistics for group performance highlight basic patterns in this asymmetric commons dilemma. Namely, the average performance of the treatments with limited and full information are similar, but there is substantially more inequality when communication is constrained and information is limited. Will we see a similar effect in the ability of groups to cope with disturbances between treatments? Table 2 shows that the group earnings in rounds 1 to 10 fall between the Nash and Social Optimum. There is no significant difference between groups with full and limited information for the first 10 rounds using a Mann-Whitney test (p=0.467). When there is a high variability of infrastructure decline (large, less frequent shocks) we see much lower performance, especially when information is limited, but the sample is too small (=5) to find a statistically significant effect using the Wilcoxon ranked sum test. More generally, when we compare the performance for the different treatments between full and limited information we find no significant differences except for W-HV (Mann-Whitney test, p=0.045). Hence for constrained communication the performance is significantly better than full information when there is a high variability of water availability. This effect is mainly caused by one poorly performing group in the full information condition, so additional work is required to substantiate this claim.

Table 2: Percentage of earnings relative to Nash and Social Optimum. This measure shows how much of the difference in earnings between the Nash and the social optimum the groups were able to capture through collective action. Thus, 0% is represents the case in which a group is stuck at the Nash solution, and 100% represents the case where the group achieved the social optimum.

Treatment	Rounds 1-10		Rounds 11-20	
	Full	Limited	Full	Limited
I-LV	43%	56%	43%	44%
I-HV	49%	55%	17%	-17%
W-LV	49%	48%	41%	64%

W-HV	54%	44%	31%	63%

We will now discuss a series of statistical analyses in which we look at the explanatory variables for effects between groups and individuals in investment and appropriation decisions. At the individual level we estimate a linear multi-level mixed effect model controlling for group effects (Table 3). We find that position has a significant effect; those downstream earn less, invest less and extract less water. We also find that there is a learning effect leading to better earnings in later rounds. Constrained communication and limited information lead to higher earnings for those in positions A, B and C. However, it significantly reduces the earnings of those participants downstream. Inequality of appropriation impacts investment decisions, which we tested by including the share of appropriation as observed in the previous round as an explanatory variable. The higher the share of appropriation for participants downstream, the higher the investment in the infrastructure. Hence if downstream participants receive a decent amount of water, they reciprocate through higher investments.

Understanding of the experiment, as measured by the number of correct answers to quiz questions asked before the real experiment started, does not have a significant effect on earnings of individuals. Better understanding of the experiment will not help if you are a downstream participant. There is a modest significant effect of levels of understanding and investment. Since groups generally overinvest in the infrastructure at the start of the experiment, this significant effect indicates that those who better understand the experimental instructions overinvest less. We find that gender has a small effect on the earnings because males extract less during the crop growing period.

Various features of the biophysical conditions have a significant impact on the earnings. Interestingly in rounds 11-20, there is a modest but significant negative effect of water supply in the previous round on investment levels. If groups experience scarcity they may expect a good round (e.g. "things can only get better") and invest more in the round after a round of scarcity.Not surprisingly a higher initial infrastructure level leads to higher earnings, and when water supply is fluctuating in rounds 11 to 20, groups with higher infrastructure levels benefit from the higher water supply (and loses only a little when water supply is lower than average).

Table 3: Regression results of earnings, investments and appropriation of individuals per round. Standard deviations are shown in brackets. The first column are the dependent variables, and if the variables are statistical significant this is indicated by * P < 0.1; ** P < 0.05; *** P < 0.01.

