A Minimum Effort Coordination Game Experiment in Continuous Time*

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Abstract

We conduct an experiment on a minimum effort coordination game in a (quasi-)continuous time-frame, where effort choices can be switched freely during a 60-second period. The cooperation levels of the continuous time treatments are not significantly different from the discrete time treatments. Providing subjects with the information on the effort choices of all group members increases the average effort level in continuous time only. The minimum effort level in continuous time with full information feedback is also substantially higher than that with limited information feedback, but the difference is statistically insignificant. With limited information feedback, subjects rarely coordinate to increase their efforts simultaneously to change the group minimum within a period. Our findings imply that continuous time games are not behaviorally equivalent to infinitely repeated discrete time games.

Keywords: Continuous time, Minimum effort game, Coordination game, Information, Laboratory experiment

JEL Classification: C72 C92 D70

1 Introduction

The majority of game theoretic models are in discrete time, where a single action is taken in each round. Accordingly, when these games are tested in experiments, a subject can make only one decision before the end of each period. In reality, though, decisions can often be made and

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changed asynchronously and swiftly — that is, in continuous time. Are discrete time models innocuous simplifications of these situations? Are the theoretical discrepancies between discrete and continuous time models (see Simon and Stinchcombe, 1989) significant in experiments?

This paper aims to answer these questions for a specific game: the minimum effort coordination game. Subjects in previous laboratory experiments of this game (Van Huyck et al., 1990; Devetag and Ortmann, 2007; Camerer, 2003) typically fail to coordinate on the efficient outcome, particularly when the group size gets large. Is the failure to coordinate an artifact of the discrete time setting? Would allowing subjects to interact in continuous time restore efficient coordination? Is the difference (or the lack thereof) in coordination between discrete and continuous time settings related to the information structure? These questions are important for two reasons. First, it helps us to understand the minimum effort coordination game in its own right. This game is often used to model teamwork (in which a member's extra effort cannot completely make up for her teammate's shirking), a pervasive and important form of economic organization. Exploring the implications of discrete and continuous time modeling allows us to assess the applicability of this game to many real-life situations. Second, and more broadly, the minimum effort game is a stylized coordination game. It possesses features that are of interest for coordination games in general: multiple Pareto-ranked equilibria, the selection between the payoff-dominant (i.e. efficient) equilibrium and the risk-dominant equilibria, and the existence of a potential function (see Goeree and Holt, 2005). Therefore, experimental results regarding the minimum effort game in continuous time will be informative for a wide range of coordination games as well.

Previous laboratory experiments have shown differences in subjects' behavior between continuous time and discrete time. Friedman and Oprea (2012) conduct an experiment on the continuous time prisoner's dilemma and find median cooperation rates above 80% in their continuous time treatment, as opposed to nearly zero in their discrete time treatment. Recently, Bigoni et al. (2015) confirmed these high cooperation rates in the continuous time prisoner's dilemma, along with finding other behavioral differences (such as the response to stochastic termination rules) in discrete and continuous time. However, the ability to sustain coordination in continuous time does not extend across games. In a four-player public goods experiment (Oprea et al., 2014), group contributions are not higher in continuous time unless free-form chat is available. Likewise, in a twelve-player Hawk-Dove game (Oprea et al., 2011), cooperation is not improved in the continuous time treatment. In light of these results, one may wonder how a continuous time set up would affect behavior in the minimum effort game, which, unlike these previously studied games, is a common interest game. On that note, Deck and Nikiforakis (2012) conduct an experiment on the minimum effort game in continuous time, but the payoffs in their experiment are determined only by the choices at the end of a period. As such, under their full information feedback treatment ("real-time monitoring" in their terminology), switching to a higher effort level before the end of the period is costless. In this regard, how individuals would behave when actions are consequential in continuous time remains an open question.

To this end, we conduct an experiment on a minimum effort coordination game in (quasi-) continuous time, in which subjects are able to change their effort levels every 0.3 seconds (or three or four times per second).[1] We expect that subjects will reach a higher cooperation level in our continuous time treatment compared with our discrete time treatments. This is because, when the group is stuck in an inefficient low-effort equilibrium, one or two subjects may increase their effort temporarily. If other group members do not follow, the ability to switch effort quickly in continuous time means that these subjects can switch back to the group minimum with only a loss of a few cents. Thus the cost of unilaterally increasing effort is relatively small in continuous time. If other players follow, the group can reach a more efficient equilibrium and enjoy a higher payoff in the rest of the period (or go even further up). Moreover, previous experiments have shown that the payoff-dominant equilibrium can be reached when a minimum effort game is repeated for sufficiently many times (Berninghaus and Ehrhart, 1998). Since a continuous time (coordination) game can sometimes be theoretically approximated by a sequence of discrete time games with the grid length going to zero, one may expect that the repetition will foster cooperation.

Apart from the timing protocol, we also investigate the effect of the information structure on the equilibrium selection. In discrete time experiments on the minimum effort game, it was standard to provide subjects only with information about the group minimum effort level (e.g., Devetag and Ortmann, 2007; Van Huyck et al., 1990; Brandts and Cooper, 2006a). When more information is provided in discrete time, the effect on coordination is mixed (e.g. Brandts and Cooper, 2006b; Devetag, 2005; Berninghaus and Ehrhart, 1998; Van Huyck et al., 1990; Engelmann and Normann, 2010). However, in continuous time, it is plausible that players can observe not only the cooperation outcome but also the behavior of their opponents. Can this information help? Intuitively, one would expect that full information feedback should enable subjects to coordinate on simultaneous increases in effort levels. Alternatively they can signal their intention to move to a higher effort equilibrium by setting their own effort above the group minimum. Either way, it should be easier to reach the payoff-dominant equilibrium.

The findings from the experiment, however, contradict our expectations. The timing protocol has no effect on the cooperation levels. Regardless of the type of information feedback, there are no statistically significant differences in the cooperation levels (either measured by the group minimum effort or by the group average effort) between the continuous time and discrete time treatments. The impact of the type of information feedback is mixed. In continuous time, the group average effort is significantly higher when full information feedback is provided, but the increase in the group minimum effort is statistically insignificant. Meanwhile, providing more information makes no difference in the discrete time setting.

We probe the reasons behind our findings by comparing the within-period performance of the two continuous time treatments. Although the difference in the group minimum level is statistically

[1] No experiment is in continuous time in the strictest sense, as there are always software delays. For brevity, quasi-continuous time will be referred to as continuous time for the rest of this paper.

insignificant between the two continuous time treatments, there are more upward switches of the group minimum in the full information treatment. This result indicates that, under full information feedback, subjects signal by setting their effort level above the group minimum, which can induce increases in the group minimum effort level. Unfortunately, the average size of these increases is small. With limited information feedback, it is difficult to coordinate on a simultaneous increase in effort levels. As a result, the upward switches of the group minimum are more likely to occur at the start of a period than within a period, as the former provides a natural focal point for coordination. Meanwhile, subjects under limited information feedback have to increase their efforts more often for each upward switch of the group minimum. One interpretation of these observations is that continuous time with full information feedback is a form of costly and limited communication. When this channel is blocked, increasing individual effort is ineffective in increasing the group minimum.

Our findings have several important implications. First, continuous time games are not always behaviorally similar to infinitely repeated games. We find no difference between our continuous time and discrete time treatments, but the discrete time minimum effort coordination game has been shown to reach the payoff-dominant equilibrium as long as the number of repetitions is sufficiently large (Berninghaus and Ehrhart, 1998). In addition, the focal point provided by the start of each period can lead to a significant "restart effect". Second, how payoffs are determined in a continuous time set up affects the coordination outcome. When payoffs are accumulated throughout each period, we find no significant difference between our continuous time and discrete time full information treatments. On the other hand, when Deck and Nikiforakis (2012) determined payoffs only by the last choice in each period, allowing subjects to constantly monitor the effort levels of the other group members does improve the cooperation level. Third, the performance in continuous time depends on the complexity of the game. While a continuous time setting can improve cooperation levels in a two-player prisoner's dilemma (Bigoni et al., 2015; Friedman and Oprea, 2012), its effect is much weaker in our six-person minimum effort game, as it has been in several other more complicated games (e.g., Oprea et al., 2011, 2014).

