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Perfect and imperfect real-time monitoring in a minimum-effort game

Cary Deck · Nikos Nikiforakis

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Abstract This paper presents the results from a minimum-effort game in which individuals can observe the choices of others in real time. We find that under perfect monitoring almost all groups coordinate at the payoff-dominant equilibrium. However, when individuals can only observe the actions of their immediate neighbors in a circle network, monitoring improves neither coordination nor efficiency relative to a baseline treatment without real-time monitoring. We argue that the inefficacy of imperfect monitoring is due to information uncertainty, that is, uncertainty about the correct interpretation of a neighbor's actions. Information uncertainty prevents individuals from inferring safely that their group has managed to coordinate from the available information.

Keywords Information uncertainty · Real-time monitoring · Imperfect monitoring · Circle network · Cheap talk

JEL Classification C72 · C92 · D82

1 Introduction

This paper investigates how the ability to monitor the concurrent actions of others affects coordination in a minimum-effort game. The game, which has multiple Pareto-ranked, pure-strategy, Nash equilibria, models situations in which the group outcome depends on the performance of the 'weakest link.' An important feature of

C. Deck
Department of Economics, Walton College of Business, University of Arkansas, Fayetteville, USA
e-mail: cdeck@walton.uark.edu

N. Nikiforakis (✉)
Department of Economics, University of Melbourne, Melbourne, Australia
e-mail: n.nikiforakis@unimelb.edu.au

Table 1 Payoff table for the minimum-effort game

		Minimum effort chosen by any group member						
		7	6	5	4	3	2	1
Effort chosen by individual	7	$1.65	$1.40	$1.15	$0.90	$0.65	$0.40	$0.15
	6	–	$1.50	$1.25	$1.00	$0.75	$0.50	$0.25
	5	–	–	$1.35	$1.10	$0.85	$0.60	$0.35
	4	–	–	–	$1.20	$0.95	$0.70	$0.45
	3	–	–	–	–	$1.05	$0.80	$0.55
	2	–	–	–	–	–	$0.90	$0.65
	1	–	–	–	–	–	–	$0.75

the minimum-effort game is the tension that exists between the secure action and the action required to maximize earnings (see Table 1). The secure choice is to exert minimal effort which maximizes the minimum possible payoff. However, in order to maximize earnings each group member must exert maximal effort.

A large body of experiments on the minimum-effort game has established that when individuals are not able to monitor the actions of others they have difficulty in coordinating at the payoff-dominant equilibrium (see Devetag and Ortmann 2007). The leading explanation for coordination failure is *strategic uncertainty*, that is, uncertainty regarding the actions of others due to the existing tension in incentives. As Van Huyck et al. (1990; p. 247) explain "some subjects conclude that it is too 'risky' to choose the payoff-dominant action."[1]

Strategic uncertainty implies that allowing individuals to monitor the actions of others could lead to improvements in coordination and efficiency. We study the impact of monitoring on coordination under *perfect real-time monitoring* when individuals can observe the actions of all group members in real time; *imperfect real-time monitoring* when individuals can only observe the concurrent actions of their immediate neighbors in a circle network; and *no real-time monitoring* when individuals make their choices with no information about the concurrent choices of others.

Real-time monitoring should not be confused with ex-post monitoring. Ex-post monitoring means that individuals can observe the choices of others *at the end of a period*, that is, after earnings are realized. Based on this information, subjects can adjust their behavior in the following period. While our study is the first to examine the impact of real-time monitoring on coordination, at least four studies have examined the effect of perfect ex-post monitoring. The results are mixed. Berninghaus and Ehrhart (2001) and Brandts and Cooper (2006) find that perfect ex-post monitoring reduces coordination failure. In contrast, Devetag (2005) and Van Huyck et al. (1990) find that perfect ex-post monitoring leads to outcomes which are as inefficient as those under no monitoring.

[1] In line with this explanation, Goeree and Holt (2005) show that outcomes in the minimum-effort game are a function of the cost of effort: the lower the cost is, the more likely groups are to coordinate at the payoff-dominant equilibrium.

Real-time monitoring is common outside the laboratory. Employees working on a team project can usually monitor the progress of their colleagues and adjust their effort accordingly. For example, they can work harder to finish the project earlier if others have been working hard or they can slow down if others appear to be taking longer. Furthermore, the ability to monitor the actions of others in real time removes some of the uncertainty associated with exerting greater effort. For this reason, we expect that, all else equal, real-time monitoring will lead to more efficient outcomes than ex-post monitoring.

A novel feature of our study is the analysis of imperfect monitoring. In naturally occurring settings, it may not be feasible to perfectly monitor all parties involved. This begs the question: Can imperfect monitoring improve efficiency? In principle, strategic uncertainty is greater under imperfect than under perfect monitoring. However, circle networks (like the one we investigate) allow information to flow among individuals. So if, for example, one observes his neighbor choosing a high level of effort, he might conclude that his neighbor's neighbor is also choosing a high level of effort. For this reason, we hypothesize that imperfect monitoring will improve efficiency relative to the condition without real-time monitoring, but lead to outcomes no more efficient than under perfect monitoring.

Our main findings are the following: under perfect monitoring, almost all groups manage to eventually coordinate at the payoff-dominant equilibrium. However, under imperfect monitoring, efficiency is as low as in our baseline treatment without real-time monitoring. This result is perhaps surprising given that individuals are placed in a circle network. We provide evidence that imperfect monitoring does not improve efficiency because it fails to fully eliminate strategic uncertainty. The reason is the existence of *information uncertainty*, that is, uncertainty about the correct interpretation of the available information: if my neighbor is choosing a high level of effort it may be because her neighbor is also choosing a high level, but it may also be that she is signaling to her neighbor to increase her effort.

