The Effect of Sequentiality on Cooperation in Repeated Games

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Sequentiality of moves in an infinitely repeated prisoner's dilemma does not change the conditions under which mutual cooperation can be supported in equilibrium relative to simultaneous decision-making. The nature of the interaction is different, however, given that sequential play reduces strategic uncertainty. We show in an experiment that this has large consequences for behavior. In particular, we find that with intermediate incentives to cooperate, sequentiality increases the cooperation rate by around 40 percentage points, whereas with very low or very high incentives to cooperate, cooperation rates are respectively very low or very high in both settings.
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Folk theorems show that both opportunism and cooperation can be sustained in a prisoner's dilemma game when the interaction is repeated and players are sufficiently patient (Fudenberg and Maskin, 1986). A remarkable property of this setup is that whether players move simultaneously or sequentially in the stage game does not affect the conditions that support mutual cooperation in equilibrium.[1] In both cases, mutual cooperation can be sustained if the discount factor is

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[1] Sequential moves, whereby the first mover's choice is revealed to the second mover before the latter makes a choice, are common in the context of trust (Kreps, 1990), borrower-lender relations (Thomas and Worrall, 1990; Kehoe and Levine, 1993), employer-employee relations (Akerlof, 1982; Fehr, Kirchsteiger and Riedl, 1993), and trade (Greif, 1993; Brown, Falk and Fehr, 2004).

above a threshold that depends on the parameters of the game (Wen, 2002).[2] Yet, given that sequentiality reduces strategic risk for the player who moves second, it creates a very different strategic environment. Specifically, the second mover can reap the benefits of cooperation and at the same time avoid being betrayed by cooperating if and only if the first mover cooperates. If the first mover understands this, then the strategic risk he faces is also lower than that of a player in a simultaneous game. Consequently, one might plausibly expect that sequentiality is a key determinant of cooperation. This paper reports on a controlled experiment that studies whether and under what conditions sequentiality leads to more cooperation. The paper is relevant for understanding cooperation across a wide range of applications (e.g. trade, employer-employee relations, borrower-lender relations) and contributes to the literature that investigates determinants of cooperation.

The role of strategic uncertainty has been highlighted as a crucial determinant of behavior within the class of repeated simultaneous prisoner's dilemmas (PDs). As summarized by Dal Bó and Fréchette (2018), the more money a player might lose by cooperating, the less she is willing to cooperate.[3] Two distinct but related approaches formalize the role of strategic uncertainty: Blonski, Ockenfels and Spagnolo (2011) and Blonski and Spagnolo (2015) who apply the concept of risk dominance to the repeated PD and Dal Bó and Fréchette (2011) who appeal to the basin of attraction of repeated-game strategies. These approaches also help to formalize the intuition that the sequentiality of moves may facilitate cooperation. A key element is that the second mover in a repeated sequential PD can, unlike a player in a repeated simultaneous PD, avoid ending up with the *sucker* payoff by conditionally cooperating. This leads to the prediction that second movers conditionally cooperate and first movers cooperate whenever mutual cooperation is supported in equilibrium. Otherwise, they defect.[4] With simultaneous decision-making, in contrast, the approaches predict a smooth relation between payoffs and the likelihood of cooperation, conditional on mutual cooperation being supported in equilibrium. In summary, if strategic uncertainty is taken into account, the cooperation rate in sequential PDs is predicted to be (weakly) higher than that in simultaneous PDs in games in which mutual cooperation is supported in equilibrium.

In our experiment, participants play a series of indefinitely repeated sequential or simultaneous PDs. In each round, players proceed to the next round with a

[2]This builds on the use of the grim trigger strategy as a cooperative strategy (Friedman, 1971). Since that strategy leads to minimax payoffs (equal to static Nash payoffs) independently of sequentiality, it is the worst possible punishment strategy in both settings (Fudenberg and Maskin, 1986).

[3]Strategic uncertainty is also an important factor in finitely repeated PDs (Embrey, Fréchette and Yuksel, 2018), repeated entry games (Calford and Oprea, 2017) and dynamic dilemma games (Vespa and Wilson, 2019).

[4]The prediction is reminiscent of a case discussed by Camera, Casari and Bigoni (2013) in relation to a game where strangers decide whether to help one another in exchange for fiat money. In this case, the only two stable population configurations are a population of defectors and a population of conditional cooperators (traders), with basins of attraction depending on the parameters of the game.

constant and known continuation probability δ.[5] The experiment covers six parameter configurations that vary between subjects, as in Dal Bó and Fréchette (2011). In one configuration, cooperation cannot be sustained in equilibrium because δ is below the threshold of the standard theory of infinitely repeated games, while in the others, δ is above the theoretical threshold. We formulate predictions while taking into account strategic uncertainty. In the treatment in which mutual cooperation cannot be sustained in equilibrium, no difference is predicted between the sequential and simultaneous versions. In the other treatments, sequentiality is predicted to (weakly) increase the cooperation rate to above that in the simultaneous equivalent, with the largest effect predicted for the games where δ is closest to the theoretical threshold. The reason for this is that in the simultaneous version of the latter games, strategic risk is largest.

The experimental results show strong support for the predictions that take into account strategic risk. In the treatments that are characterized by relatively high strategic risk in the simultaneous version, sequentiality increases the cooperation rate by 40 percentage points. In the treatments with relatively little strategic risk, sequentiality has no significant effect on the cooperation rate; the cooperation rate is close to one then when mutual cooperation is sustainable, and close to zero when it is not.