2 Experimental Design and Implementation

This paper studies the effect of continuous time on the minimum effort game. To be consistent with previous studies, we adopt the payoff matrix used by most minimum effort experiments since Van Huyck et al. (1990). Effort choices available to subjects are integers from 1 to 7.[2] Each player's payoff function is defined as

$$\pi_i(\sigma_i, \sigma_{-i}) = 0.6 + 0.1 * \min\{\sigma_i, \sigma_{-i}\} - 0.1 * (\sigma_i - \min\{\sigma_i, \sigma_{-i}\}) \tag{1}$$

[2] To avoid confusion or biasing of decision making, the word "effort" is replaced with "value" in the instructions.

Table 1: Payoff Table of the Minimum Effort Game

	Lowest Effort Chosen Within Group						
Your Choice of Effort	7	6	5	4	3	2	1
7	130	110	90	70	50	30	10
6	—	120	100	80	60	40	20
5	—	—	110	90	70	50	30
4	—	—	—	100	80	60	40
3	—	—	—	—	90	70	50
2	—	—	—	—	—	80	60
1	—	—	—	—	—	—	70

where σ_i is the action chosen by player i, σ_{-i} denotes $(\sigma_i, ..., \sigma_{i-1}, \sigma_{i+1}, ...\sigma_n)$.

Subjects' point earnings are shown in Table 1. Each cell on the diagonal of the payoff table is a Nash equilibrium payoff. The payoff-dominant equilibrium is when everyone chooses effort 7. The risk-dominant equilibrium is when everyone chooses effort level 1.

In our paper, we study two treatment dimensions: timing protocol (continuous versus discrete) and information feedback (minimum versus full). For the rest of this paper, we will refer to our four treatments as:

ConMin Continuous time-frame with information on the group minimum effort level only;

ConFull Continuous time-frame with information on the effort level chosen by each group member;

DisMin Discrete time-frame with information on the group minimum effort level only;

DisFull Discrete time-frame with information on the effort level chosen by each group member.[3]

As explained in the introduction, with respect to the timing protocol, the ConMin treatment and the ConFull treatment are expected to reach higher cooperation levels compared with the DisMin treatment and the DisFull treatment respectively, because the cost of setting effort levels above the group minimum is reduced in continuous time. With respect to the type of information feedback, the ConFull treatment is expected to further improve the cooperation levels achieved in the ConMin treatment, because the timing of effort increases can be coordinated more easily and subjects can signal effort increases by setting higher effort levels. The differences between the DisFull treatment and the DisMin treatment are uncertain as previous experimental findings on minimum effort game in discrete time are mixed (e.g. Brandts and Cooper, 2006b; Devetag, 2005; Berninghaus and Ehrhart, 1998; Van Huyck et al., 1990; Engelmann and Normann, 2010).

In the two continuous time treatments, subjects can change their own effort levels as many times as they wish during a period. The point earnings for each period are flow payoffs accumulated

[3]See Appendix B for the experimental instructions for the ConFull treatment.

by the time subjects spend playing an action. In the discrete time treatments, neither the group minimum nor effort levels picked by other subjects are revealed until the end of a period. To ensure the discrete time treatments are consistent and comparable with the continuous time treatments, subjects can still change effort levels freely before the 60-second-period ends but only the last effort level before the end of the period is taken into account to calculate the payoffs for that period.

The experiment consists of ten consecutive periods. Each period lasts 60 seconds and the period length is kept constant across treatments.[4] The 60-second period is long enough for subjects to respond to effort level changes and not too long to possibly bore subjects. Before the start of each period, subjects are required to choose their initial effort levels and click the "OK button".[5]

Each group in the experiment consists of six subjects. In most of the previous discrete time studies using the same payoff table as in Table 1, coordination failed at group sizes larger than five (Camerer, 2003; Engelmann and Normann, 2010). Our group size of six should be large enough for coordination to fail in the two discrete time treatments, leaving room for the two continuous time treatments to improve the coordination towards higher levels. Group composition remains fixed throughout the entire session. No communication between subjects is allowed. Ten groups participate in each treatment and in total, the experiment involves 240 subjects.

The experiment is programmed and conducted with the z-Tree software package (Fischbacher, 2007). In the experiment, subjects are able to change their effort levels every 0.3 seconds, or three or four times per second.[6] A screenshot of the program interface is shown in Figure 1. The left side displays the payoff table. Actions can be changed freely by clicking the purple buttons on the left. The row corresponding to the subject's chosen action and the column corresponding to the group minimum are both highlighted in different colors. Accumulated earnings are displayed in red near the top right corner. Changes in the subject's payoff are recorded in the table at the middle part of the right. A new row is added whenever the group minimum or the subject's own chosen effort level is changed. In the ConFull treatment, effort levels chosen by all group members are listed below the accumulated earnings as in Figure 1, while the list is omitted in the ConMin treatment. In the two discrete time treatments, the right side of the screen is not shown and only the row of subject's own effort level is highlighted.

[4]The experiment has ten 60-seconds periods instead of one 10-minute period. This is to avoid the persistent effect of mistakes in the first few minutes, especially because the coordination level can be highly sensitive to the effort level at the beginning of a period. We do not offer unpaid periods for practice, so that subjects cannot signal their intention to choose high effort levels (in the paid period) without incurring any costs in the practice period.

[5]We let subjects pick their initial effort levels because the initial effort levels cannot be randomly assigned by our program without affecting the results. If some subjects choose to match the group minimum as closely as possible in a period, the minimum effort in the period will be the same as the initial minimum effort randomly picked by our program.

[6]The visual response time, measured by how long it takes to click a mouse immediately when a dot appears on a screen, is 0.2 seconds for an average person (Sanders and Sanders, 2013), while some trained athletes can reach nearly 0.11 seconds (Lipps et al., 2011). Although the refresh interval in our experiment is slightly longer than the average response time, we believe that the delay should not affect decision making. Even if subjects do not experience the experiment setting as a continuous time frame, thinking about the strategy and moving the mouse to the right position as required in our experiment will take more time than an immediate visual response.

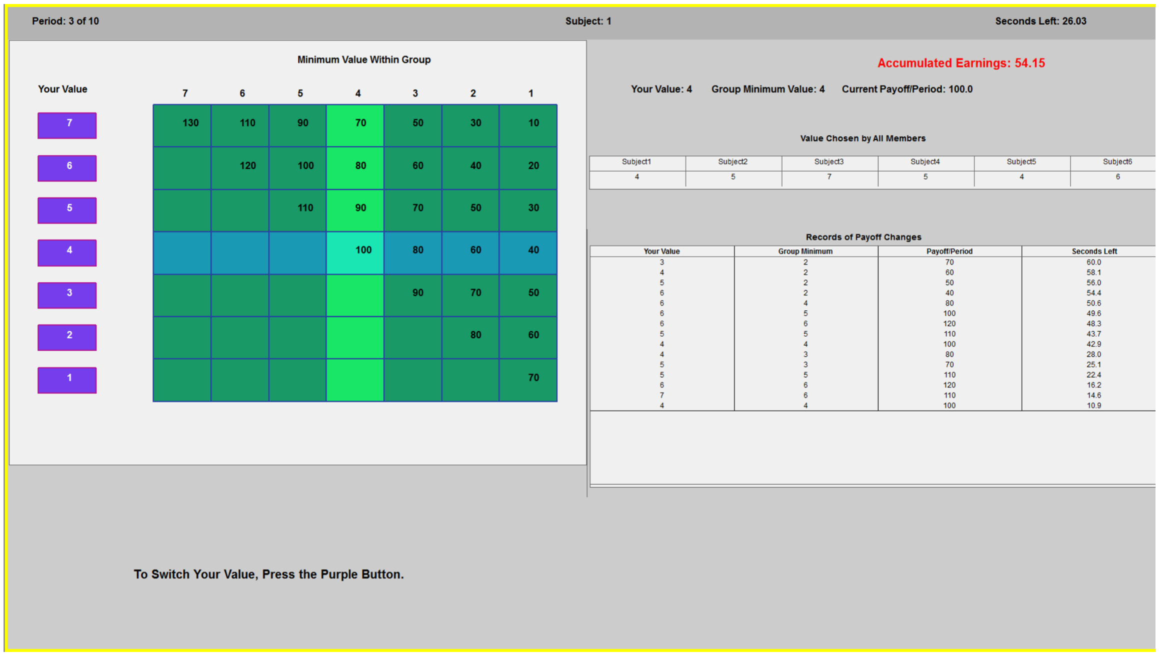


Figure 1: Program User Interface

After each period, subjects are shown a history table. The history table records the average effort level, the group average minimum effort level, along with the accumulated points and its Australian dollar equivalent for all previous periods. In the discrete time treatments, the effort levels shown are the levels last picked instead of the accumulated average. In full information treatments, average effort levels of all members are also listed.