The paper proceeds as follows. The next section offers a brief review of studies related to the experiment presented in this paper. Section 3 describes the experimental design and procedures. Section 4 presents the results from the experiment. In Sect. 5, we provide evidence that imperfect monitoring fails to eliminate strategic uncertainty fully. Section 6 concludes by discussing the implications of our results and suggesting questions that can be addressed in future research.

2 Literature review

To date there here have been only a few studies on the effects of real-time monitoring. All of these studies have focused exclusively on social dilemmas.

Dorsey (1992) was the first to conduct an experiment using real-time monitoring. In some treatments, subjects were only allowed to increase their contribution over time (a kind of commitment), while in other treatments they were allowed to both increase and decrease their contributions (cheap talk). Dorsey studied the effects of these rules on cooperation by using a linear voluntary contribution mechanism and a provision-point mechanism.[2] The results show that, in general, real time monitoring improves cooperation rates, but that this effect is significant only when a provision point is used and contributions are irrevocable. The latter is presumably due to the fact that the irrevocability of contributions alleviates any concerns about last minute defections.[3]

Kurzban et al. (2008) study behavior in a real-time trust game.[4] The real-time environment allows first movers to evaluate the intentions of the second movers, but also provides incentives for second movers to avoid exploiting the first-movers' trust early in the game. The authors report that while results are mixed, in general, real-time monitoring improves efficiency.

Our experiment contributes towards a better understanding of the properties of real-time monitoring. The fact that we use a coordination game simplifies our analysis relative to previous studies by removing any concerns that individuals may have regarding the existence of free-riding incentives. Note that in our experiment subjects can adjust their intended level of effort both upwards and downwards. Therefore, the decisions during a period are a form of cheap talk. Numerous previous studies have shown that costless pre-play communication improves coordination and increases efficiency in coordination games (see Bangun et al. 2006; Blume and Ortmann 2007; Cooper et al. 1992; Duffy and Feltovich 2002, 2006; Van Huyck et al. 1992). These results provide additional support for our hypothesis that real-time monitoring will have a positive effect on coordination. We are not aware of any studies in which cheap talk occurs only between a subset of the parties involved. In this context, our Neighbors treatment resembles the well-known children's game "Broken Telephone" or "Chinese Whispers".

3 The experiment

3.1 The minimum-effort game

The experiment uses the minimum-effort game of Van Huyck et al. (1990). The basic game is as follows. Let $e_1, \ldots, e_n$ denote the effort level chosen by n players in a group. The dollar payoff for each individual i is

$$\pi_i(e_i, e_{-i}) = a + b * \min(e_i, e_{-i}) - c * e_i$$

[2]The linear voluntary contribution mechanism is analogous to a Prisoner's Dilemma with n players and m strategies (see Gangadharan and Nikiforakis 2009). The provision-point mechanism is similar to the voluntary contribution mechanism. The difference is that unless a certain level of cooperation is reached, the public good is not provided.

[3]Similar results are reported in Goren et al. (2003, 2004), Kurzban et al. (2001) and Duffy et al. (2007). Friedman and Oprea (2010) examine behavior in a continuous-time prisoners' dilemma with flow payoffs and find near-maximal rates of cooperation.

[4]The trust game is a social dilemma in which two players move sequentially. One player makes a money transfer to another which increases total surplus. The second player must then decide whether to return a part of the money he received.

where $e_{-i} = \min(e_1, \ldots, e_{i-1}, e_{i+1}, \ldots, e_n)$ and $e_i \in \{1, 2, \ldots, \bar{e}\}$. In the experiment the payoff function and the parameter values $a = 0.6$, $b = 0.25$, $c = 0.1$, $\bar{e} = 7$ and $n = 6$ are common information.

The parameters used in the experiment generate the payoff matrix seen in Table 1. The game has seven Pareto-ranked, pure-strategy, Nash equilibria in which $e_i = e_j$ for all i and j.[5] The payoff-dominant equilibrium is $e_i = 7$ for all i. The maximum payoff is therefore $\pi_i(7, 7) = 1.65$. However, choosing $e_i = 7$ is risky in the sense that the player might earn as little as $\pi_i(7, 1) = 0.15$. The action that maximizes the minimum possible payment, and thus the safest choice, is $e_i = 1$. Choosing $e_i = 1$ guarantees $\pi_i(1, \bullet) = 0.75$.

3.2 Experimental treatments

Behavior in the basic game is investigated in three experimental treatments. The treatments differ with respect to the information observed by subjects. In the *Baseline* treatment individuals cannot monitor the choices of others before making a decision. The game in Baseline is therefore equivalent to the static game. In the *Neighbors* treatment individuals can observe the concurrent effort choices of their two immediate neighbors in a circle network. Finally, in the *Community* treatment individuals can observe the concurrent effort choices of all five other group members.

Group composition remains the same for the duration of the experiment in all treatments. Despite this, participants cannot identify the other group members as there are always multiple groups in each experimental session.

The game is repeated 10 times. At the beginning of each period, individuals are given 60 seconds in which they can choose their effort level, e_i. The starting value for effort is $e_i = 1$. At any point during the period, effort can be adjusted upwards or downwards subject to the constraint that $1 \le e_i \le 7$. The effort level at the end of 60 seconds is used to determine payoffs. A sample screen from the Neighbors treatment is shown in Fig. 1. As can be seen, subjects can observe the remaining decision time and adjust their own choice using arrows (both on the left edge of the screen). A profit calculator is provided to assist subjects with their decisions (bottom of the screen). The experimental design is summarized in Table 2.