Other experimental studies have compared sequential and simultaneous social di-lemma games. Evidence from one-shot experiments, in which repeated-game incentives are absent, indicates that the effect of sequentiality on cooperation appears to depend on the game's parameters and the subject pool (Ahn, Ostrom and Walker, 2003; Ahn et al., 2007; Khadjavi and Lange, 2013). Oskamp (1974) who compares repeated sequential- and simultaneous-move PDs with different payoff *levels* but otherwise the same repeated-game incentives, finds evidence for an interaction between sequentiality of moves and payoff levels. In sequential-move games, cooperation rates tend to be less responsive to a change in the payoff level than in simultaneous-move games.[6] Furthermore, there is a literature on leading-by-example where a leader is modeled as the first mover in a voluntary-contributions setting. In this literature, (exogenously imposed) sequentiality of moves increases contributions relative to a simultaneous-move setting if the leader has private information about the game's parameters (Potters, Sefton and Vesterlund, 2005) but leads to mixed results in full information settings (for example Andreoni, Brown and Vesterlund, 2002; Güth et al., 2007).[7] Finally, Kartal and

[5]Building upon the assumption that participants do not discount the future in the short period of time they are in the lab, δ has the same role as that of the rate at which risk-neutral players discount the future in an infinitely repeated game (Roth and Murnighan, 1978).

[6]In these experiments, it was announced that the repeated game would last for 60 rounds but was ended after 50 to avoid end-game effects.

[7]See also Clark and Sefton (2001) who study the effect of stakes and subject pool on the cooperation rate in one-shot sequential PDs; Engle-Warnick and Slonim (2006) who study behavior in infinitely repeated trust games; and Reuben and Suetens (2012) who elicit stage-game strategies of players in infinitely repeated sequential PDs in which players can condition their strategy on whether or not they are playing the last round.

Table 1—Stage game of a simultaneous PD.

	Cooperate	Defect
Cooperate	c, c	s, t
Defect	t, s	d, d

Note: $t > c > d > s$ and $2c > t + s$.

Müller (2018) compare simultaneous and sequential infinitely repeated PDs in an experiment inspired by their model with heterogeneity in cooperation preferences and private information. They focus on a case in which cooperation cannot be sustained in equilibrium and find that sequentiality increases the cooperation rate by about 20 percentage points.

The remainder of the paper is organized as follows: Section I provides the theoretical background; Section II describes the experimental design and procedures and presents predicted effects of sequentiality in our experiment; Section III presents the main results, with focus on the treatment effect of sequentiality and on the behavior of first and second movers in the sequential games; Section IV concludes.

I. Theoretical Background

In a repeated simultaneous PD with a stage game as shown in Table 1, the standard theory of infinitely repeated games prescribes that mutual cooperation can be supported as an equilibrium outcome if $\delta \geq \delta^* \equiv (t-c)/(t-d)$ (see proposition 4 in Friedman, 1971). Both players playing grim trigger (GT) strategies constitutes an equilibrium then.[8] If the PD is played sequentially, then the theory predicts that mutual cooperation can be supported in equilibrium under the same condition as in the simultaneous PD, that is, if $\delta \geq \delta^*$. Likewise, GT leads to the harshest possible punishment and both players using a GT strategy constitutes an equilibrium (see Section C.1 of the Appendix for calculations).[9] In summary, standard game theory does not provide a specific reason why cooperation rates should be different in sequential PDs than in simultaneous ones: if $\delta < \delta^*$, the only equilibrium is one in which both players defect, and if $\delta \geq \delta^*$, cooperative and non-cooperative equilibria exist in both cases.

More precise predictions can be obtained by appealing to risk dominance (Blonski, Ockenfels and Spagnolo, 2011) or to the basin of attraction of repeated-game strategies (Dal Bó and Fréchette, 2011). These approaches help to identify under which conditions players are more likely to coordinate on a mutually cooperative

[8]GT is defined as follows: start by cooperating and continue to do so if both players cooperate, and if one of the players defects, switch to defection forever.

[9]Since a second mover never moves first, the implementation of GT is as follows: the second mover should cooperate if the first mover cooperates and if she himself cooperated in the previous move, and switch to defection forever after a defection of one of the two players.

equilibrium in games with $\delta \geq \delta^*$. A key element is that the relative cost of cooperating with a partner who defects, becomes an important determinant of behavior for players who do not know with certainty whether or not their partner will defect. In particular, consider a simplification of the repeated game to a game in which players choose at the beginning of the repeated game between the always defect strategy (AD) and a conditionally cooperative strategy (CC) à la GT.[10] We assume that the payoffs in the reduced game represent utilities and that they are common knowledge. The basin of attraction of AD versus CC (referred to as SizeBAD) is defined as the maximum probability that the partner will follow the CC strategy that makes AD optimal, which is based on the set of beliefs about the partner's strategy that makes AD optimal. SizeBAD turns out to be highly useful in understanding how behavior in sequential PDs might differ from that in simultaneous PDs. In what follows, we explain the intuition. The detailed calculations are presented in Section C.2 of the Appendix.