Sessions were conducted during April 2015 to June 2015 at the Experimental Economics Laboratory at the University of Queensland. Subjects were randomly recruited from the ORSEE experimental database managed by the School of Economics (Greiner, 2015). Participants are mostly undergraduate students from Business, Economics, and Law Faculty. None of the subjects have participated in a minimum effort experiment previously. Each subject is given written instructions which are read aloud to ensure common knowledge. Subjects are required to successfully complete a quiz consisting of ten (continuous time treatments) or six (discrete time treatments) questions before the experiment starts. To guarantee full understanding of the rules of the experiment, subjects are not allowed to move on to the next question unless they have entered the correct answer for a question. Sessions last one hour on average. The exchange rate used is 40 points for 1 AUS$. In addition to the earnings from the coordination game, subjects are paid another AUS$5 for participation. The average amount subjects earned is AUS$27.50 (approximately US$21.20 at the time of the experiment), with the earnings range being from AUS$16.80 to AUS$37.50.

3 Results – Treatment Differences

As mentioned earlier, subjects are in fixed groups of six. All analysis is conducted at the statistically independent group level. There are ten groups per treatment. The minimum effort level in a group and the average effort in a group are used as the two main measures of cooperation. The minimum effort measures the group output level and determines the payoff subjects get. The average effort provides information on the effort levels chosen by all members. To compare with the discrete time treatments, the effort level for the two continuous time treatments are accumulated (i.e., time-weighted average) effort within each period. Unless otherwise specified, the unit of observation for all tests is the average at the statistically independent group level, and p-values are from two-sided Mann-Whitney rank sum tests.

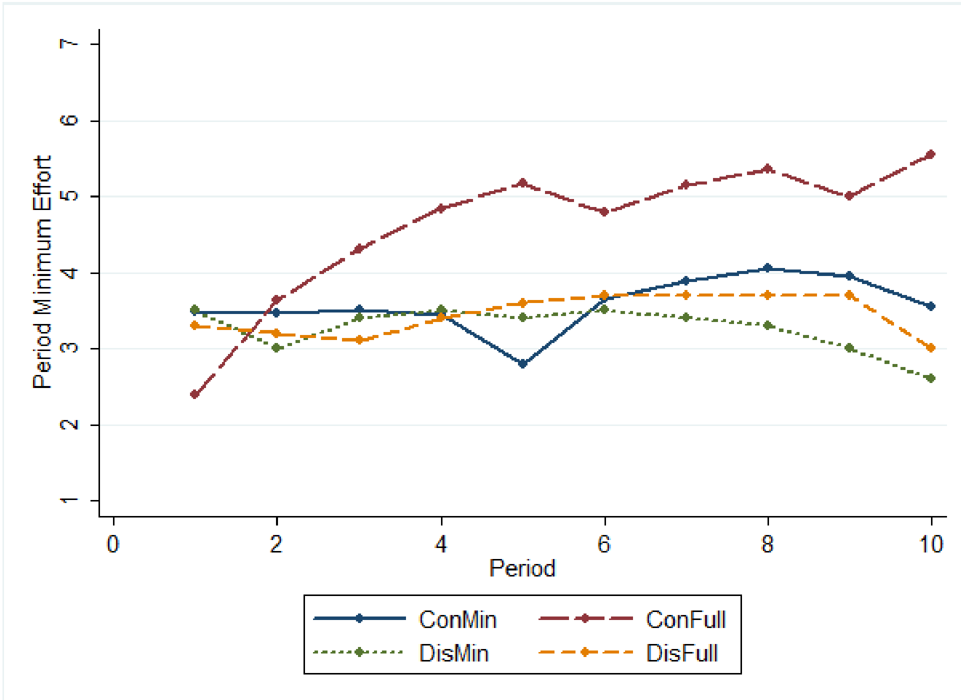
The minimum and the average efforts in all ten periods averaged across the ten groups per treatment are shown in Figure 2a and Figure 2b, respectively.[7] Table 2 lists the summary statistics of the group minimum effort and the group average effort with the first five and last five periods summarized separately. As can be seen in Figure 2a and Figure 2b, the group performances stabilize after the fifth period.

Figure 2a shows that the ConFull treatment has a higher group minimum effort than the other three treatments. Although the minimum effort starts at low levels in the ConFull treatment, it increases rapidly before stabilizing in the fifth period. For the other three treatments, the group minimum efforts change only slightly across the ten periods. All three start with effort levels around 3.5. In the last period, they finish with effort levels between 2.5 and 3.6. In the last five periods, the ConFull treatment has the highest mean value of the minimum effort (see Table 2). The minimum effort of the ConFull treatment is 1.36 higher than the next highest treatment (ConMin), with a substantial increase of around 36%.

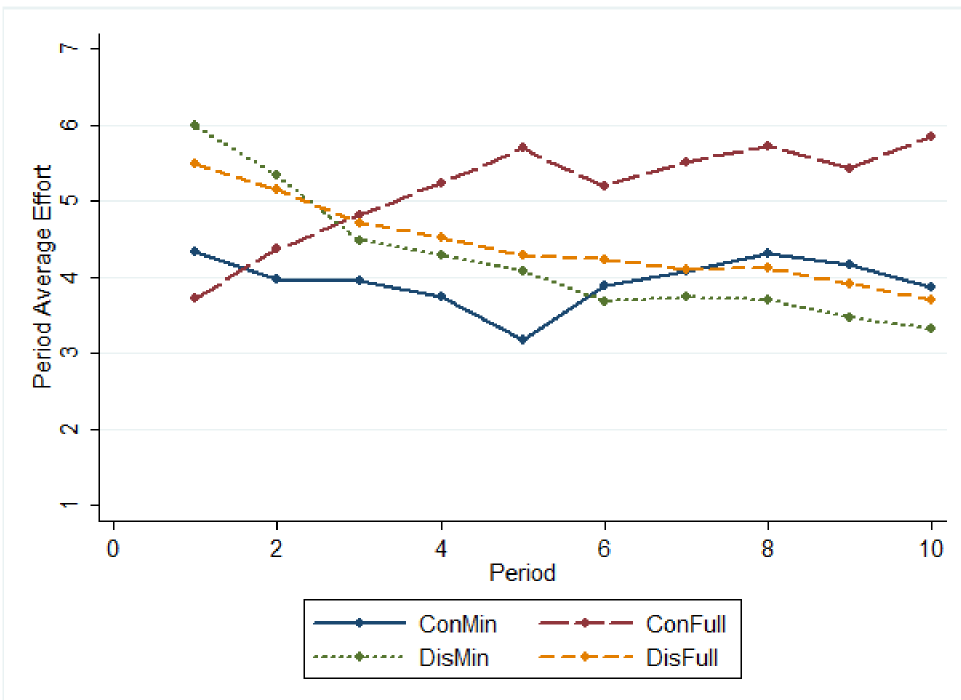
The pattern of the average effort level in the ConFull treatment is similar to that of the minimum effort level: it keeps increasing until the fifth period and remains the highest among all treatments. The average effort levels of the two discrete time treatments decrease over time. Although the average effort levels of the two discrete time treatments start high, they finish slightly below the ConMin treatment. The mean value of the average effort of the ConFull treatment in the last five periods is 1.48, or 36%, higher than the ConMin treatment (Table 2). The mean values of the average effort levels of the ConMin, DisMin and DisFull treatments in the last five periods are approximately the same.