3.3 Information

To focus on the impact of *real-time* monitoring, individuals in all treatments are informed about the final choice of each group member. Therefore, all of the treatments involve ex-post monitoring, and thus our approach for evaluating the positive effects of real-time monitoring is conservative. Apart from the real-time information, at the end of each of the 10 periods, each individual is informed about his payoff from the period. Participants are also given a table with information about their past actions in the experiment and the associated payoffs (see Fig. 1).

[5] The game also has a continuum of mixed-strategy equilibria (see Anderson et al. 2001).

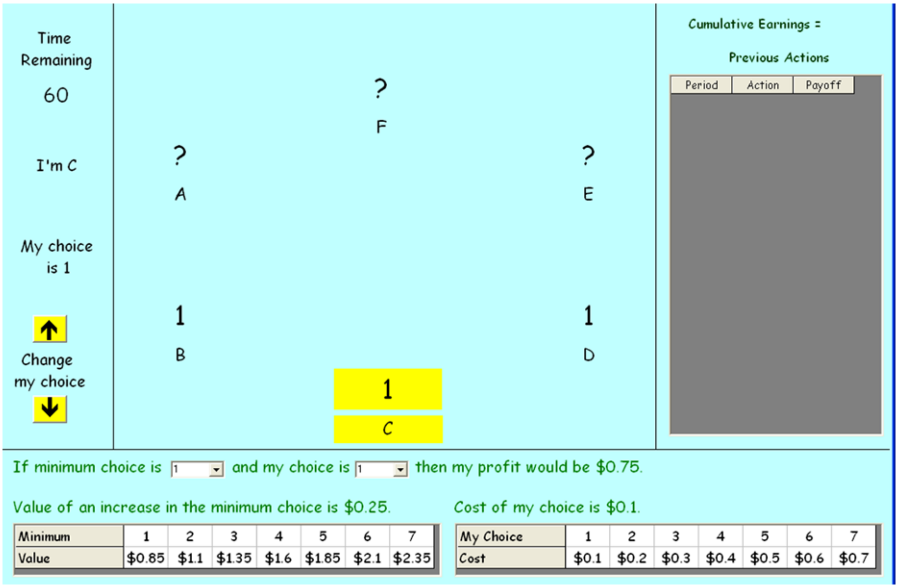

Fig. 1 Screen shot of decision stage (*Neighbors* treatment)

Table 2 Experimental design

Treatment name	Real-time monitoring	Ex-post monitoring	Number of groups	Subjects per group
Community	Perfect	Perfect	10	6
Neighbors	Imperfect	Perfect	10	6
Baseline	None	Perfect	10	6

Real-time monitoring means that subjects can observe the concurrent choices of others; *Ex-post* monitoring means that subjects can observe the actions of others at the end of a period; *Perfect* monitoring means that subjects can observe the actions of all other group members; *Imperfect* monitoring means that subjects can observe the actions of their immediate neighbors in a circle network

The payoff function, the size of the groups, the matching protocol, the number of periods and the information to be received are explicit in the instructions and common knowledge.[6] Note that to simplify the discussion, when discussing monitoring henceforth, we will be referring to real-time monitoring unless otherwise specified.

3.4 Hypothesis

In all three treatments, the Nash equilibrium predictions of the static game are identical. However, the nature of monitoring in each treatment could impact on equilibrium selection.

[6] The experimental instructions, questionnaire, and summary announcements can be downloaded at www.economics.unimelb.edu.au/nnikiforakis.

The Baseline treatment is similar to previous experiments with perfect ex-post monitoring and includes fixed groupings. These factors are expected to have a positive effect on coordination and profitability as compared to previous results obtained using random groupings and no ex-post monitoring (see Schmidt et al. 2003; Van Huyck et al. 1990).

Intuition suggests that perfect monitoring in the Community treatment should improve coordination and efficiency as strategic uncertainty is greatly (if not fully) reduced. This intuition is supported by the empirical evidence from the studies discussed in Sect. 2.

Predicting the effect of imperfect monitoring is less straightforward. Subjects have an intermediate level of information and thus one might expect effort choices to lie somewhere between that in Community and Baseline. At the same time, the effort choice of one's neighbor reflects information about what others are doing and thus one can indirectly monitor everyone in the group. Therefore our *a priori* hypothesis is as follows:

Hypothesis *Efficiency will be higher with perfect monitoring* (*Community*) *than without monitoring* (*Baseline*). *Efficiency with imperfect monitoring* (*Neighbors*) *will be at least as high as without monitoring*, *but not higher than with perfect monitoring*.

3.5 Procedures

One hundred and eighty students from Chapman University participated in the experiment (60 participants per treatment). Students were drawn from the general undergraduate population. Each student took part in only one of the treatments. Sessions lasted approximately forty five minutes on average including instruction time. After reading the instructions and answering a set of control questions which ensured that subjects understood the properties of the game, a summary of the instructions was read aloud. Participants were paid in cash at the completion of the experiment. Participants received a show up payment of $7. Average salient earnings were $10.42.