First, consider a repeated simultaneous PD. If $\delta \geq \delta^*$, the reduced game in which players choose between AD and CC is a game with two pure-strategy equilibria: (AD, AD) and (CC, CC). Players are more likely to choose CC and thus to end up in equilibrium (CC, CC) if the expected payoff of CC exceeds that of AD. This holds true if they believe that their partner will choose CC with sufficiently high probability, namely with a probability that exceeds $\frac{d-s}{c+d-t-s+\frac{\delta(c-d)}{1-\delta}} \equiv \bar{p}$. The threshold belief $\bar{p}$, which we refer to as SizeBAD, depends on the game's parameters and decreases *ceteris paribus* as c or δ increases. Thus, it is predicted that for $\delta \geq \delta^*$, the likelihood that participants cooperate, depends on the game's parameters. It is predicted to be higher, the higher is c or δ. For $\delta < \delta^*$, the cooperation rate is predicted to be zero.

Next, consider a repeated sequential PD. If $\delta \geq \delta^*$, the expected payoff for the second mover of choosing CC is (weakly) larger than that of choosing AD for *all* possible beliefs about the strategy of the first mover. This is because, in contrast to a player in a simultaneous PD, a second mover who uses CC avoids the sucker payoff. She prefers CC if the discounted payoff of CC is higher than that of AD, namely if $\delta \geq \delta^*$, and plays AD if $\delta < \delta^*$.[11] The first mover is not confronted with strategic uncertainty either, because he anticipates that the second mover will conditionally cooperate (due to the assumption that the PD's payoffs represent the utilities of the players and that is common knowledge). Therefore the first mover imitates the strategy of the second mover and also plays CC if $\delta \geq \delta^*$ and AD if $\delta < \delta^*$. Therefore, it is predicted that the cooperation rate will be equal to 100% if $\delta \geq \delta^*$ and zero otherwise.[12] In summary, the

[10]Since players are assumed to choose their strategy at the beginning of the repeated game, tit-for-tat (TFT) or another conditionally cooperative strategy with punishment would also qualify as CC.

[11]She is indifferent if $\delta = \delta^*$.

[12]Notice that the same predictions hold in the limit of a quantal response equilibrium, since noise completely vanishes (Turocy, 1995). If noise has not vanished, then a smooth relation is predicted between the parameters of the game and the cooperation rate, even in Seq if $\delta > \delta^*$ (see Section C.3 of the Appendix for predictions based on quantal responses).

cooperation rate in a repeated sequential PD is predicted to be (weakly) higher than in the repeated simultaneous PD with corresponding parameters. In Section II, we formulate more precise comparative-static predictions for the parameters used in the experiment.

Finally, allowing for heterogeneity of players, for example in terms of other-regar-ding preferences, does not change the core prediction that the cooperation rate in a sequential PD is (weakly) higher than in the simultaneous version.[13] However, if players have heterogeneous preferences, then the threshold above which CC is preferred over AD is player-specific. For example, sufficiently pro-social players would prefer CC over AD in the role of second mover in a sequential PD even if $\delta < \delta^*$, whereas relatively spiteful players would need a larger δ than δ^* to prefer CC over AD. Thus, for a given distribution of selfish, pro-social, and spiteful players in the population, the cooperation rate depends on the parameters of the game, even in sequential PDs with $\delta > \delta^*$. In Section C.4 of the Appendix we illustrate the effect of heterogeneity using a Charness and Rabin (2002) utility function without a reciprocity component. A heterogeneity model with privately informed players can be found in Kartal and Müller (2018).

II. The Experiment

A. *Design and Procedures*

Participants in the experiment play 50 repeated games. The number of periods in a repeated game (referred to as rounds) is stochastic and *ex ante* unknown to both the participants and the experimenter. In each round, the (known) probability that the game proceeds to the next round is δ. At the beginning of each repeated game, participants are randomly divided into pairs within matching groups of ten. They remain matched with the same counterpart for all rounds of a repeated game. In the sequential PDs, participants are also randomly allocated the role of first or second mover at the beginning of each repeated game. We expect that letting participants play in both roles helps them understand the strategic nature of the game.[14] The software had a built-in history box that participants could use to review all previous actions in the current repeated game.

We use the same parameters and treatment variations as in the simultaneous PD experiment conducted by Dal Bó and Fréchette (2011) (henceforth, DBF): $d = 25$, $t = 50$, $s = 12$; $c = 32$, $c = 40$ *or* $c = 48$; and $\delta = 0.5$ *or* $\delta = 0.75$. These parameters cover a wide range of settings ranging (in expectation) from short games with low gains to mutual cooperation to longer games with high gains

[13] A large literature shows that players are heterogeneous in that at least some of them hold pro- or anti-social preferences (e.g. Levine, 1998; Fehr and Schmidt, 1999; Charness and Rabin, 2002). For them, payoffs in PDs do not represent utilities. Ahn, Ostrom and Walker (2003) and Ahn et al. (2007) illustrate how heterogeneity models help to understand cooperation in one-shot simultaneous and sequential PDs.

[14] Reassigning roles at the beginning of each repeated game also ensures that contagion effects à la Kandori (1992) are constant across simultaneous and sequential treatments.

Table 2—The treatments.