	Earnings		Investments		Appropriation	
	Rounds 1-10	Rounds 11-20	Rounds 1-10	Rounds 11-20	Rounds 1-10	Rounds 11-20
Constant	**10.650*** (1.094)**	**-4.433*** (1.436)**	**9.551*** (0.567)**	**9.567*** (0.782)**	**5.501*** (0.932)**	**-8.480*** (1.235)**
Round	**0.213*** (0.052)**	**0.184*** (0.049)**	**-0.052** (0.022)**	0.027 (0.023)	**0.168*** (0.043)**	**0.129*** (0.043)**
Position	**-0.816*** (0.117)**	**-0.703*** (0.118)**	**-0.391*** (0.071)**	**-0.522*** (0.088)**	**-1.030*** (0.117)**	**-0.888*** (0.115)**
Initial infrastructure	**0.112*** (0.013)**	**0.177*** (0.007)**	**-0.063*** (0.007)**	**-0.063*** (0.004)**		
Capacity					**0.218*** (0.020)**	**0.290*** (0.011)**
Constrained communication	**7.110*** (0.720)**	**4.264*** (0.700)**	**2.353*** (0.393)**	**2.543*** (0.424)**	**9.408*** (0.630)**	**6.976*** (0.600)**
Position * Constrained Communication	**-2.510*** (0.168)**	**-1.533*** (0.169)**	**-0.455*** (0.074)**	**-0.541*** (0.085)**	**-3.094*** (0.167)**	**-2.274*** (0.165)**
Share appropriation (t-1)			**-1.675* (0.888)**	**-3.103*** (1.076)**		
Share appropriation(t-1) * position			**1.531*** (0.277)**	**2.210*** (0.319)**		
Fraction QQ correct	0.294 (0.511)	-0.223 (0.513)	**-1.097 *** (0.212)**	**-0.501** (0.251)**	-0.763 (0.496)	**-0.971* (0.483)**
Male	**-0.859*** (0.263)**	-0.222 (0.264)	-0.004 (0.108)	0.093 (0.129)	**-0.982*** (0.255)**	-0.088 (0.723)
Water Supply		**0.335*** (0.033)**				**0.334*** (0.032)**
Water Supply (t-1)				**-0.051*** (0.017)**		
N	2030	2030	1894	1733	2030	2030
Log likelihood	-6317.29	-6332.71	-4133.35	-4010.11	6296.94	6261.096
Walt test	883.02	1084.89	531.47	720.12	1390.18	1620.36
$p>\chi^2$	<0.001	<0.001	<0.001	<0.001	0.049	0.001

We conclude our analysis of the data by looking at the group level using ordinary least squares (OLS) on a linear model of attributes of the groups. This may lead to different insights than our analysis this far since the group dynamics cannot be addressed at the individual level. Consistent with earlier studies we find that in the first 10 rounds, inequality of appropriation leads to lower levels of earnings [9]. There is no impact of the average understanding of the experiments by the group members during the first 10 rounds. Surprisingly, constrained communication leads to higher earnings on average, but – as shown in Figure 6 – there is more inequality within the group. The chat data show that with full information, players coordinate and correct misjudgments. With constrained communication, the upstream participants are not confronted with the voices of the low earning downstream participants and still can maintain the functioning of the irrigation system among themselves.

In the second set of rounds where variability in infrastructure decline/water availability is included, we do not see a significant effect of inequality of appropriation in the round just previous to the current round (Table 4). However, we find that inequality in the first 10 rounds does have a significant negative effect on the earnings in the second 10 rounds. We also find that the effect of the number of correct answers in the quiz questions becomes significant and positive. Hence, in the more complex rounds, it is important for groups to understand the instructions. It is important to realize that at the individual level, a better understanding of the experiment has no significant effect since participants are constrained by their biophysical condition (position).

What may explain the fact that the gini of appropriation for the first 10 rounds has such a long term effect? Inequality in investments propagates to the inequality of appropriation. When groups were constrained in their communication, this also led to higher levels of inequality of appropriation. As the rounds progress, the gini coefficient declines; a pattern which might be caused by learning and coordination. This is consistent with the finding that groups with better understanding of the experiment experience a lower level of inequality.

There is a difference in dynamics in rounds 11-20. Constrained communication is not a significant factor, but inequality of appropriation from the first 10 rounds explains a significant component of the inequality experienced in the second 10 rounds. This may suggest some path dependency of group dynamics started in the first 10 rounds. We find some effects of the treatments (I-HV and W-HV). Groups who experience a high variability of infrastructure decline also experience a higher level of inequality of appropriation, while groups who experience a low variability of water availability experience a lower level of inequality.

This analysis confirms the earlier finding of Anderies et al. [9] that dynamical process of inequality of appropriation causing long term performance challenges if the group is exposed to disturbances. The disturbance scenario with major infrastructure decline leads to a significant reduction of the performance in terms of earnings, while other scenarios do not have a significant effect. Groups need to have built up sufficient social capital to rebuild the infrastructure after a major breakdown. Since inequality of investments and appropriation reduce the willingness to contribute by those downstream, their lack of contributions hinder groups to rebuild their infrastructure. The most important additional insights the come from the new treatment with constrained communication are 1) constrained communication increases inequality which, taken with our earlier results may make groups more vulnerable to large, infrequent shocks, 2) limited communication may cause groups to overinvest slightly, making them more robust to frequent, smaller shocks, and 3) constrained communication works against all-group collective action by potentially generating subgroups who do not communicate, and thus do not have a shared mental model about system function or outcomes. That is, with limited communication, players A, B, and C form a subgroup that performs well at the expense of the second subgroup of players D and E. This works well for the upstream group until there is a shock that operates on the scale of the entire group which they can't handle. Given the loss of social capital between the upstream and downstream groups, they can't mobilize sufficient collective action to provide the necessary public infrastructure to overcome the shock. This result comes out very clearly in Figure 7.