4 Results

We use four metrics for evaluating group performance in the different treatments: minimum effort, total effort, wasted effort and profit. Table 3 provides data on each measure by group, for all ten periods and for the last five periods. Given our ordered hypothesis, all reported statistical tests are one-sided Mann-Whitney tests. Since each group is an independent observation, each test is based on comparing 10 independent observations for each treatment, unless otherwise noted. Table 4 provides a summary of the treatment comparisons. Our main results are unaffected if one considers behavior across the ten periods or only from the last five periods in the experiment. Unless otherwise noted, the statistical tests below use averages across all ten periods.

Table 3 Group and treatment averages

Treatment	Group	Minimum effort		Total effort		Wasted effort		Average effort	
		Periods		Periods		Periods		Periods	
		1–10	6–10	1–10	6–10	1–10	6–10	1–10	6–10
Baseline	1	5.1	6.4	34.1	39.8	3.5	1.4	1.3	1.5
Baseline	2	1.0	1.0	12.1	12.0	6.1	6.0	0.7	0.7
Baseline	3	5.1	6.0	38.7	40.2	8.1	4.2	1.2	1.4
Baseline	4	1.7	1.2	21.4	18.4	11.2	11.2	0.7	0.6
Baseline	5	5.1	6.2	36.5	41.0	5.9	3.8	1.3	1.5
Baseline	6	1.0	1.0	11.1	6.6	5.1	0.6	0.7	0.7
Baseline	7	2.9	2.8	27.8	22.8	10.4	6.0	0.9	0.9
Baseline	8	1.1	1.0	18.7	16.0	12.1	10	0.6	0.6
Baseline	9	1.0	1.0	14.2	15.2	8.2	9.2	0.6	0.6
Baseline	10	4.0	6.4	33.9	40.0	9.9	1.6	1.0	1.5
	mean	2.8	3.3	24.9	25.2	8.1	5.4	0.9	1.0
Neighbors	1	6.0	7.0	38.5	42.0	2.5	0.0	1.5	1.7
Neighbors	2	1.2	1.2	16.1	15.8	8.9	8.6	0.6	0.6
Neighbors	3	1.0	1.0	8.2	6.6	2.2	0.6	0.7	0.7
Neighbors	4	2.4	3.8	24.4	33.2	10.0	10.4	0.8	1.0
Neighbors	5	5.1	7.0	32.6	42.0	2.0	0.0	1.4	1.7
Neighbors	6	4.0	4.2	30.8	32.0	6.8	6.8	1.1	1.1
Neighbors	7	1.0	1.0	8.6	7.0	2.6	1.0	0.7	0.7
Neighbors	8	4.4	5.8	29.2	34.8	2.8	0.0	1.3	1.5
Neighbors	9	2.6	2.2	22.0	18.4	6.4	5.2	0.9	0.8
Neighbors	10	4.3	6.4	29.2	39	3.4	0.6	1.2	1.6
	mean	3.2	4.0	24.0	27.1	4.8	3.3	1.0	1.1
Community	1	5.2	7.0	31.2	42.0	0.0	0.0	1.4	1.7
Community	2	6.8	6.8	41.5	41.2	0.7	0.4	1.6	1.6
Community	3	4.0	6.4	28.3	38.4	4.3	0.0	1.2	1.6
Community	4	6.7	7.0	40.6	42.0	0.4	0.0	1.6	1.7
Community	5	5.2	7.0	34.3	42.0	3.1	0.0	1.4	1.7
Community	6	5.3	7.0	33.8	42.0	2.0	0.0	1.4	1.7
Community	7	3.7	6.4	24.5	38.4	2.3	0.0	1.2	1.6
Community	8	6.3	7.0	37.9	42.0	0.1	0.0	1.6	1.7
Community	9	1.0	1.0	13.2	13.2	7.2	7.2	0.6	0.6
Community	10	1.4	1.6	16.4	16.2	8.0	6.6	0.7	0.7
	mean	4.6	5.7	30.2	35.7	2.8	1.4	1.2	1.4

Table 4 Non-parametric comparison of treatments

Periods	Minimum effort		Total effort		Wasted effort		Average effort	
	All	Last 5	All	Last 5	All	Last 5	All	Last 5
Community vs. Neighbors	0.051	0.041	0.065	0.029	0.061	0.089	0.076	0.048
Neighbors vs. Baseline	0.323	0.143	0.381	0.056	0.014	0.182	0.145	0.225
Community vs. Baseline	0.017	<0.01	0.128	<0.01	<0.01	0.163	0.010	<0.01

Entries are p-values from one-sided, Mann-Whitney tests. Alternative assumptions are that Community outperforms Neighbors, Neighbors outperforms Baseline, and Community outperforms Baseline. Each test is based upon $n_1 = n_2 = 10$ observations, where an observation is an average within a group over the stated time interval

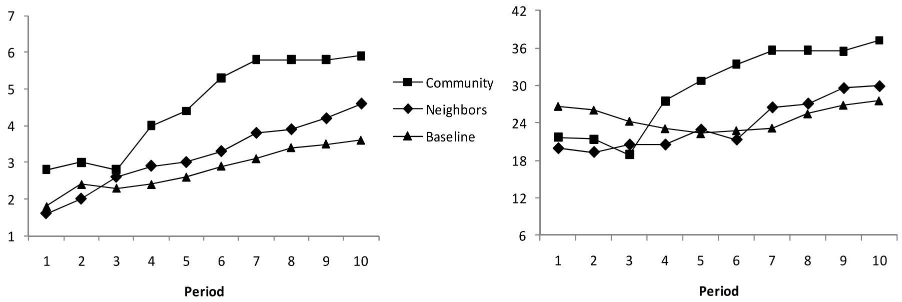

Fig. 2 Comparison of effort in each treatment across periods *Panel A* minimum effort *Panel B* total effort

4.1 Minimum and total effort

The left panel of Fig. 2 presents the average minimum-effort level in each period for every treatment. The right panel of Fig. 2 presents the average total effort in each period. Three patterns from these figures are noteworthy.