	Sim						Seq						Total
	$\delta = 0.5$			$\delta = 0.75$			$\delta = 0.5$			$\delta = 0.75$			
$c =$	32	40	48	32	40	48	32	40	48	32	40	48	
# Participants	30	30	30	30	30	30	60	60	60	60	60	60	540
# Matching groups	3	3	3	3	3	3	6	6	6	6	6	6	54
# Repeated games	50	50	50	50	50	50	50	50	50	50	50	50	600
# Rounds (mean)	1.8	1.9	1.9	4.1	4.1	4.1	1.8	1.8	1.8	4.3	4.3	3.3	–
One-round games (share)	0.60	0.54	0.54	0.24	0.26	0.26	0.54	0.54	0.54	0.25	0.25	0.26	–

Note: Sessions were conducted with 40, 50, or 60 participants and treatments were distributed across several sessions. Apart from one exception, matching groups in a session faced the same δ and the same style of decision-making but a different c.

to mutual cooperation. Table 2 presents an overview of the treatments, where Sim and Seq refer to the treatments with simultaneous and sequential moves, respectively. As can be seen from the table, both the average lengths of the repeated games and the share of repeated games that last just one round are in line with expectations.

The experiment was programmed with zTree (Fischbacher, 2007) and conducted at the LINEEX lab in Valencia between July 2017 and April 2018. Sessions lasted 106 minutes on average and participants earned on average of €22.7. The procedures are described more in detail in Section A of the Appendix, and an English translation of the instructions can be found in Section B of the Appendix.[15]

B. Predictions

The predictions are based on the basin-of-attraction approach discussed in Section I. Table 3 provides an overview of the values of SizeBAD for all treatments based on the assumption that PD payoffs represent utilities. The larger the difference in SizeBAD between two particular treatments, the larger is the expected difference in cooperation between them. Taking into account that DBF have already shown that the cooperation rate is close to one in Sim with $c = 48, \delta = 0.75$, we can summarize the predictions as follows:

1) The cooperation rate is expected to be close to zero in Sim and Seq in treatment $c = 32, \delta = 0.5$.

2) The cooperation rate is expected to be close to one in Sim and Seq in treatment $c = 48, \delta = 0.75$.

[15] We also ran treatments in which the strategy method was used to elicit choices of second movers, and we plan to use these data in a future paper that compares hot and cold decision-making in sequential PDs.

TABLE 3—SIZEBAD BY TREATMENT.

		c		
		32	40	48
δ	0.5	1	0.72	0.38
	0.75	0.81	0.27	0.16

(a) Sim

		c		
		32	40	48
δ	0.5	1	0	0
	0.75	0	0	0

(b) Seq

Note: The table indicates the basin of attraction of AD (SizeBAD) in the different treatments. SizeBAD is defined as the maximal probability of the partner following a CC strategy that makes AD optimal.

3) The cooperation rate is expected to be (weakly) higher in Seq than in Sim in the other treatments, and the difference in cooperation rate is expected to (weakly) increase with the difference in SizeBAD between Seq and Sim: $c = 32, \delta = 0.75 \leq c = 40, \delta = 0.5 \leq c = 48, \delta = 0.5 \leq c = 40, \delta = 0.75$.

III. Results

A. *Effect of Sequentiality on Cooperation Rates*

This section reports the treatment effects of sequentiality on cooperation rates. We focus on cooperation rates across first rounds because (a) repeated games may have different lengths and (b) the adopted theoretical framework involves the choice of whether to use a cooperative or non-cooperative strategy at the beginning of the repeated game.[16] We first focus on comparative-static results after learning has taken place and then discuss dynamic patterns.

Figure 1 shows first-round cooperation rates across the last twenty repeated games.[17] We find that the difference between Sim and Seq is small in the treatments with the lowest or highest incentive to cooperate ($p = 0.200$ and $p = 0.635$, respectively).[18] The cooperation rate is respectively close to zero and close to one in these two treatments. In the Seq treatments with intermediate incentives to cooperate, the cooperation rate is substantially higher than in the corresponding Sim treatments. In particular, in treatments $\delta = 0.5, c = 40$; $\delta = 0.5, c = 48$; and $\delta = 0.75, c = 32$, sequentiality increases the post-learning cooperation rate by 38

[16]Statistics and graphs based on all rounds are included in Sections F and G in the Appendix, respectively. Patterns are generally very similar to those reported in the main text.

[17]Figure G.1 in the Appendix includes predicted cooperation rates in Seq and cooperation rates observed in DBF's simultaneous PDs. As can be seen, DBF cooperation rates generally fall within 95% confidence intervals of the cooperation rates in Sim in our experiment, suggesting that the patterns are robust to changes in language, subject pool and small changes in procedure.

[18]Unless otherwise mentioned, the statistics reported in the results section are based on pairwise treatment comparisons of behavior in the last 20 repeated games using probit regressions. The regressions take the choice to cooperate in the first round of a repeated game as the dependent variable and include a treatment dummy as an independent variable. Standard errors are clustered at the matching-group level. Estimated treatment effects on the cooperation rate are presented in detail in Tables F.1 and F.4 in the Appendix.

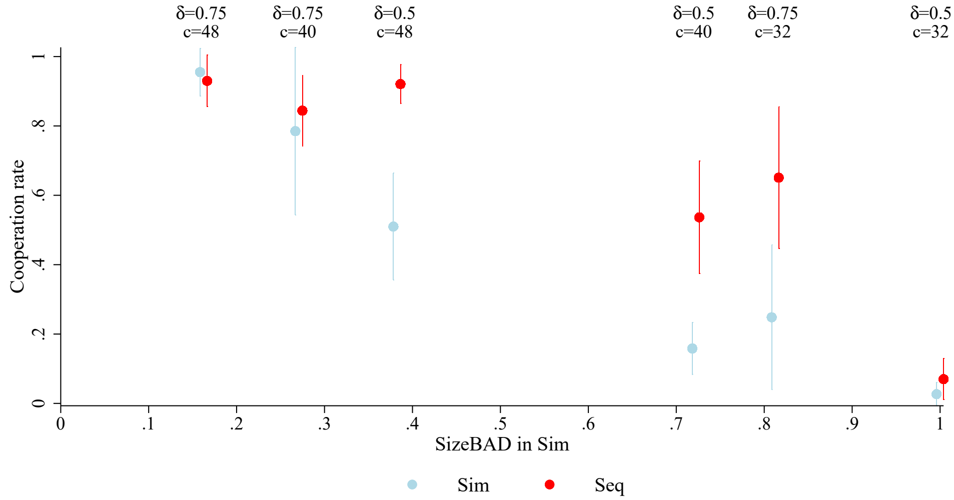


Figure 1. Cooperation rates.