Table 4: Regression results of earnings of groups per round. Standard deviations are shown in brackets. The first column are the dependent variables, and if the variables are statistical significant this is indicated by * P < 0.1; ** P < 0.05; *** P < 0.01.

	Earnings		Investments		Appropriation	
	Rounds 1-10	Rounds 11-20	Rounds 1-10	Rounds 11-20	Rounds 1-10	Rounds 11-20
Constant	**71.893*** (5.031)**	**-24.320*** (7.730)**	**25.324*** (3.071)**	**28.618*** (6.175)**	**29.108*** (3.869)**	**-53.364*** (5.485)**
Round	-0.087 (0.232)	0.222 (0.258)	0.413*** (0.142)	0.530*** (0.190)	0.299* (0.165)	0.207 (0.189)
Initial Infrastructure	**0.232*** (0.048)**	**0.818*** (0.039)**	-0.029 (0.029)	**-0.253*** (0.029)**		
Capacity					**0.738*** (0.064)**	**1.288*** (0.053)**
Constrained communication	-3.64 (1.914)	-2.108 (2.075)	**2.896** (1.168)**	-0.117 (1.534)	**4.172*** (1.413)**	-1.362 (1.563)
Gini appropriation (t-1)	**-32.899*** (4.484)**	1.880 (5.085)	0.330 (2.737)	1.837 (3.930)	**-25.315*** (3.447)**	3.932 (3.833)
Gini investment (t-1)	3.041 (3.980)	5.989 (4.819)	**-9.629*** (2.429)**	**-7.552** (3.560)**	-3.657 (2.995)	4.842 (3.653)
Fraction qq correct	3.814 (4.984)	**19.063*** (5.938)**	-4.678 (3.042)	**9.584** (4.395)**	**1.624 (0.658)**	**19.217*** (4.494)**
Fraction male	-0.500 (2.261)	**6.656** (2.691)**	0.500 (1.380)	1.065 (1.989)	1.567 (1.705)	**5.866*** (2.026)**
Water supply		**1.749*** (0.165)**				**1.771*** (0.126)**
Water Supply (t-1)				-0.224 (0.140)		
Avg Gini extr (R1-10)		**-31.353*** (9.070)**		6.699 (6.751)		**-23.241*** (6.812)**
Avg Gini inv (R1-10)		-0.973 (8.597)		-4.321 (6.636)		-5.056 (6.486)
I-LV		1.512 (2.047)		-0.709 (1.514)		-0.014 (1.541)
I-HV		**-9.746*** (2.164)**		**-4.374*** (1.605)**		**-6.396*** (1.678)**
W-HV		-2.715 (2.027)		-1.191 (1.497)		**-3.345** (1.528)**
N	356	326	356	0.326	0.468	0.784
R^2	0.217	0.668	0.102	0.308	356	326

Conclusions

In this paper we report on the use laboratory experiments to study the performance of a specific type of "Coupled Infrastructure System (CIS)" that is a defining feature of human societies: the irrigation system. The term CIS characterizes systems in which hard, human-made infrastructure (e.g. irrigation canals) is coupled with soft human-made infrastructure (e.g. institutional arrangements for water distribution and canal maintenance), and natural infrastructure (a watershed) to produce outputs that are valued by the human groups that construct them (e.g. food) [17]. "Governance" is an essential feature of CISs; it operates as a feedback control mechanism to allocate resources within the CIS. Although the characteristics of communities (e.g. trust levels, groups size, institutional arrangements) that facilitate collective action and effective governance have been extensively studied [1], the effect of biophysical context defined by the nature of the hard human-made and natural infrastructure has received much less attention. Ostrom and Gardner's work [6] on asymmetric commons is a notable exception and we extend that work here. Specifically, we constructed a simplified CIS in the laboratory that mimics the real-world analogue of the small-scale irrigation system.

Populating this CIS with experimental subjects has enabled us to analyze the consequences of changing the biophysical structure of an irrigation dilemma such that communication and information availability is constrained to the direct neighbors of each player. Due to constrained communication and limited information availability, upstream participants do not see the low earnings of the downstream participants and the downstream participants cannot direct their concerns to the upstream participants. Likewise, agents in developed countries have limited capacity to make their voices heard. As a consequence, upstream participants appropriate more water from the common-pool resource compared to the experiments with full information. The upstream participants increase their investments in the public infrastructure to compensate for the lower level of investments of the downstream participants.