First, imperfect monitoring increases neither the minimum nor the total effort level relative to the Baseline. This is somewhat unexpected given that individuals are placed in a circle network. The performance is not significantly different for either metric (p-values 0.323 and 0.381 for minimum effort and total effort, respectively).

Second, in contrast to imperfect monitoring, perfect monitoring facilitates coordination at the payoff-dominant equilibrium. Eight of the ten groups managed to coordinate at the payoff-dominant equilibrium.[7] The minimum level of effort is significantly higher in Community than in either Baseline or Neighbors (p-values 0.017 and 0.051, respectively). The difference in total effort between Community and Neighbors is significant (p-value = 0.065). The difference in total effort between Community and the Baseline is marginally insignificant (p-value = 0.128).

[7] In both instances where a Community session did not coordinate at the payoff-dominant equilibrium, the outcome appears to be due a single individual in the group who would decrease their effort shortly before the end of the period. This behavior demonstrates the fragility of coordination in minimum effort games.

Third, effort levels tend to increase over time in all three treatments. This can in part be explained by the fixed matching and the revelation of individual effort levels at the end of the period. The increase in the minimum effort level is significant in all treatments based on a Spearman test (p-values < 0.01). The upward trend could suggest that groups in the Baseline and the Neighbors treatment would perhaps eventually coordinate on the payoff-dominant equilibrium if the experiment was to last longer. The aggregate information presented in Fig. 2, however, masks the considerable between-group variation in these treatments.

Figure 3 presents the evolution of minimum effort separately for each group. Five of the ten groups in the Baseline treatment were able to coordinate on the payoff-dominant equilibrium after steady gradual improvements. Of the remaining five groups, four quickly collapsed and remained at (or near) the lowest effort level. This provides further evidence that perfect ex-post monitoring does not necessarily lead to coordination at the payoff-dominant equilibrium. In the Neighbors treatment, only four of the ten groups managed to coordinate at the payoff-dominant equilibrium. Of the remaining six groups, five collapsed at the lowest effort level. This finding suggests that extending the duration of the experiment would not necessarily lead to further increases in minimum and total effort. Result 1 summarizes the main findings from this subsection.

Result 1 *Minimum and total effort are highest under perfect monitoring* (*Community treatment*). *Imperfect monitoring* (*Neighbors treatment*) *increases significantly neither the minimum effort nor the total effort relative to the Baseline treatment without real-time monitoring*.

4.2 Wasted effort and profit

Despite the fact that the minimum effort level in the Neighbors treatment is similar to that in the Baseline treatment, it is possible that imperfect monitoring reduces coordination failure (i.e. $e_i \neq e_{-i}$ for some i). To measure the extent of coordination failure we define *wasted effort* as $WE = \sum_{i=1}^{n} e_i - n * \min\{e_i, e_{-i}\}$. Average wasted effort is highest in Baseline (8.05) followed by Neighbors (4.76) and Community (2.31). Using group-level observations averaged across all periods, the difference between Community and Baseline is significant (p-value < 0.001) as are the differences between Community and Neighbors (p-value $= 0.061$) and Baseline and Neighbors (p-value $= 0.014$, respectively). It is interesting to note that, the reduction in wasted effort is manifest immediately. Wasted effort in the first period is highest in Baseline (15.90) followed by Neighbors (10.40) and Community (5.10) (all pairwise comparisons, p-value < 0.015), despite there being no statistical difference between any of the three treatments in terms of minimum effort.[8]

Profits in the experiment reflect the minimum effort within a group, as well as wasted effort. Given that imperfect monitoring reduces significantly wasted effort, but

[8] As shown in Table 4, wasted effort is not statistically different between the Baseline and either of the other two treatments, in the second half of the experiment. This is due to the large variance in wasted effort in the Baseline treatment as some groups managed to coordinate(at either the maximum or minimum effort level), while other groups did not.