Note: The graph shows first-round cooperation rates and 95% confidence intervals across the last 20 repeated games depending on the SizeBAD (including treatment labels). Estimates and confidence intervals are based on predictions from probit regressions run on a treatment dummy with clustered standard errors at the matching-group level.

to 41 percentage points ($p < 0.001$, $p < 0.001$ and $p = 0.015$, respectively). In the Seq treatment with $\delta = 0.75, c = 40$, the cooperation rate is somewhat higher than in the corresponding Sim treatment but the difference is not statistically significant ($p = 0.639$). Therefore, patterns of cooperation are overall closely in line with the SizeBAD predictions.

The results are robust to controlling for individual-level variables, such as proxies for other-regarding preferences, risk preferences and proneness to mistakes, and experienced length of the first ten repeated games (see Table F.2 in the Appendix).[19] The results are also robust to a re-estimation of treatment effects on the basis of a dataset in which our data is merged with that of DBF (see Table F.3 in the Appendix).[20]

With respect to the effects of c and δ on the cooperation rate, Figure 1 shows that we have replicated the result of DBF that an increase in c or δ generally leads to an increase in the cooperation rate in Sim after learning. A similar

[19] Overall, we find a positive relation in the first rounds between pro-sociality and risk-loving on the one hand and cooperation on the other whereas our proxy for proneness to mistakes is less related to cooperation. We also find that, in line with, for example, Engle-Warnick and Slonim (2006) and Dal Bó and Fréchette (2018), the difference between expected and median realized length of the first ten repeated games has a positive effect on cooperation after learning.

[20] DBF data are provided in "Replication Data for: The Evolution of Cooperation in Infinitely Repeated Games: Experimental Evidence", American Economic Association, Inter-university Consortium for Political and Social Research; `http://doi.org/10.3886/E112401V1` (Dal Bó and Fréchette, 2019).

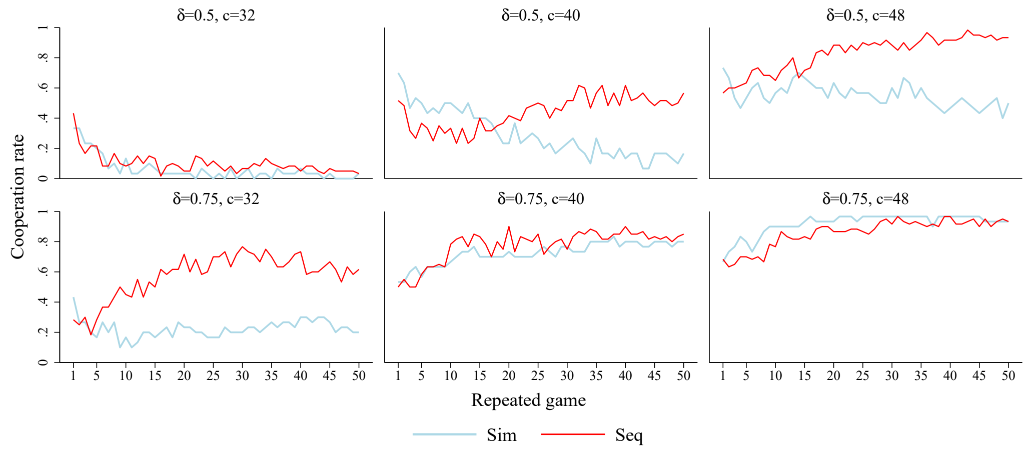


Figure 2. Evolution of cooperation rates.

Note: The graphs show cooperation rates across first rounds of repeated games by treatment.

effect is also observed in Seq, even when focusing solely on the treatments with $\delta > \delta^*$. In both Sim and Seq with $\delta > \delta^*$, the effect of c and δ on cooperation is statistically significant ($p \leq 0.01$ in probit regressions; see Table F.5 in the Appendix). Although such an effect is not predicted in Seq among rational payoff-maximizing players, it is consistent with the notion that players make mistakes, as in a quantal response equilibrium. It is also consistent with players being heterogeneous, for example in terms of social preferences, as outlined at the end of Section I.

We now turn to the learning dynamics. Figure 2 illustrates how first-round cooperation rates evolve across the fifty repeated games for each treatment.[21] The graphs show that some learning is necessary before the above-reported treatment effects set in. In the treatment with $\delta = 0.5, c = 32$, in which cooperation cannot be sustained in equilibrium, the cooperation rate is first well above zero and then sharply declines to a rate close to zero, whereas in the treatments in which SizeBAD predicts a cooperation rate of one, the cooperation rate increases across games. In Sim, the cooperation rate increases substantially only in treatments $\delta = 0.75, c = 40$ and $\delta = 0.75, c = 48$, which are both characterized by a low SizeBAD, and shows a decaying trend in the treatments with a higher SizeBAD.[22]

[21] Patterns by matching group are shown in Figure G.3 in the Appendix.