The most striking finding is that the change in the biophysical context captured by this experiment does not affect the *average* performance of the group, but it affects the *distribution of earnings* and, as a result, the ability to cope with disturbances. Specifically, as found in [9], inequality of water appropriation during times of stability has a significant negative effect on the earnings during times of instability. The higher levels of inequality due to limited information and constrained communication therefore has the potential to amplify the negative effect on the adaptive capacity of the groups. Furthermore, groups in which more members better understand the instructions of the experiment do better when they are exposed to disturbances.

The experimental results provide insights into the importance of the interplay between different types of infrastructure (i.e. biophysical context and institutional arrangements) and outcomes. When, due to biophysical context or social context, there is limited information exchange between members of an irrigation system, those systems will function well on average (even better than the case without limited information exchange) but will experience a major increase of inequality of earnings. This type of outcome is, in fact, fundamental to CISs. Specifically, CISs as examples of feedback systems exhibit fundamental performance-robustness trade-offs [18]. In our experiments, constraining communication actually makes the system perform better under three of the four scenarios but becomes more vulnerable (less robust) to large shocks to infrastructure. Further, in our experiments there was no exit option, other than not investing in the infrastructure. One can expect that limited communication would lead to the exit of participants and a decline of the group if other exit options were available. Thus, subtle changes in biophysical context may introduce hidden vulnerabilities that are only revealed when the CIS is exposed to a new type of disturbance.

Small scale irrigation systems around the world are now experiencing many new challenges to their capacity to continue to function and produce food. One of the challenges is the lack of time community members can spend communicating with one another to share information due to other job opportunities (wage labor) and modernity (TV, mobile phones, etc). This may reduce information flows between participants, lead to less coordination and cooperation and a less even distribution of income. In the long-term, this inequality may have negative effects on the communities with serious implications for the ability of small-scale irrigation systems to produce food and feed the roughly 3 billion people it now does.

Acknowledgements

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Experimental Instructions for
"The effect of limited information in a behavioral irrigation experiment"

Instruction Script Summary

The pages that follow contain the instruction script used during the experiments. Page 2 shows the overall progression of the experiment (not read to subjects). The instructions to subjects begin on page 3. Following the general introduction, participants are taken through the screenshots of the actual experiment. The text boxes that appear on each page are the instructions read to the participants by the facilitator when each screen appears on their computers. The instructions were administered interactively, and the students following along filling in values as appropriate. After instructions were read for each screen, participants were asked whether they had any questions regarding that screen. The instructions for the 4 different treatments were slightly different. At the end of the instruction script, there are two variations of the last paragraph that were read for the appropriate treatment.

Overall scheme of instructions and practice

- Introduction to experiment [text]
- Chat [“type in hi”]
- Investment page [“explain and type in 7”]
- Result investments [explain]
- Screenshot crop growing [explain]
- 50 seconds crop growing
- Results view of practice round 1
- Quiz questions
- Give answers to questions [store answers from participants]
- Do practice round 2
- Experiment start 10 rounds + 10 rounds

General Introduction

[WHEN PEOPLE COME IN THE SCREEN GIVES A WELCOME MESSAGE. WHEN EVERYBODY IS READY ALLEN (DAVID) WILL START THE GAME]

Welcome, I am Dr. Anderies, a professor here at ASU and we will conduct a decision-making exercise today. Allen Lee (or David Yu) will assist me during the exercise. Before we go to the instructions, I will ask you to turn off any mobile phones and other mobile devices that might disrupt the exercise. I also ask that you not speak during the exercise. If you have a question, raise your hand, and I will address your question.

This exercise consists of two practice rounds and twenty rounds for real. Each round is about two minutes.

[TELL ALLEN (DAVID): START INSTRUCTION SCREEN]

Carefully follow the instructions on the screen as I read them aloud.

Instructions

You have already earned 5 dollars by showing up for this exercise. You can earn more, up to a maximum of about 45 dollars by participating in this experiment which will take about an hour to an hour and a half. The amount of money you earn will depend on the decisions made by you and the other members of your group.

Groups

You will be participating in this exercise as a part of a group of participants. Your group has been formed by randomly selecting you and FOUR other participants in the room.

How to participate

This exercise mimics decisions people make in irrigation systems. In each round you will receive 10 tokens which you can invest in the irrigation infrastructure. Based on the water delivery capacity of the irrigation infrastructure and the availability of water you will be able to grow crops. Tokens earned in a round are the sum of tokens not invested plus tokens earned by growing crops. Each token is worth 5 cents. In each round you will first decide how much to invest in the irrigation infrastructure. Based on the combined contributions of all 5 participants in your group in each round, your group can maintain the capacity of the irrigation infrastructure to grow crops.