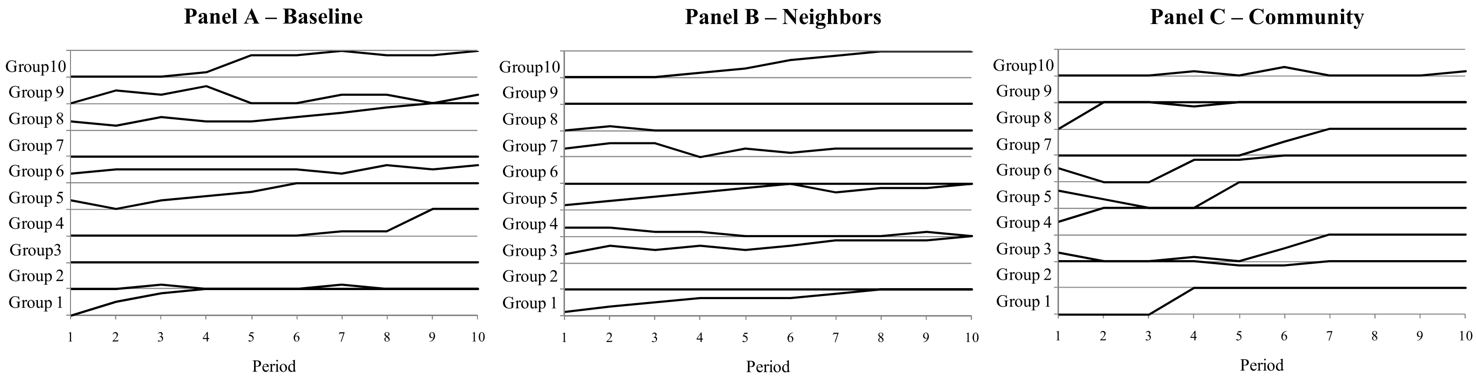

Fig. 3 Minimum effort by group. *Panel A*—Baseline *Panel B*—Neighbors *Panel C*—Community. Each row indicates the behavior of a group. The height of each row indicates the minimum effort of the group at the end of the period. Minimum effort ranges from low (1) to high (7). For example, the minimum effort at the end of the first period in Group 1 in the Baseline treatment is 1; thereafter, it increased steadily until it reached the highest possible value in period 4 never to decrease until the end of the experiment

fails to raise minimum effort, it is interesting to see whether profits are higher in the Neighbors treatment than in the Baseline treatment. Average profit per subject was \$12.37 in the Community treatment, \$10.00 in the Neighbors treatment, and \$8.59 in the Baseline. If a group coordinated on the payoff-dominant outcome in every period then each subject would have earned \$16.50. The worst possible payoff outcome is where one person chooses the minimum effort while everyone else chooses the maximum effort every period resulting in an average payoff of \$2.50. Therefore, efficiency measured as the percentage of possible gains achieved was 71% in Community, 53% in Neighbors, and 45% in the Baseline.[9] Average profit is significantly higher in the Community treatment than in either the Baseline or the Neighbors treatment (p-values = 0.010 and 0.076). Despite the monitoring opportunities that exist in Neighbors, profit is not statistically higher than it is in Baseline (p-value = 0.145). Result 2 summarizes the main findings from this subsection.

Result 2 *Profits are highest under perfect monitoring (Community treatment). Despite reducing wasted effort, profits are not significantly higher under imperfect monitoring (Neighbors treatment) relative to the Baseline treatment without real-time monitoring.*

4.3 Speed of Pareto improvement

One pattern that distinguishes the Neighbors from the Baseline treatment is the speed at which efforts increase across periods; the rate of increase from a low minimum effort to the optimal level is much faster in the Neighbors treatment (Fig. 3). Using as the unit of measurement the number of periods it took a group to go from the lowest minimum effort to the maximum level (conditional on the maximum level being obtained by period 10), the difference is statistically significant (p-value $<$ 0.10, based upon the 4 and 5 groups that coordinated at the optimal level in Neighbors and Baseline in the last period, respectively). A similar phenomenon occurs in the Community treatment where it never takes more than three periods to go from the lowest minimum effort observed in the group to everyone providing full effort.[10]

5 Imperfect monitoring and information uncertainty

In this section, we explore the reasons why imperfect monitoring fails to produce a Pareto improvement. Consider the following example of a group that failed to coordinate at the payoff-dominant equilibrium in the Neighbors treatment. As can be seen

[9] Efficiency is calculated as (realized profit—minimum possible profit)/(maximum possible profit—minimum profit) or in this case (realized profit—\$2.50)/\$14. Since the minimum and maximum profit are the same across treatments the same statistical results hold for efficiency that hold for profit.

[10] It is interesting to look at the rapid increase in minimum effort in the Community treatment. In Group 1, five of the subjects had an effort level of 7 within 11 seconds of the start of the first period. By the twentieth second, when one subject (subject C) still had not increased his effort above 1, many of the other subjects dropped their own effort. This pattern repeated in periods 2 and 3, but in period 4 subject C increased his effort to 7 after 10 seconds and the group coordinated at the optimal outcome in all subsequent periods. Similar patterns were observed in other Community groups that experienced sharp increases in minimum effort from one period to the next.

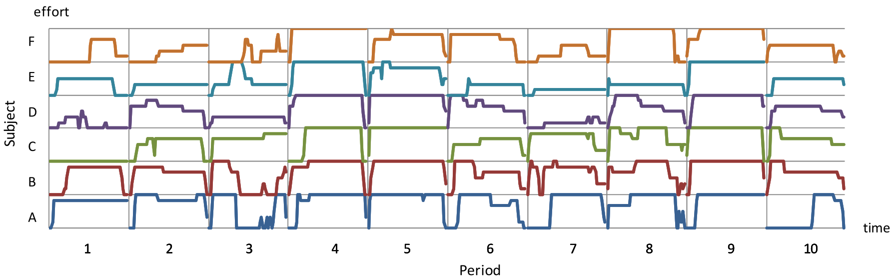

Fig. 4 Real-time effort by subject for group 2 in neighbors treatment. Each row indicates the behavior of a single individual (A-F). The height of each row indicates the level of effort from low (1) to high (7). Vertical lines indicate the start of a period. For example, Subject A chose an effort of 6 in period 1 and started period 2 by choosing a level of 7 for about 20 seconds. Subject C choose an effort of 1 in period 1. Each individual could see the behavior of the person 'above' him and 'below' him. The subject at the bottom of the figure could see the person on the top of the figure and vice versa

in Fig. 4, this group nearly managed to coordinate at the payoff-dominant equilibrium in periods 4, 5, and 9. In particular, in period 4, subjects had coordinated at the high-effort level. However, with 3 seconds remaining, one of the subjects (subject C) reduced his effort. The reduction triggered a strong reaction by C's neighbors (subjects B and D), which in turn caused a reaction by their neighbors (subjects A and E). In just three seconds, four subjects dropped from an effort of 7 to an effort of 1 (subject A was lowering effort when time expired, while subject F—the person furthest from subject C—did not have enough time to react). A similar situation occurred in periods 5 and 9.[11]