[22] Probit regressions with standard errors clustered at the matching-group level corroborate the result. For each treatment, we regress the first-round cooperation choice on a time trend. In Seq, the average marginal effect is positive and statistically significant for $\delta > \delta^*$ ($p \leq 0.021$) and negative and significant for $\delta < \delta^*$ ($p < 0.001$). In Sim, a positive and significant effect is obtained for $\delta = 0.75, c = 40$ and $\delta = 0.75, c = 48$ ($p = 0.021$ and $p < 0.001$, respectively), while the effect is negative and significant for $\delta = 0.5, c = 32$ and $\delta = 0.5, c = 40$ ($p < 0.001$ and $p < 0.001$, respectively). The effect is not statistically

B. Cooperation Rates by Role in the Sequential PDs

In this section, we further study what drives cooperation in the sequential PDs after learning. Figure 3 splits up the cooperation rate in Seq by role according to: first-mover cooperation rate; second-mover cooperation rate conditional on cooperation by the first mover (which we shall refer to as the conditional cooperation rate); and second-mover cooperation rate conditional on defection by the first mover. The first observation is that the conditional cooperation rate among second movers ranges from 43.9 to 95.4 percent depending on the treatment, and it is in all treatments significantly higher than the cooperation rate conditional on the first mover defecting ($p < 0.001$). Overall, second movers rarely cooperate if the matched first mover defects. This provides support for our focus on conditional cooperation as the most important cooperative strategy for second movers.

The second observation is that in the three treatments in which the difference in SizeBAD between Seq and Sim is highest, the first-mover cooperation rate and the second-mover conditional cooperation rate in Seq are both higher than the cooperation rate in Sim ($p \leq 0.007$ and $p < 0.001$, respectively). This supports a key feature of the SizeBAD predictions, namely that sequentiality does not just reduce strategic uncertainty for second movers relative to players who move simultaneously, but also for first movers. Such an effect is not observed in treatments $\delta = 0.75, c = 48$ and $\delta = 0.75, c = 40$, in which differences in SizeBAD between Sim and Seq are low ($p \geq 0.357$ for first movers and $p \geq 0.320$ for second movers). In treatment $\delta = 0.5, c = 32$, in which cooperation cannot be supported in equilibrium, the second-mover conditional cooperation rate is substantially higher than the cooperation rate in Sim ($p < 0.001$), while the first-mover cooperation rate is not ($p = 0.079$).

The third observation, also in line with the SizeBAD predictions, is that both the first-mover cooperation rate and the second-mover conditional cooperation rate are higher in the treatments with $\delta > \delta^*$ than in the treatment with $\delta < \delta^*$ ($p < 0.001$ and $p < 0.001$, respectively).[23]

If we focus on whether first- and second-mover choices are aligned, then three other noteworthy patterns emerge from Figure 3. First, in treatment $\delta = 0.5, c = 32$, the conditional cooperation rate of second movers is well above the cooperation rate of first movers ($p < 0.001$). Second, in the treatments with $\delta > \delta^*$, the first-mover cooperation rate and the second-mover conditional cooperation rate are

significant for $\delta = 0.5, c = 48$ and $\delta = 0.75, c = 32$ ($p = 0.182$ and $p = 0.748$, respectively).

[23] If we compare $\delta = 0.5, c = 32$ to $\delta = 0.5, c = 40$, then we get respectively $p < 0.001$ and $p = 0.014$, while if we compare $\delta = 0.5, c = 32$ to $\delta = 0.75, c = 32$, we get $p < 0.001$ and $p = 0.001$. For an overview of the statistical test results of treatment comparisons, see Table F.4 in the Appendix. Moreover, as shown in Figure G.5 in the Appendix, with $\delta < \delta^*$ the first-mover cooperation rate tends to decrease over time (negative linear trend with $p = 0.004$) while the second-mover conditional cooperation rate shows no trend ($p = 0.980$), whereas with $\delta > \delta^*$, both cooperation rates increase over time (positive linear trend with $p \leq 0.054$ and $p \leq 0.029$, respectively).

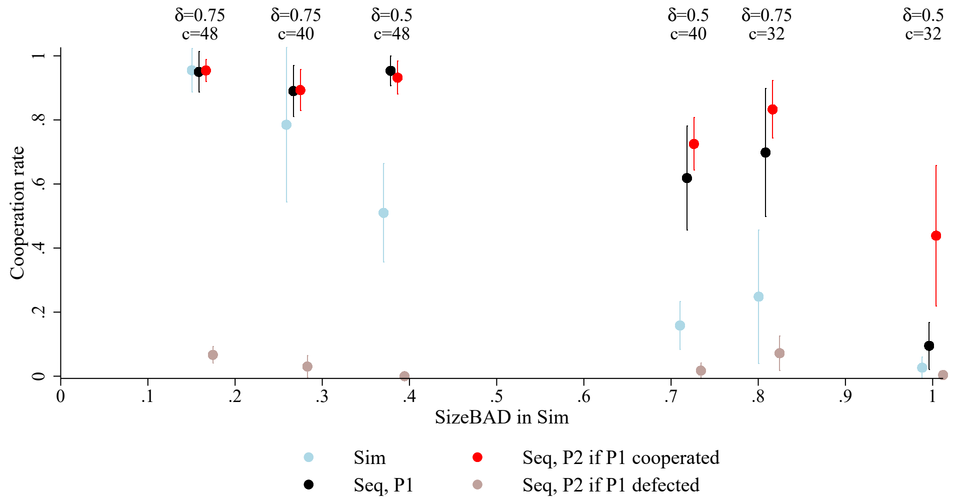


Figure 3. Cooperation rates by role.