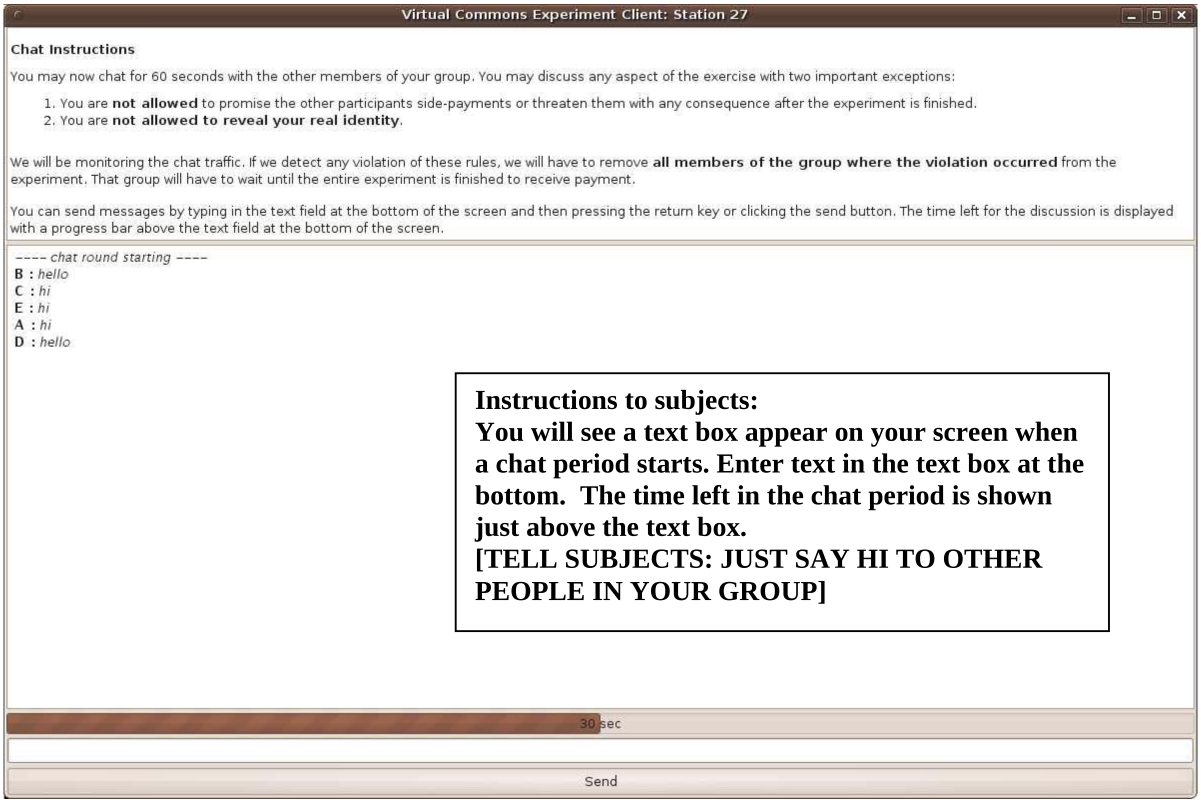
We will now start a practice round to help illustrate the experiment. Before each round in this experiment you will have a chat period of 60 seconds where you can send text messages to the other participants. NOTE: You can only communicate with and observe the actions of your immediate neighbors. You may discuss any aspect of the exercise with two important exceptions:

1. You are not allowed to promise the other participants side-payments or threaten them with any consequence after the experiment is finished.
2. You are not allowed to reveal your real identity.

We will be monitoring the chat traffic. If we detect any violation of these rules, we will have to remove all members of the group where the violation occurred from the experiment. That group will have to wait until the entire experiment is finished to receive payment.

These practice rounds will not contribute to your earnings. They are only intended to acquaint you with the functioning of the experimental environment.

[TELL ALLEN (DAVID): START CHAT ROUND]