To measure the significance of the treatment differences described in Figure 2a, Figure 2b and Table 2, two-tailed Mann-Whitney tests are conducted using the efforts averaged across the last five periods. As discussed earlier, the continuous time treatments are expected to reach higher cooperation levels compared with the discrete time treatments. However, the effect of continuous

[7] The group minimum effort of each group is shown in Figure A.1 in Appendix A. In each treatment, there are groups cooperating at effort level 7 and groups stuck at effort level 1.



(a) Average Minimum Effort



(b) Average Effort

Figure 2: Effort Levels (Time-weighted within Each Period)

Table 2: Minimum and average effort in the first and the last five periods

	ConMin	ConFull	DisMin	DisFull
Minimum Effort: Period 1–5				
Mean	3.34	4.07	3.36	3.32
Std. Dev	1.71	2.06	2.64	1.90
Minimum Effort: Period 6–10				
Mean	3.81	5.17	3.16	3.56
Std. Dev	1.93	2.30	2.65	2.46
Average Effort: Period 1–5				
Mean	3.83	4.77	4.83	4.83
Std. Dev	1.50	1.70	2.05	1.73
Average Effort: Period 6–10				
Mean	4.06	5.54	3.58	4.01
Std. Dev	1.80	1.96	2.61	2.38

time in the experiment is mixed. There is no significant difference between the ConMin treatment and the DisMin treatment for either the group minimum effort ($p = 0.303$) or for the group average effort ($p = 0.496$). While the minimum and average efforts are substantially higher in the ConFull treatment compared to the DisFull treatment (by 45% and 38%, respectively), the differences are only weakly significant ($p = 0.110$ for the group minimum effort; $p = 0.160$ for the group average effort). Regardless of the type of information feedback, continuous time has no statistically significant effect on coordination level. These findings are summarized as follows.

Result 1.

(a) There is no significant difference in the minimum effort level between the ConMin and DisMin treatments, and between the ConFull and DisFull treatments.

(b) There is no significant difference in the average effort level between the ConMin and DisMin treatments, and between the ConFull and DisFull treatments.

Full information feedback is expected to improve cooperation levels in continuous time. However, although the group minimum is substantially higher (36%) in the ConFull treatment than in the ConMin treatment, the difference is not significant ($p = 0.120$). But the difference in the group average effort levels is significant ($p = 0.049$). There is no significant difference between the two discrete-time treatments, measured either by the minimum effort level ($p = 0.667$) or the group average effort ($p = 0.820$). These results can be summarized as follows.

Result 2.

(a) There is no significant difference in the group minimum effort level between the ConMin and DisMin treatments, and between the ConFull and DisFull treatments.

(b) The group average effort level in the ConFull treatment is significantly higher than that in the ConMin treatment. There is no significant difference in the group average effort level between the DisFull and DisMin treatments.

Overall, continuous time itself does not affect coordination levels. With full information feedback, subjects in continuous time set high average effort levels to increase the group minimum, but the level of the increase is small.[8]

4 Results - Within Period Performance

Our results so far indicate the importance of full information for continuous time to improve coordination. However, as effort levels can be changed continuously in the two continuous time treatment, the accumulated effort discussed in Section 3 may have concealed information regarding behavior within a period. We therefore dedicate this section to analysing within-period performances in the two continuous time treatments. Our goal is to further understand how and why full information improves coordination.

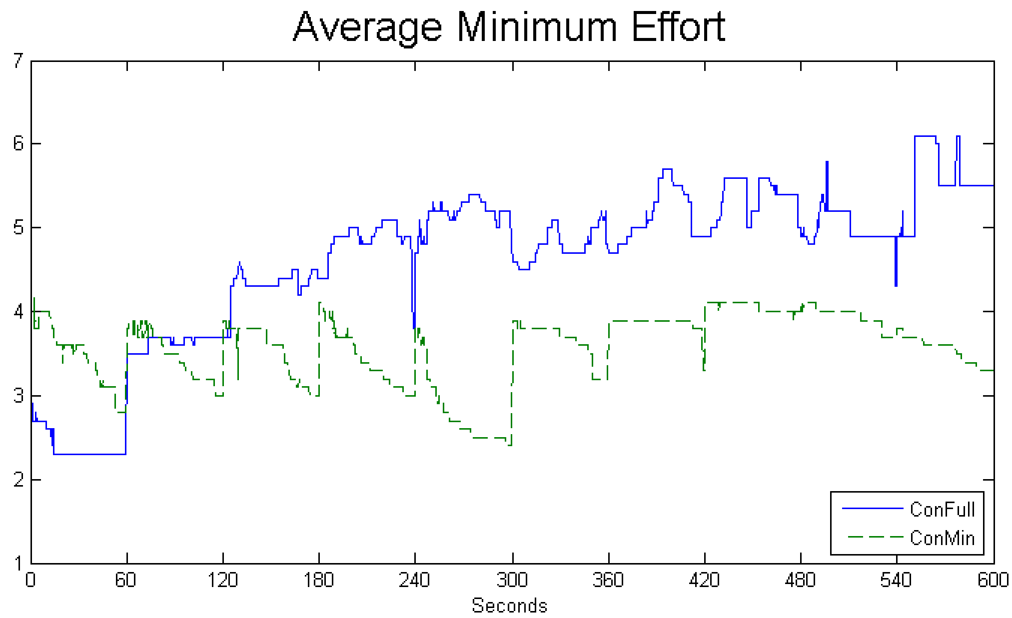
4.1 Within-period effort levels

Figure 3a and Figure 3b respectively, plot the average minimum effort and the average effort in the two continuous time treatments in each 0.3 second time grid. The dashed line plots the minimum effort or the average effort for the ConMin treatment. The solid line plots the minimum effort or the average effort for the ConFull treatment. The x-axis denotes seconds passed with the start of each 60-second period labeled.

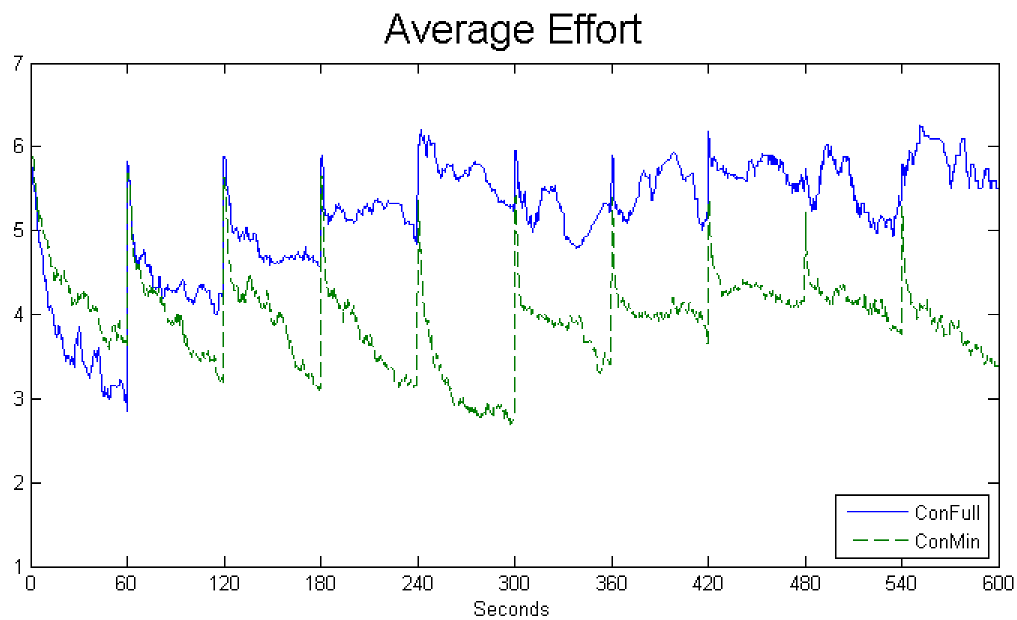
Apart from the first two periods, the solid line is above the dashed line, meaning that the ConFull treatment outperforms the ConMin treatment most of the time. For the ConMin treatment, the group minimum effort keeps decreasing until the next period starts. It seems that in the ConMin treatment, the group minimum can rarely be increased within a period. Even if there is an increase, it is often short-lived. In the ConFull treatment, the group minimum can be both increased or decreased within a period. Similar patterns are also shown for the average effort. In the ConMin treatment, the average effort decreases sharply soon after the beginning of each period. The decline is more modest during the middle and the end of a period. In the ConFull treatment, the decline of the average effort is more gradual compared with the ConMin treatment.