Note: The graph shows first-round cooperation rates of P1, cooperation rates of P2 conditional on P1 defecting or cooperating, and cooperation rates in Sim, and 95% confidence intervals across the last 20 repeated games depending on the SizeBAD (including treatment labels). Estimates and confidence intervals are based on predictions from probit regressions run on treatment-role dummies with clustered standard errors at the matching group level.

relatively well-aligned.[24] Third, both cooperation rates are positively related to c and δ, even for $\delta > \delta^*$ ($p \leq 0.012$ for both c and δ in probit regressions excluding treatment $\delta = 0.5, c = 32$). These patterns cannot be explained based on a strict interpretation of the SizeBAD predictions, but are consistent with a quantal response explanation or with the notion that players are heterogeneous. In the next section, we examine the results more closely at the individual and matching-group levels and provide evidence that supports a heterogeneity interpretation.

C. *Disaggregated Analysis*

Second Movers. — We have shown that the conditional cooperation rate of second movers is well above zero in treatment $\delta = 0.5, c = 32$ (with $\delta < \delta^*$) and well below 1 in treatments $\delta = 0.5, c = 40$ and $\delta = 0.75, c = 32$ (with $\delta > \delta^*$). This implies either that *some* second movers *often* behave differently than a rational payoff-maximizer (consistent with a heterogeneity interpretation) or that *most* second movers *sometimes* behave differently than a rational payoff-maximizer (consistent with quantal response behavior). In order to differentiate between

[24]Specifically, $p = 0.013$ in $\delta = 0.5, c = 40$, $p = 0.516$ in $\delta = 0.5, c = 48$, $p = 0.017$ in $\delta = 0.75, c = 32$, $p = 0.850$ in $\delta = 0.75, c = 40$, and $p = 0.816$ in $\delta = 0.75, c = 48$.

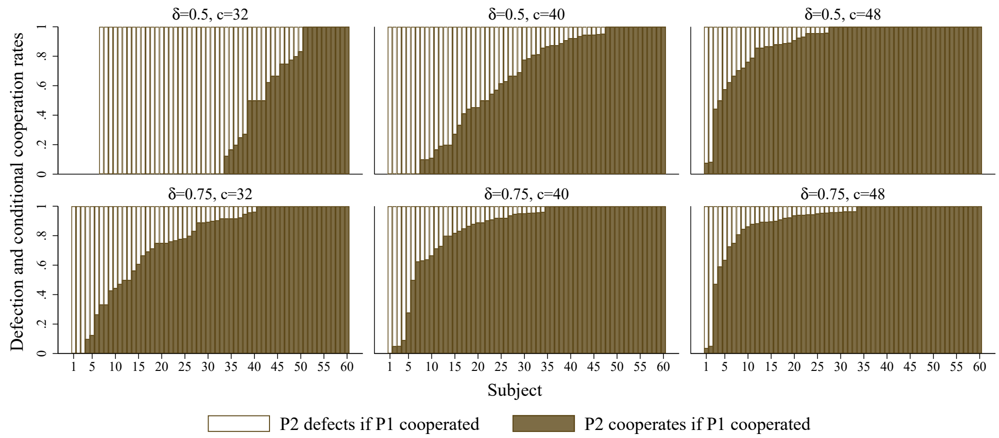


FIGURE 4. CONDITIONAL COOPERATION RATES BY SUBJECT.

Note: The graphs show first-round defection and cooperation rates in the role of second mover by subjects in Seq, conditional on the matched first mover cooperating. In $\delta = 0.5, c = 32$, 6 second movers never encountered cooperation by the first mover, while the remaining 54 second movers encountered cooperation by the first mover between 1 and 12 times with a median of 3. In the other treatments, all second movers encountered cooperation by the first mover at least 4 times with the median ranging from 12.5 to 22 across the 5 treatments.

these two explanations, we examine the frequency with which each subject cooperates in the role of second mover, conditional on the first mover cooperating. If second movers are homogeneous in the extent to which they deviate from the predicted choice, as is the case in representative-player models like the quantal response model, then the share of conditionally cooperative choices should be similar across subjects in a given treatment. Alternatively, if second movers are heterogeneous in the sense that some of them systematically deviate from the rational payoff-maximizing benchmark, then the share of conditionally cooperative choices should differ across subjects in a given treatment.

As can be seen in Figure 4, most of the conditional cooperation choices in treatment $\delta = 0.5, c = 32$ can be attributed to just a few subjects.[25] These subjects can be viewed as conditional cooperation types; types who conditionally cooperate because they have a preference to do so. In the treatments with $\delta > \delta^*$, where conditional cooperation types cannot be identified because they pool with payoff maximizers, many more subjects always or almost always conditionally cooperate.