The example above suggests an explanation why imperfect monitoring fails to improve coordination in our experiment: *information uncertainty*. Individuals cannot *safely* infer whether their group has coordinated at a given level of effort from the actions of their neighbors. A high level of effort by a neighbor can be interpreted in two ways. On the one hand, it may be interpreted as evidence that 'distant neighbors' are also choosing high effort levels. On the other hand, it may be interpreted more pessimistically, as a signal to a distant neighbor exerting low effort to increase his effort. Therefore, uncertainty regarding the actions of 'distant' group members persists despite them being placed in a circle network.

It is possible that the interpretation of the available information under imperfect monitoring depends on past outcomes. If a group failed repeatedly to coordinate successfully in the past (like the group of subject C in the example above), then a neighbor's high level of effort during a period, may more likely be interpreted as a signal to distant neighbors rather than as evidence that distant neighbors are choosing high

[11] This example is not unique. The likelihood that an individual reduces his effort in the last 10 seconds of a period when the group members observed by him have coordinated at level of effort other than the minimum is substantially higher in the Neighbors treatment. In particular, eight of the ten groups in the Neighbors treatment experienced at least one such reduction in effort in the second half of the experiment (some of them experienced multiple such reductions). The same happened in only two of the ten groups in Community. In most cases, the sudden reduction in effort led others to reduce their effort too in both treatments.

levels of effort. Thus, past failed attempts at coordination at high effort levels could make individuals less likely to match a neighbor's higher level of effort. This would make escaping coordination failure difficult under imperfect monitoring. By contrast, under perfect monitoring, the absence of information uncertainty may allow groups to overcome previous failed attempts at coordination. Based on this reasoning, we offer the following conjecture.

Conjecture *The presence of information uncertainty under imperfect monitoring makes escaping coordination failure more difficult than under perfect monitoring.*

In order to provide some support for our conjecture, Fig. 5 presents the evolution of average effort *within* periods in each treatment. The figure reveals two interesting facts. First, in periods 1–5, average effort appears to decline sharply 10 seconds before the end of the period in both Neighbors and Community. To determine whether this decline is significant, we compare average effort in each group across the first five periods, 10 seconds prior to the end of the period and at the end of the period. We find that there is a significant decrease in the average effort in both Community and Neighbors (p-value $= 0.005$ in both treatments, two-tailed Wilcoxon signed-rank test). In fact, the average effort 10 seconds before the end of a period is higher than the end-of-period effort in *all groups* in both the Community and the Neighbors. However, in Baseline there is no change in average effort during the last 10 seconds of a period in the first half of the experiment (p-value $= 0.247$, two-tailed Wilcoxon signed-rank test) as one might have expected since no information is being revealed during this time period. The second interesting fact is that the sudden drop in effort prior to the end of the period persists in the second half of the experiment in the Neighbors treatment (as can be seen in Panel B of Fig. 5), while it seems to largely disappear in the Community treatment. The reduction in effort in the last 10 seconds of a period in the second half of the experiment is significant in Neighbors (p-value $= 0.008$, two-tailed Wilcoxon signed-rank test), but neither in Community nor in Baseline (p-values $=$ 0.324 and 0.603, respectively, two-tailed Wilcoxon signed-rank test). The average effort 10 seconds before the end of a period is higher than the end-of-period effort in 8 out of 10 groups in the Neighbors treatment, and only in 2 out of 10 groups in the Community treatment. These findings support our conjecture. Result 3 summarizes.

Result 3 *Effort decreases significantly a few seconds prior to the end of a period in the first half of the experiment, under both perfect and imperfect monitoring. This pattern persists in the second half of the experiment under imperfect but not under perfect monitoring.*

6 Conclusion

This paper presented the results from an experiment investigating whether real-time monitoring can improve coordination in the minimum-effort game. The results show that the form of monitoring is critical. While perfect monitoring leads to significant Pareto improvements relative to a control treatment without real-time monitoring, imperfect monitoring does not. When monitoring is imperfect (that is, when individuals