The steady decline of the group minimum in the ConMin treatment within the period implies that subjects rarely coordinate successfully to increase the group minimum. The sharp declines of the average effort in the ConMin treatment after the start of a period imply that subjects in the

[8]We also conducted panel data regressions which yield results similar to those discussed in this section. We include the regression results in Appendix A.



(a) Average Minimum Effort



(b) Average Effort

Figure 3: Within-Period Performance

Table 3: The Number of Switches for Continuous Time Treatments

	All Periods		Within Period		Start of Period	
	ConMin	ConFull	ConMin	Con Full	ConMin	ConFull
Group Minimum						
Total Switch	175	179	130	149	45	30
Upward Switch	73	103	34	85	30	13
(Percentage)	(41.71%)	(57.54%)	(26.15%)	(57.05%)	(86.67%)	(60.00%)
Downward Switch	102	76	96	64	6	12
(Percentage)	(58.29%)	(42.46%)	(73.85%)	(42.95%)	(13.33%)	(40.00%)
Individual Effort						
Total Switch	4500	2072	4082	1799	418	273
Upward Switch	2102	1057	1703	816	399	241
(Percentage)	(46.71%)	(51.01%)	(41.72%)	(45.36%)	(95.45%)	(88.28%)
Downward Switch	2398	1015	2379	983	19	32
(Percentage)	(53.29%)	(48.99%)	(58.28%)	(54.64%)	(4.55%)	(11.72%)

ConMin treatment are less willing to wait for increases in the group minimum effort than in the ConFull treatment. They decrease their effort levels quickly to the group minimum, because the group minimum is the only information given to them. In the ConFull treatment, subjects seem more willing to wait for group members to increase their effort level.

4.2 Within-period effort switches

To quantify the subjects' behavior mentioned above, we counted the number of switches in the two continuous time treatments, with these measures summarized in Table 3. We report both changes in the group minimum effort level and changes in the individual effort levels chosen by subjects. The group minimum switch indicates a change in the coordination outcome, while individual effort switches reflect attempts to change the group minimum.[9] The effort changes are categorized into two types. A within-period switch captures an effort change that occurs within a period; and the start-of-period switch is a change between the effort level at the end of a period and the effort level at the start of the next period. We anticipate subjects will behave differently within a period compared with at the start of a period, because subjects choose effort levels at the start of each period without observing the group minimum or effort levels chosen by other group members.

We begin by analyzing switches in the group minimum effort level. Table 3 shows that the total number of switches is almost the same in the two continuous time treatments. Indeed, two-tailed Mann-Whitney tests using the number of group minimum switches in each group fails to detect

[9] Although the number of switches does not measure the change in effort level, it can still indicate the cooperation performance.

any significant differences between the ConMin and ConFull treatments either using all-period switches (p = 0.820), within-period switches (p = 0.909), or start-of-period switches (p = 0.123).

We measure the direction of group minimum effort switches by comparing the percentage of upward switches. The ConFull treatment has a significantly higher percentage of all-period upward switches (p = 0.006) and within-period switches (p = 0.010) than the ConMin treatment. Although the ConMin treatment has more upward switches at the start of the period than the ConFull treatment, the difference is only weakly significant (p = 0.093).[10] While the difference in the group minimum effort level between the two continuous time treatments is not significant (see Section 3), there are more upward group minimum switches in the ConFull treatment. These two observations are consistent with each other when the average size of the upward group minimum switches in the ConFull treatment is small.

To measure the differences in group behavior within a period versus at the start of a period, we compare the percentage of upward within-period switches with the percentage of upward start-of-period switches in the group minimum effort level. In the ConMin treatment, the percentage of upward group minimum switches at the start of a period is 60 percentage points higher than within a period (p = 0.001), while the percentages are nearly the same in the ConFull treatment (p = 0.789). That is, in the ConMin treatment upward switches are significantly more likely to occur at the start of the period than within a period, while in the ConFull treatment upward changes are equally likely to occur at both times. These results are consistent with the behavior depicted in Figure 3a. Without full information, subjects rarely coordinated successfully to increase the group minimum within a period and the group minimum is increased often at the start of a period.

This result is unexpected. Although the cost of an effort increase is small in continuous time, without full information feedback, subjects are unable to coordinate their timing to increase their effort level. Most of them increase their effort level (and consequently the group minimum level) at the start of a period, probably because the ten starting points serve as special focal points. We summarize these findings regarding switches in the group minimum effort level as follows.

Result 3.

(a) The total numbers of group minimum effort level switches (over all periods, within periods or at the start of each periods) in the two continuous time treatments are not significantly different.

(b) In terms of the percentage of upward switches in the group minimum effort level (out of all group minimum effort level switches):

  (i) The percentage of upward switches out of all period switches is higher in the ConFull treatment than in the ConMin treatment;

[10] In the ConFull treatment, one group does not have any switches within period, and another group does not have any switches at the start of period. The former group is excluded from Mann-Whitney test of the within-period comparison and the latter is excluded from the start-of-period comparison.

(ii) The percentage of upward switches out of all within-period switches is higher in the ConFull treatment than in the ConMin treatment; and

(iii) The percentage of upward switches out of all start-of-period switches is weakly significantly lower in the ConFull treatment than in the ConMin treatment.

(c) In the ConMin treatment, an increase in the group minimum effort level is more likely to occur at the start of a period than within a period. In the ConFull treatment, the likelihood of a group minimum effort level increase within a period is not significantly different from that at the start of a period.

The number of individual effort switches can also be informative about subjects' attempts to coordinate. The all-period and the within-period individual effort switches of the ConMin treatment are more than double those of the ConFull treatment. This is because when subjects are unable to see the effort levels chosen by others, they are uncertain about when to increase their effort. As a result, some subjects keep switching their efforts between the group minimum and higher efforts to find out whether they are the only group member staying at the minimum level. Two-tailed Mann-Whitney tests confirm that the ConMin treatment has more all-period ($p = 0.028$), within-period ($p = 0.041$) and start-of-period ($p = 0.002$) individual effort switches than in the ConFull treatment.

Notice that upward individual effort switches are more telling about a subject's *attempt* to coordinate, rather than actual coordination, as in the case of upward group minimum switches. There are subjects in the ConMin treatment switching their effort choices up and down to find the group minimum. There are also subjects in the ConFull treatments signaling to the other group members to choose a higher effort level by switching their own effort rapidly between the group minimum and the higher effort level. Indeed, the percentages of upward individual effort switches are close to 50% in the two treatments (see Table 3). The ConFull treatment does have a higher percentage of upward all-period individual effort switches than the ConMin treatment ($p=0.034$), but the two treatments have similar percentages of upward within-period and start-of-period effort switches ($p = 0.597$ and 0.643 respectively).[11]

To measure the differences in within-period and start-of-period behavior, we compare the percentage of upward within-period and start-of-period individual effort switches. In both treatments, the percentage of within-period upward individual effort switches is approximately half of the percentage of start-of-period switches, a significant difference in both the ConMin ($p<0.001$) and the ConFull ($p=0.001$) treatments. At the start of a period, when subjects can observe neither the group minimum nor the effort levels of other group members, they choose higher effort levels than

[11] Although the intuition is that the percentages of all-period individual effort switches should be the same in the two treatments if the percentages of within-period and start-of-period individual effort switches are the same, our test results indicate that the ConFull treatment has a higher percentage of individual effort switches. When the start-of-period switches are summed with the within-period switches, the rank of percentage of upward all-period switches is changed.

the effort levels at the end of preceding period. As a result, the average effort level increases sharply at the start of each period in *both* continuous time treatments (see Figure 3b). We summarize these findings regarding switches in the individual effort level as follows.

Result 4.

(a) There are more individual effort switches (over all periods, within periods or at the start of each periods) in the ConFull treatment than in the ConMin treatment.