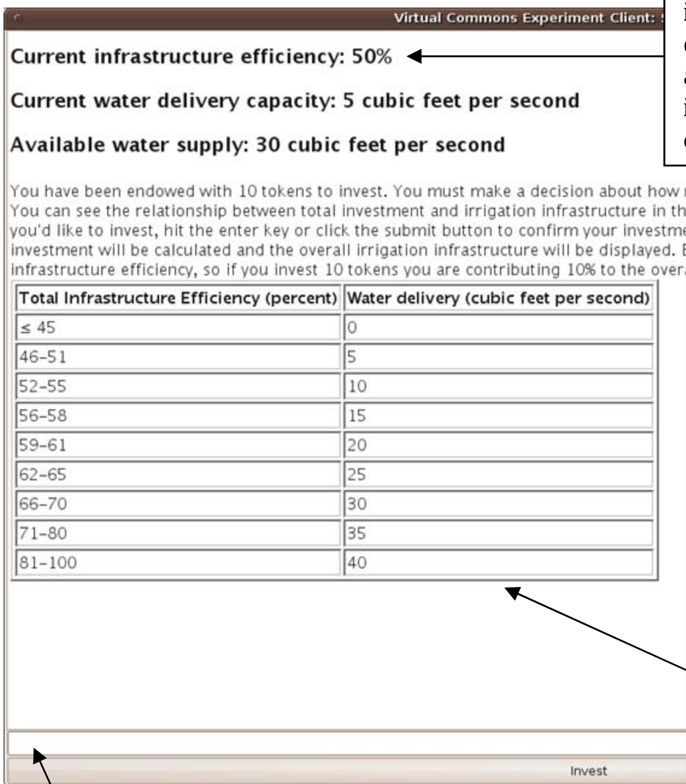
Instructions to subjects:
You will see a text box appear on your screen when a chat period starts. Enter text in the text box at the bottom. The time left in the chat period is shown just above the text box.
[TELL SUBJECTS: JUST SAY HI TO OTHER PEOPLE IN YOUR GROUP]

[MOVE ON TO INVESTMENT PAGE]

[Explain investment table to subjects]

At the beginning of each round, each participant will be given 10 tokens. You must then decide what to do with these tokens. You may invest some tokens in the irrigation infrastructure or to keep the tokens. For example, if you keep the tokens, you will earn 10 tokens in that round. On the other hand, if you invest some tokens in the irrigation infrastructure, you may be able to earn more than this amount by growing crops. In fact, you can triple your earnings compared to doing nothing. But note that the actual earnings depend on what you and the other participants in the experiment do.

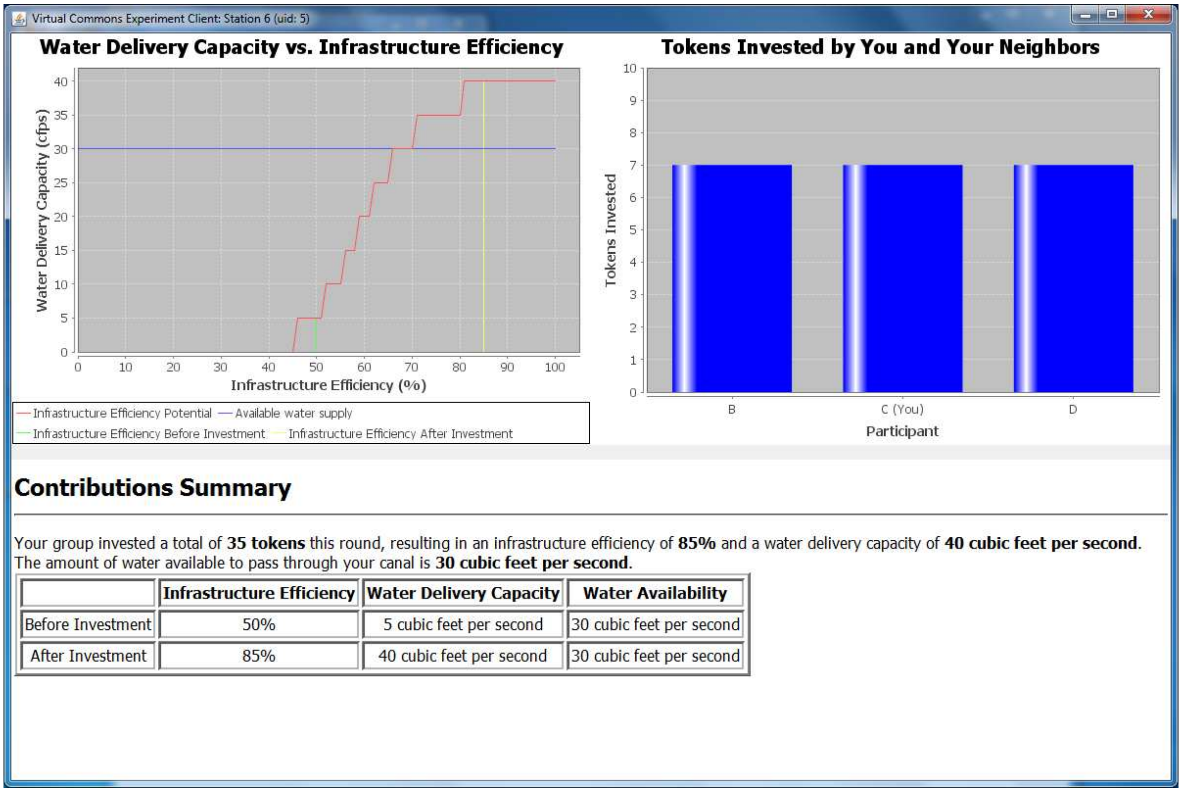
1. Instructions to subjects:
After each round the condition of the Irrigation system declines such that its water delivery efficiency drops by 25%. Investment is necessary to keep the irrigation infrastructure from deteriorating. If you decide to invest in irrigation infrastructure, you must decide on the amount, as you will need a certain level of irrigation infrastructure before you can grow crops.