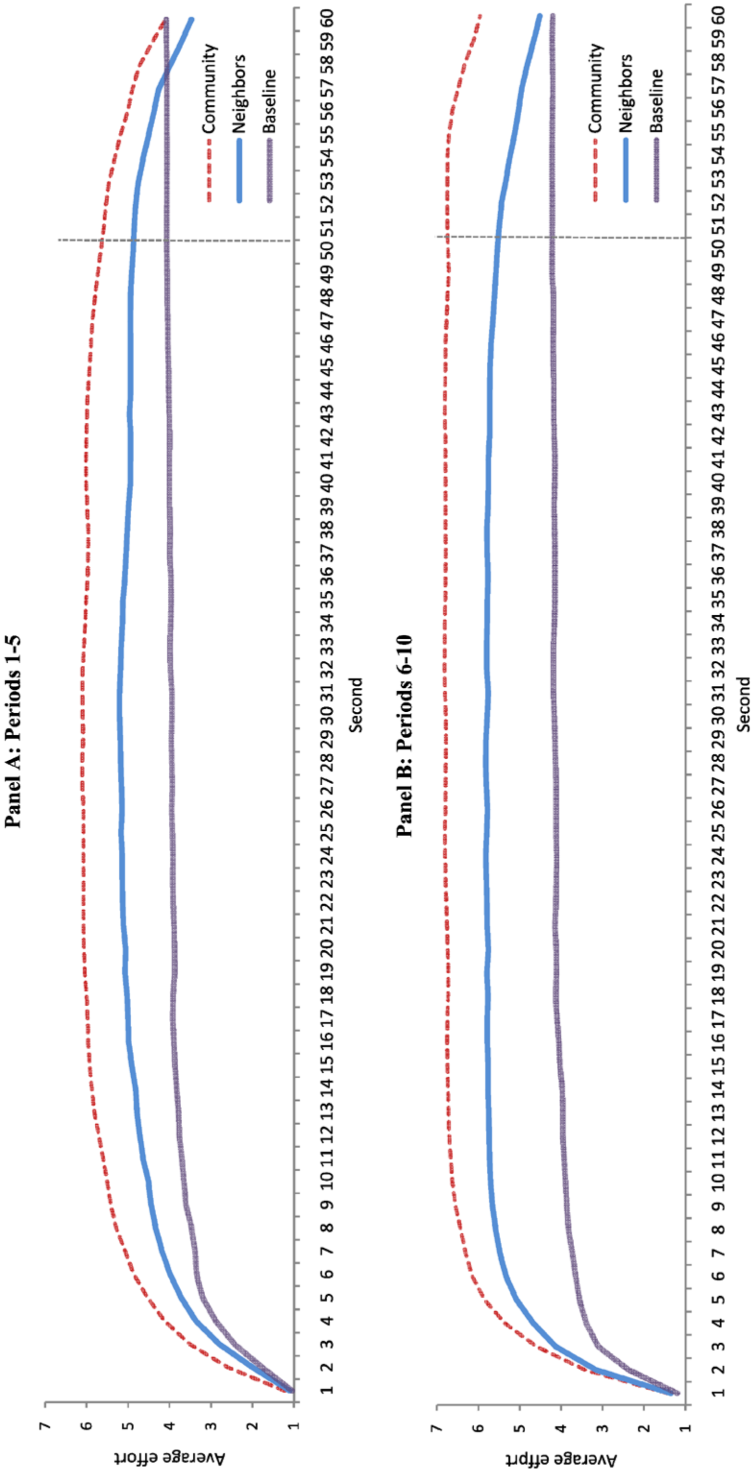

Fig. 5 The evolution of average effort *within* periods across treatments. The vertical dashed line indicates the start of the last 10 second within a period

can only observe the choices of a subset of their group members), 50% of the groups converged to the equilibrium with the lowest effort similar to the rate observed in the control treatment with no monitoring, despite the fact that individuals are placed in a circle network that allows the flow of information across the network. In contrast, almost all groups managed to coordinate at the payoff-dominant equilibrium under perfect monitoring.

The data suggests that the inability of groups to overcome coordination failure under imperfect monitoring can be attributed to information uncertainty, that is, uncertainty regarding the correct interpretation of a neighbor's choice. A high effort level may signal that a distant neighbor is also exerting a high effort level, but it could also be a signal for distant neighbors to increase their effort. Information uncertainty implies that there is still considerable uncertainty regarding how other group members will make their decisions. The result is that, a few seconds before the end of a period, many groups experience a 'panic' and a sudden reduction in effort. Some of the groups managed to overcome these panics, but most did not. These panics are akin to bank runs where concerns about the actions and the concerns of others can destabilize otherwise stable situations. By contrast, the absence of information uncertainty with perfect monitoring implies that monitoring mitigates strategic uncertainty and enabled groups to eventually coordinate at the payoff-dominant equilibrium.

Our results are similar to those in Chaudhuri et al. (2009) who investigate the use of (free-form) advice as a coordinating device in the minimum-effort game. The game is played by non-overlapping generations of players who, after they play the game, pass on advice to their successors who take their place in the game. The results show that coordination is most likely to result when the advice is made public *and* distributed in a manner that makes it common knowledge. Our results are also reminiscent of the bullwhip effect in experiments in supply-chain management (e.g., Croson and Donohue 2006). In these experiments, individuals are placed in a linear network and must coordinate their actions in order to maximize their earnings. Information about downstream players reduces, but does not eliminate, the bullwhip effect which is a form of coordination failure.

The fact that imperfect monitoring is arguably more common than perfect monitoring outside the laboratory together with its surprising inability to help reduce coordination failure suggests that it would be interesting for future studies to investigate its impact further, in a range of different environments. First, it will be interesting to explore whether imperfect monitoring can improve coordination and efficiency in different network structures from the one explored here. Second, it would also be interesting to explore whether imperfect monitoring continues to fail to improve outcomes when individuals can commit to their level of effort (i.e. when effort is not cheap talk).[12] Third, future studies could examine whether imperfect monitoring fails to improve coordination and bring forth Pareto improvements in coordination games

[12] To that end, Berninghaus and Ehrhart (1998) is a related study. They explore the impact of decreasing the length of each period (and thus increasing the number of periods) on coordination in a minimum-effort game. Subjects observe the minimum effort in their group at the end of each period, that is, after they have chosen their level of effort. The decreased length of a period implies that subjects receive feedback more frequently in the experiment. They find that decreasing the length of a period from 90 seconds to 10 seconds has a positive effect on the likelihood groups coordinate at the payoff-dominant equilibrium.

where outcomes are not determined by the weakest link. Finally, it will be interesting to study the impact of imperfect monitoring in different games such as social dilemmas.

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