(b) In both the ConMin and the ConFull treatments, upward individual effort switches are more likely to occur at the start of a period than within a period.

One way to understand this result is to view continuous time with full information feedback as a form of costly and limited communication. With full information feedback, subjects are able to set higher efforts to indicate their expected equilibrium and signal to other members to set their efforts at the same level. When this communication channel is blocked in the ConMin treatment, subjects need to increase their efforts more times to increase the group minimum. To measure the effectiveness of individual effort switches in increasing the group minimum, we construct the ratio of total upward within-period individual effort switches to total upward within-period group minimum switches. This ratio averages 50.1 in the ConMin treatment — that is, there has to be 50.1 increases in effort in a group in order to increase the group minimum once. In other words, on average each subject needs to increase their effort 8.3 times for each upward group minimum switch. The average ratio is 9.6 in the ConFull treatment. Put differently, subjects in the ConMin treatment need to increase their efforts 5.2 more times for each upward group minimum switch than in the ConFull treatment. Quantitatively, the ratio concerned is significantly lower in the ConFull than that in the ConMin treatment (p=0.002),[12] indicating that the increase of individual effort in the ConFull treatment is more effective in increasing the group minimum than in the ConMin treatment.

Result 5. The ratio of upward within-period individual effort switches to upward within-period group effort switches is lower in the ConFull treatment than in the ConMin treatment.

5 Conclusion and Discussion

We examine a minimum effort coordination game in continuous time. In our continuous time treatments, subjects are able to change their effort levels as many times as they wish during each period and payoffs are accumulated by the time they spent playing an action. We find no significant differences between our continuous time and discrete time treatments. In continuous

[12] There are two groups in each continuous time treatment that do not have any within-period upward group minimum switches. The ratio cannot be calculated for these four groups and they are excluded from the two-tailed Mann-Whitney test.

time, providing full information feedback significantly increases the group average effort but not the group minimum effort.

Although the difference in the group minimum effort between the two continuous treatments is statistically insignificant, our within-period analysis finds more upward switches of the group minimum in the ConFull treatment. It seems that subjects with full information feedback set higher average efforts with an attempt to increase the group minimum effort. While they are more successful in raising the group minimum effort level than their peers in the ConMin treatment, the average level of an increase seems small. In the ConMin treatment, the group minimum can hardly be raised within a period because subjects rarely coordinate to increase their efforts simultaneously. Consequently, the group minimum is often increased at the start of a period, which provides a natural focal point for coordination. Moreover, subjects in the ConMin treatment need to increase their efforts more often for each upward switch of the group minimum than in the ConFull treatment. Our interpretation is that the effect of continuous time with full information feedback can be viewed as a costly and limited communication channel. If this channel of communication is blocked as in the ConMin treatment, an increase of individual effort level is ineffective in raising the group minimum.

While we find no statistically significant difference in the effort levels between our ConMin and DisMin treatments, Berninghaus and Ehrhart (1998) show that the payoff dominant equilibrium is played when a coordination game is repeated sufficiently many times. In other words, experimental subjects behave differently when a coordination game is played in continuous time and when the same game is repeated many times. We believe that the difference is related to the ability to coordinate on the timing of an increase in effort levels. In a discrete but repeated game, each period provides a commonly known possible timing to raise the effort level. In our continuous time treatment, however, subjects are unable to coordinate on the timing of an increase in their effort level within a period. The strong restart effect in our experiment is suggestive of focal points created by sectioning the experiment into periods.

Meanwhile, how payoffs are determined in a continuous time frame can have a significant effect on equilibrium selection. When the total payoffs are accumulated flow payoffs, as in our experimental set up, we find no significant difference between our ConFull and DisFull treatments. When the total payoffs are determined only by the last effort choice made before the end of each period, as in Deck and Nikiforakis (2012), providing continuous time full information feedback increases both the group minimum effort and the group average effort significantly from the discrete time baseline. This discrepancy is not surprising. When payoffs are determined only by the action at the end of the period, signaling an intended Pareto improvement by setting a higher effort level is costless. On the other hand, each individual upward effort switch incurs a cost when flow payoffs are accumulated. Even if this cost is only a few cents, it is salient enough for coordination to fail.

Finally, our results imply that the effect of a continuous time frame on behavior varies across games. A continuous time frame by itself (i.e., without additional information feedback or communication) had no significant impact in our six-player, seven-choice minimum effort coordination game, nor in a twelve-player Hawk-Dove game (Oprea et al., 2011), nor in a four-player public goods game (Oprea et al., 2014). These results stand in contrast with the remarkably high cooperation rates in continuous time two-player prisoner's dilemma experiments (Friedman and Oprea, 2012). One possible factor relevant for such variation in results is the group size. When group size gets large, continuous time alone cannot resolve the strategic uncertainty, and additional mechanisms such as full information feedback or free-form communication (Oprea et al., 2014) are required to facilitate cooperation. Relatedly, the complexity of the game may have diverted subjects' cognitive resources from figuring out how one may utilize the continuous time frame to achieve cooperation. In our opinion, these mixed results demonstrate the importance of investigating the effect of a continuous time frame across a variety of games.

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A Supplementary Analysis

A.1 Minimum Effort Level by Groups

Figure A.1 plots the minimum effort level for each group over periods in each treatment. While there are 10 groups in each treatment, a figure may show fewer than 10 lines as some of them overlap with one another.

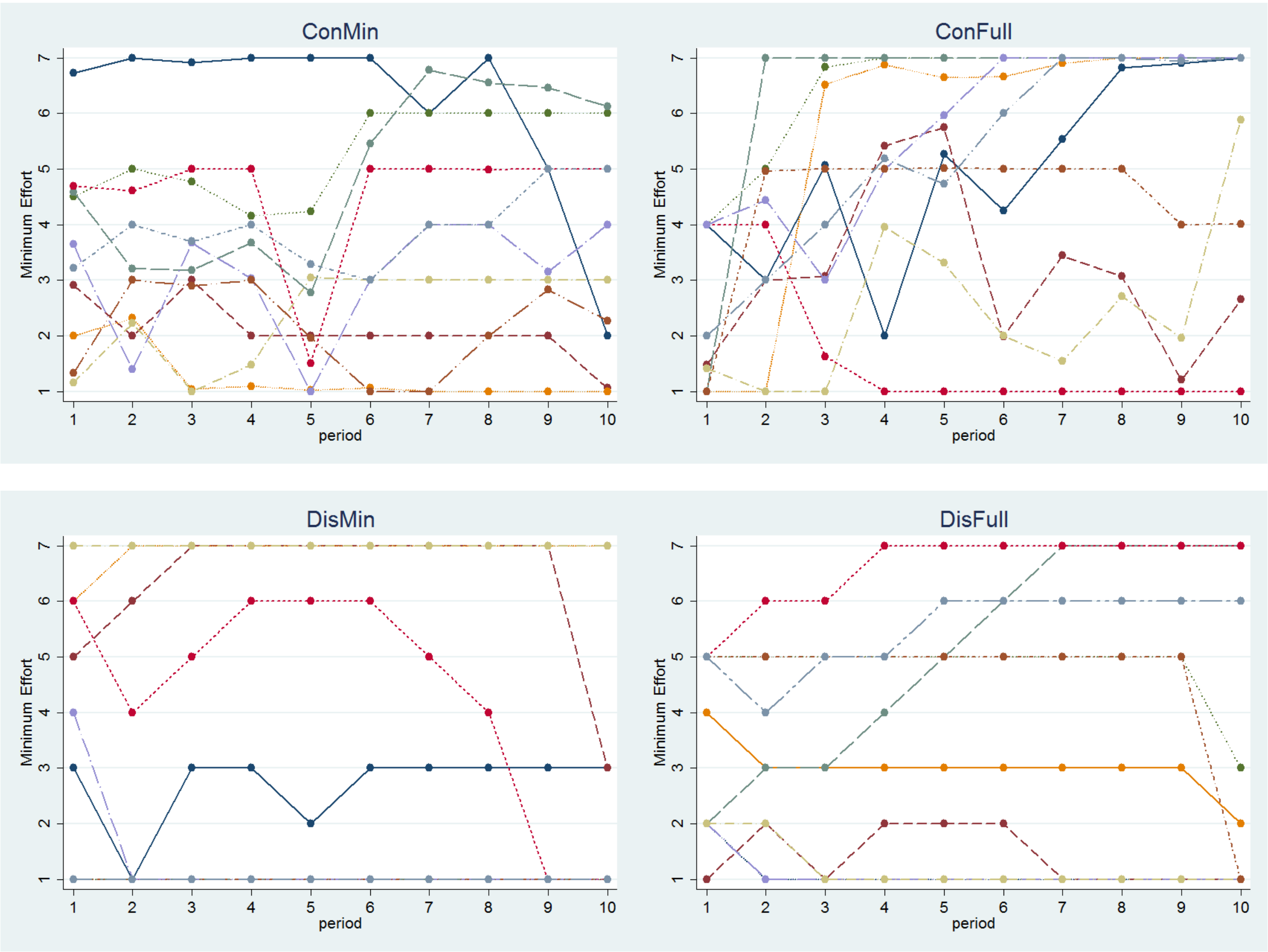

Figure A.1: Period Minimum Effort of Each Group

Table A.1: Random Effect Panel Regression Results[a]