2. Instructions to subjects: The investment of all five participants is added together and will amount to between 0 and 50 tokens. Each token invested will increase the efficiency of the system by one percentage point up to a maximum of 100%. In the table you will see the water delivery capacity measured in water units per second as a function of condition of the irrigation infrastructure. When the infrastructure is at 100% efficiency, 40 cubic feet per second will be available. If system efficiency falls below 45%, no capacity for transporting water will be available.

3. Instructions to subjects: Before the growing crops component of the exercise starts, each participant independently makes a decision as to how much to invest in irrigation infrastructure maintenance. After everybody has made their decision, the condition of the infrastructure and the associated total maximum capacity to distribute water that will be available during the crop growing component of the exercise is announced. For this practice round we just ask you to type in 7, hit return, or click the investment button.

[EXPERIMENT WILL AUTOMATICALLY MOVE ON TO INVESTMENT RESULTS PAGE]

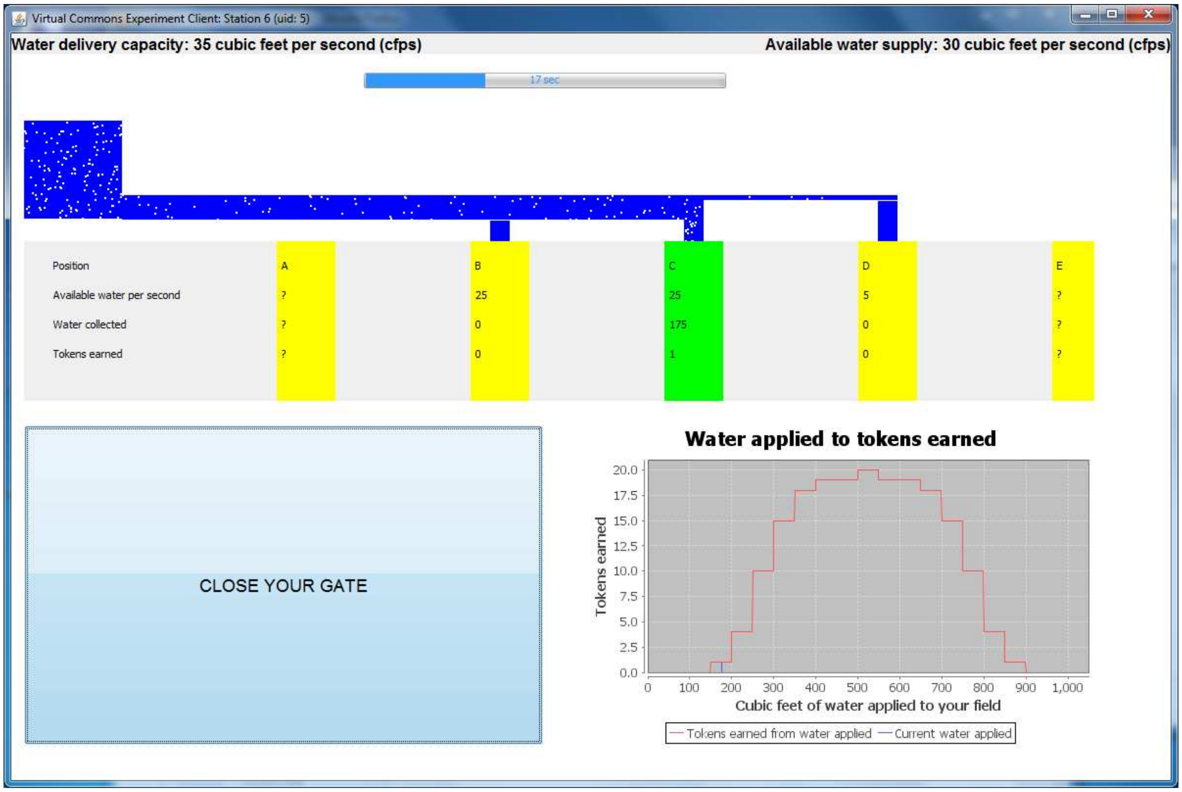


You now see a table summarizing the results of group investment. The infrastructure had an efficiency of 50% and you as a group invested 35. Now the infrastructure is 85%. Reading to the left where the yellow line hits the red, stair-stepped curve, shows the water delivery capacity, in this case 40 cfps. The blue line shows the amount of water available - in this case, 30 cfps.

In the diagram on the right you see how much your immediate neighbors contributed to the public infrastructure. Example: If you are in position C, you will see the contributions of participants in positions B and D. If you are in position A, you will only see the contributions of the participant in position B.

Finally, the investment decisions of the group are summarized in the table at the bottom of the screen.

[TELL ALLEN (DAVID): MOVE ON TO GAME INTERFACE PAGE]



There are FIVE participants, each of which is randomly assigned to one of the five positions, A, B, C, D or E. Water comes from the box to the left and the five players are located from upstream to downstream. Your location will be highlighted in green. In this case, assume you are in position C. You can see that your gate is open, and water is flowing into your field. You can open or close your gate by pressing the large button in the lower left of the screen.

As you are in position C, you only see the information for your neighbors, positions B and D. Each round will take 50 seconds and the amount of time left in the round is indicated at the top of the screen.

During this round you can irrigate your field. The earnings depend on the amount of water you put on your field as will be explained in the next screen. How fast you can grow a crop depends only on the amount of water that is available to you. The maximum flow capacity of the main canal shared by A, B, C, D, and E is 40 cubic feet per second (cfps).

The actual amount of water that is available for the group depends on the amount of water entering the system. Your group might have created an irrigation infrastructure with a capacity of 40 cfps, but due to lack of rainfall only 30 cfps is available. On the other hand, if infrastructure capacity is 30 cfps and 40 cfps of water is available to the system, only 30 cfps can be delivered.

The maximum capacity that can flow through your gate when it is opened is 25 cubic feet per second. If other people are using the canal, the water flow available to you might be less, and it may take longer to get water to your field.

The water flow capacity available for your field is shown as a number. If somebody upstream uses water, less water is available for you. The thickness of the blue bar is the relative amount of water available. To start diverting water to your field to grow crops, click on the large button “open your gate”. This will open your irrigation gate and water will begin to flow to your field. The text on the button will turn to “close your gate”. If you would like to close the gate, just click on the button again. The gate closes and the text on the button returns back to “open your gate”. The amount of water units (cubic feet) your field has received is shown on the screen, as well as the resulting amount of tokens earned from growing a crop. The number of tokens earned in each round depends on how much water you have diverted to your field. If you divert less than 150 cubic feet (cf) to your field, the crop has not received enough water to grow and you will thus not receive any tokens. The maximum earnings are generated when between 500 cf and 549 cf are diverted to your field. If more than 549 is diverted to your field, this will negatively affect the growth of the crop (i.e. overwatering) and less tokens will be earned. In the graph in the right bottom of the screen you can see the number of tokens earned as a result of the amount of water applied to your field.

Your earnings at the end of the round depend on your investment and the number of tokens received from the crop. We will now start a crop season for 50 seconds.

[TELL ALLEN (DAVID): START 50 SECOND CROPPING ROUND]

You see now a table summarizing how much you and other group members would have earned if this round was for real. You see how much you have invested (or not), and how many tokens you earned from growing a crop.

If you have any questions feel free to raise your hand and to ask your question. Do you have any questions so far?

We will now ask you to answer a number of quiz questions which gives us a better idea how well you understood the instructions. Each correct answer is worth $0.50.

[PRACTICE ROUNDS 2]

Instructions for Round 11–20: Infrastructure Shock Treatments

In the past rounds the infrastructure efficiency declined from one round to the next at a constant amount of 25%. In the following rounds the average decline of the infrastructure efficiency will remain the same, but the actual amount of decline can vary from round to round. This means that in some rounds the decline will be larger than 25% and in some rounds the decline will be smaller than 25%. Before each round begins you will continue to make a decision on how much to invest in the irrigation infrastructure. After all of your investment contributions have been submitted the resulting level of infrastructure efficiency will be displayed and then the round will begin. If you have any questions, please ask them now.

Instructions for Rounds 11–20: Water Availability Shock Treatments

In the past rounds, the amount of water available was 30 cfps each round. In the following rounds, the average amount of water available will remain the same, but the actual amount of water available can vary from round to round. This means that in some rounds the amount of water available will be larger than 30 and in some rounds it will be smaller than 30. If you have any questions, please ask them now.