Dependent Variable	(1) Effort	(2) Effort	(3) Effort	(4) Effort	(5) Minimum Effort
conmindummy	-0.263	-0.217	-0.268	-0.294	0.317
	(0.819)	(0.790)	(0.799)	(0.769)	(0.944)
confulldummy	0.949	1.020	0.830	0.822	1.360
	(0.818)	(0.804)	(0.804)	(0.787)	(0.953)
disfulldummy	0.215	0.330	0.215	0.345	0.180
	(0.909)	(0.899)	(0.873)	(0.862)	
invperiod	0.721	0.721	0.721	0.721	-0.930^{**}
	(0.472)	(0.472)	(0.472)	(0.473)	(0.412)
hardworkdummy			0.560^{**}	0.628^{**}	
			(0.261)	(0.261)	
trustdummy			0.409	0.331	
			(0.276)	(0.274)	
riskdummy			0.967^{***}	1.005^{***}	
			(0.305)	(0.299)	
quizwrong			0.039	0.085	
			(0.079)	(0.086)	
Demographics[b]	No	Yes	No	Yes	No
Constant	3.996^{***}	4.535^{***}	3.272^{***}	3.974^{***}	3.532^{***}
	(0.748)	(1.175)	(0.777)	(1.135)	(0.822)
Observations	2400	2400	2400	2400	400
Subjects	240	240	240	240	240
R-squared	0.048	0.064	0.086	0.105	
Wald test of model (p-value)	0.121	0.062	0.001	0.001	0.133
p-value of coefficient test					
ConFull vs. ConMin	0.057	0.042	0.067	0.050	0.143
ConFull vs. DisFull	0.327	0.347	0.399	0.512	0.153
ConMin vs. DisFull	0.524	0.458	0.507	0.374	0.867

[a] Numbers in parentheses are clustered standard errors. *, ** and *** indicate statistical significance at 10%, 5% and 1% levels, respectively.

[b] See Table A.2 for details on the demographic controls. None of these variables is statistically significant in any regression.

A.2 Random Effect Panel Data Regression

In addition to the Mann-Whitney tests reported in the main text, we have also run random effect panel data regressions. We give the details of these regressions here.

Five random effects models are run. In the first four models, the dependent variable is the individual time-weighted average effort in each period. The subject ID of the participants is the individual dimension and the number of periods is the time dimension. Each model has 2400 observations. Standard errors are clustered at the independent group level. In the last model, the regression is conducted at the group level instead of the individual level. The dependent variable is the time-weighted average minimum effort in each group in each period. There are 400 observations in total.

To compare the effect of the treatments, three treatment dummies are created, with the DisMin treatment being the baseline. In addition to these treatment dummies, all models include a constant term and the inverse of the period number, the latter to account for learning effect. Some models include statistics from the end of session questionnaire. (See Table A.2 for the description of each variable.)

The coefficients of the regressions are shown in Table A.1. The figures in parentheses are the standard errors.

In our five models, the test results on the differences between treatments are similar to those under the two-tailed Mann-Whitney test using the group average efforts or the group minimum efforts: The effort level under the ConFull treatment is significantly or weakly significantly higher than that under ConMin. There is no difference between the ConMin, DisMin and DisFull treatments. When measured by the group minimum effort, there is no significant difference between treatments. The hardwork dummy (whether subjects report themselves to be willing to work harder than other members on a team project) and the risk dummy (whether subjects reveals themselves to be risk-lovers in a choice of gambles) are the only individual characteristics that are significant.

Table A.2: Description of Variables Used in Regression

Variable Name	Description
Dependent Variables	
periodeffort	The (average) effort in each period
periodmineffort	The (average) minimum effort in each period
Treatment Dummies	
conmindumy	Equal to 1 if it is the ConMin treatment, 0 otherwise
confulldummy	Equal to 1 if it is the ConFull treatment, 0 otherwise
disfulldummy	Equal to 1 if it is the DisFull treatment, 0 otherwise
Learning Effect Variable	
invperiod	1/period number
Apptitude Variables	
hardworkdummy	Equal to 1 if the subject is willing to work harder than other members when completing a team project, 0 otherwise
trustdummy	Equal to 1 if the subject will trust a stranger, 0 otherwise
riskdummy	Equal to 1 if the gamble game the subject wants to play indicates that s/he is a risk-lover, 0 otherwise
quizwrong	The number of quiz questions a subject gets wrong at the first attempt, indicator of the understanding of instructions
Demographic Controls	
experiment	The number of experiment the subject has participated in the past
age	Subject's age
Languagedummy	Equal to 1 if the subject speaks a language other than English, 0 otherwise
economicsdummy	Equal to 1 if the subject has taken an economics course, 0 otherwise
maledummy	Equal to 1 if the subject is female, 0 otherwise
liveau6ydummy	Equal to 1 if the subject has lived in Australia for more than 6 years, 0 otherwise
graduatedummy	Equal to 1 if the subject is a graduate student, 0 otherwise

B. Instructions

General

Thank you for agreeing to take part in this study. Please read the instructions we give you today carefully. A clear understanding of the instructions will help you make better decisions and increase your earnings. After reading the instructions, there will be 10 questions to test your understanding. To guarantee everyone understands the experiment, you can not move on to the next question if you do not enter the correct answer. All the money you earn is yours to keep and will be paid to you in private and in cash immediately after the experiment. If you decide to leave early, you will forgo all your earnings.

If you have any questions during the experiment, please raise your hand. Please do not consult with other participants in this room or look at the computer screens of other participants. Please turn your phone off or to silent mode now and place it on the floor, along with any other materials you have brought into the room.

At the beginning of the experiment, you will be randomly assigned into a group consisting of six people, you and five others. The other people in your group are sitting in this room. You and the other five group members will remain in the same group throughout today's experiment. You and any group members will remain anonymous. Please do not attempt to communicate with other participants in the room during the experiment.

Payoff

The amount of money each participant gets paid is different. It depends on your choice and the other five group members' choices. Details are as following.

This experiment has 10 periods altogether. At the beginning of each period, you will be asked to pick a value of X. The values of X you may choose are 1, 2, 3, 4, 5, 6 or 7. The value you pick for X and the minimum value picked for X by any participant in your group, including your choice of X, will determine the payoff you receive. You are provided with a table which tells you the potential payoffs you may receive. Please look at Figure 1 on the next page now.

The earnings in each period may be found by looking across from the value you choose on the left hand side of the table and down from the minimum value chosen within group from the top of the table. For example if you choose a 4 and values chosen by five other members are 5, 5, 4, 3, and 3. Then the smallest value chosen in your group is 3, your current payoff is 80 points. In Figure 1, the payoff can be found at the cell in the fourth row and fifth column. The points will be converted into cash at the end of the experiment. 40 points equal to 1 AUD. Thus the more points you earn, the more you will get paid.

Figure 1

	Minimum Value Within Group						
Your Value	7	6	5	4	3	2	1
7	130	110	90	70	50	30	10
6		120	100	80	60	40	20
5			110	90	70	50	30
4				100	80	60	40
3					90	70	50
2						80	60
1							70

You can change your value every 0.3 seconds. In other words, you or other participants can change the choice three or four times in one second. Periods will each last 60 seconds. During the 60 seconds, you can switch your chosen value as many times as you wish. The numbers in the payoff matrix are the period payoffs you would earn if you maintained the same action throughout the period. For instance if you chose value 6 for the entire period and the minimum value chosen in your group stays at 2, you would earn 40 points.

Apart from your own value and the smallest value chosen within your group, your payoff in a period also depends on how much time is spent in each cell of the payoff table. For example, if you choose value 7 for the first 20 seconds and value 4 for the later 40 seconds while the minimum group value stays at value 2 for the whole period. The period accumulated earnings are calculated as following. In the first 20 seconds you stayed at the 1st row and 6th column cell of the payoff matrix getting payoff 30, you accumulated (20/60)30=10 points. In the later 40 seconds, you stayed in the 4th row and 6th column cell getting payoff of 60, you accumulated (40/60)60=40 points. Your period accumulated payoff would be 10points + 40points=50points.

In summary, the final payoff is accumulated by the time spent in each cell. The more time you spend in any one cell, the closer final payoff will be to the payoff in that cell. As in the above example, 50 points is closer to 60 than to 30. This is because you spent longer staying at the cell with payoff 60 than staying at the cell with payoff 30.

Details on How to Use the Software

At the beginning of each period, each participant has to choose a starting value for X. After the starting values are picked by all participants in the room, the 60 seconds for the period begins and payoffs start to accumulate.

Figure 2

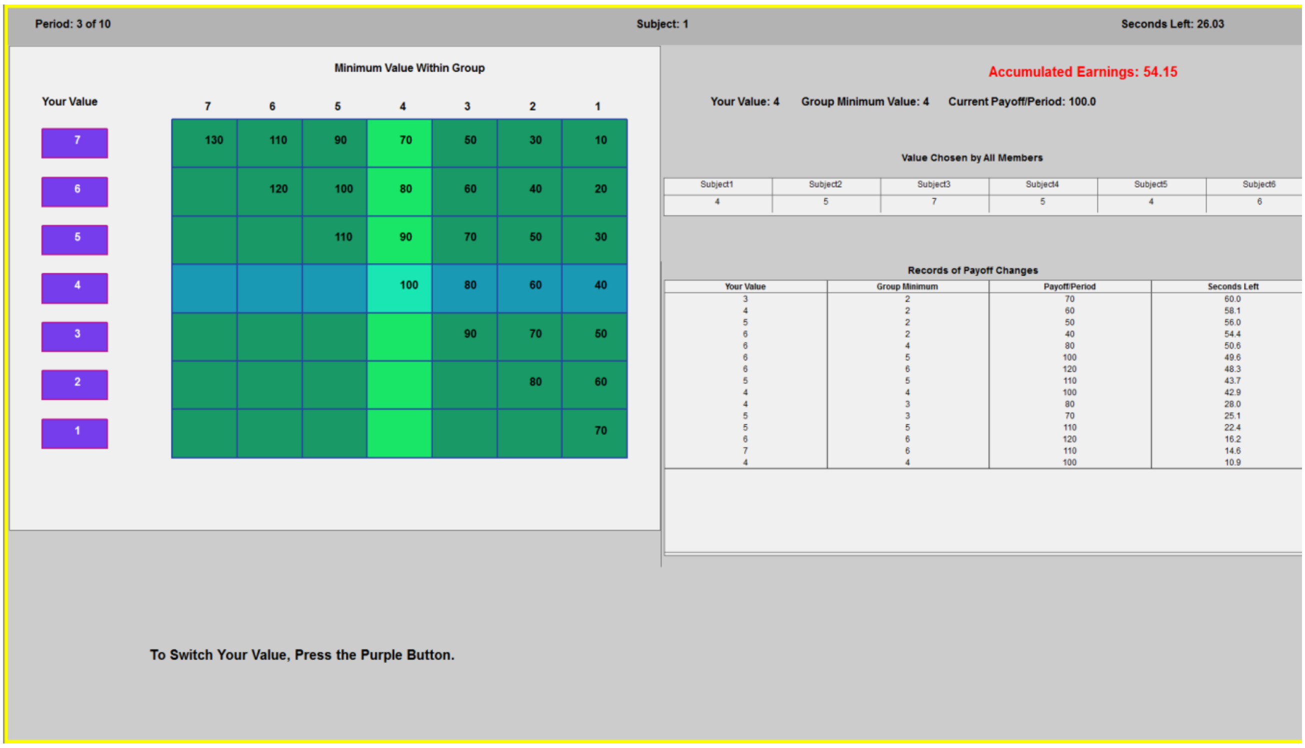

Figure 2 shows a screenshot from the experiment. The clock at the right top corner of the screen shows how much time is left in the period. The left side of the screen shows same payoff table as Figure 1. At any moment during the period, you will be able to change your action by clicking the purple buttons at the left side of screen. The row corresponding to your chosen action and the column corresponding to the group minimum will both be highlighted in different colors. For example, Figure 2 currently shows that you have chosen a value of 4, while the group minimum is also 4.

The right hand side of the screen displays your earnings during the period. A closer look at the right side of the screen is shown in Figure 3 on the next page. Your current accumulated earnings are displayed in red at the top. The accumulated earnings are updated every 0.3 seconds. The next line displays your current chosen value, group minimum value, and current payoff per minute. The table below displays the value chosen by each participant. You can easily find your subject number at the top middle of the screen.

The table in the middle displays records of changed payoff and the time that change is made. For example, the first row shows that your starting value is 3 (or you chose 3 when 60 seconds are left) and the starting group minimum is 2 giving a current payoff of 70. You changed your value from 3 to 4 when 58.1 seconds are left in the period. In other words, you spent 60.0-58.1=1.9 seconds playing the starting value 3 with the group minimum equal 2. The second row shows that you spent 58.1-56.0=2.1 seconds playing value 4 with the minimum equal 2, and so on.

Figure 3

Accumulated Earnings: 54.15

Your Value: 4 **Group Minimum Value: 4** **Current Payoff/Period: 100.0**

Value Chosen by All Members

Subject1	Subject2	Subject3	Subject4	Subject5	Subject6
4	5	7	5	4	6

Records of Payoff Changes

Your Value	Group Minimum	Payoff/Period	Seconds Left
3	2	70	60.0
4	2	60	58.1
5	2	50	56.0
6	2	40	54.4
6	4	80	50.6
6	5	100	49.6
6	6	120	48.3
5	5	110	43.7
4	4	100	42.9
4	3	80	28.0
5	3	70	25.1
5	5	110	22.4
6	6	120	16.2
7	6	110	14.6
4	4	100	10.9

At the end of each period, you are provided with another two tables. The first table lists your average value and group average minimum value, along with your period payoff and its converted money amount. Please see Figure 4. The second table records the average chosen value for all group members. Please see Figure 5. After you have finished reviewing the table, the next period will start.

Figure 4

Values Chosen and Payoffs From All Periods

Period	Your Average Value	Group Average Minimum Value	Your Accumulated Points	Converted to AUD
1	4.00	1.96	59	1.48
2	4.19	2.31	64	1.61
3	4.26	4.00	98	2.44
4	5.99	3.92	78	1.96
5	3.17	2.70	82	2.06

Figure 5

Average Values Chosen by All Members From All Periods

Subject1	Subject2	Subject3	Subject4	Subject5	Subject6
4.00	2.00	5.00	7.00	2.91	3.80
4.19	4.00	2.34	3.73	4.69	4.07
4.26	5.00	7.00	5.00	4.00	6.00
5.99	6.64	5.95	5.37	5.28	5.93
3.17	5.85	7.00	4.00	5.00	5.03

Earnings

You will be paid at the end of the experiment in cash based on the sum of point earnings throughout the experiment. The conversion rate from points to AUD is 40. That is

40 points = 1 AUD

Apart from the converted point earnings, you are paid another $5 participation fee.

Now you have 5 minutes to read the instructions and ask questions. A quiz consisting of 10 questions will start before the experiment. Feel free to ask experiment administrator questions during the quiz, if you have any confusion. A full understanding of the experiment is important.