Moreover, Figure 4 shows that the opposite pattern emerges in treatments $\delta = 0.75, c = 48$; $\delta = 0.5, c = 48$; and $\delta = 0.75, c = 40$. Here, very few subjects

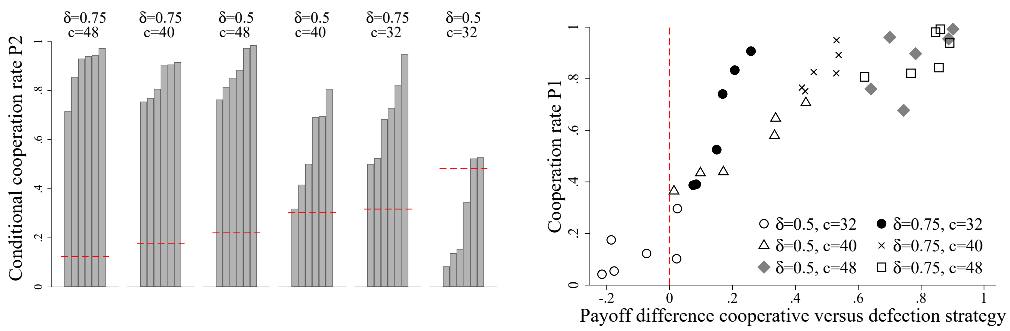
[25]For identification purposes, all analyses reported in this section include data from the first rounds of *all* the repeated games. Focusing on the last 20 repeated games would leave little power to perform disaggregated analyses.

are responsible for the majority of defection choices. Given that in these treatments, the decision to defect is more costly for second movers than in the other treatments, these subjects seem to have a strong taste for defection. We conclude therefore that a representative-player model does not suffice to explain disaggregated patterns of behavior of second movers. Instead, it appears to be necessary to allow for heterogeneity. This is backed up by an analysis which statistically compares distributions of observed choices shown Figure 4 to *iid* choices (see Section D in the Appendix for a detailed description). Overall, the findings closely align with the notion that second movers are heterogeneous with respect to their cooperation preference. This is illustrated in Section C.4 in the Appendix, in which we show that the data are well-represented by a heterogeneity model with payoff-maximizing, pro-social, and spiteful types.

First Movers. — Building on the insight that second movers come in types, we now focus more closely on behavior of first movers. Although the theoretical framework we use to formulate hypotheses builds on common knowledge of utilities, this assumption seems unrealistic if players are heterogeneous, especially in the anonymous context of our lab experiment. Instead, we assume that participants learn the distribution of second-mover types in their matching group during the course of the experiment, but do not know the specific type of their game partner (as in Kartal and Müller, 2018).[26] With this in mind, we can compare observed choices of first movers to choices that expected-payoff maximizers would make if they were faced with the same second-mover choices.

For each first mover, we first compute the conditional cooperation rate she encountered in her matching group across first rounds of all repeated games. Figure 5a shows these encountered conditional cooperation rates by treatment and matching group. The dashed horizontal lines refer to the conditional cooperation rate that leaves an expected-payoff-maximizing first mover indifferent between the repeated-game strategies of defection and cooperation. As can be seen, there is substantial variation across matching groups and treatments in the extent to which the conditional cooperation rate encountered by first movers deviates from the indifference threshold. Taking the encountered conditional cooperation rate as given, we calculate for each first mover the (normalized) difference between the expected payoff of the cooperative strategy and that of the defection strategy. A risk-neutral first mover is better off cooperating (defecting) when the difference is positive (negative) and is indifferent when the difference is zero. We then plot the first-mover cooperation rates aggregated by matching group as a function of the (normalized) payoff difference. If all first movers would be expected-payoff maximizers, then their cooperation rates would jump straight to one when the indifference threshold is crossed. Figure 5b shows that their cooperation rates are

[26]Recall that at the start of each repeated game participants are randomly allocated partners within matching groups and they randomly switch roles. Thus, in a sense each matching group constitutes a different 'population' of players.



(a) Encountered conditional cooperation rates (b) First-mover cooperation rates

FIGURE 5. COOPERATION RATES BY MATCHING GROUPS.

Note: Panel (a) shows the conditional cooperation rates encountered by first movers across first rounds of all repeated games by treatment and matching group. The horizontal lines represent the conditional cooperation rate that leaves a payoff-maximizing first mover indifferent between defection and cooperation. Treatments are ordered by the SizeBAD in Sim. Panel (b) shows first-mover cooperation rates across first rounds of all repeated games as a function of the normalized difference between the expected payoffs from cooperation and defection, given the encountered conditional cooperation rate. Each dot in the graph corresponds to a matching group, and the 6 different shapes correspond to the 6 parametrizations in the experiment.

close to zero in matching groups where the payoff difference is negative (in four of the six matching groups in treatment $\delta = 0.5, c = 32$) and that it increases as the payoff difference increases. Once cooperation is much more profitable than defection, then the cooperation rate stays close to one. We conjecture that the lack of a sudden jump at the threshold is due to heterogeneity of first movers. For example, the pattern is consistent with a substantial fraction of first movers being averse to disadvantageous inequality (see Section C.4 in the Appendix).

WITHIN-SUBJECT ANALYSIS. — Given that subjects make choices in both roles, additional insights related to heterogeneity can be obtained by investigating the choice patterns within subjects. We focus on the correlation between the conditional cooperation rate as a second mover, on the one hand, and the extent to which the cooperation rate as a first mover differs from the optimal first-mover cooperation rate, on the other hand. We define this optimal rate as the cooperation rate of a first mover who maximizes expected payoff while taking into account the conditional cooperation rate she encountered, as introduced in III.C. In most cases, it is equal to zero for $\delta = 0.5, c = 32$ and to one for the other treatments. Scatter plots by treatment are shown in Figure G.6 in the Appendix.

The first finding is that in the treatments with $\delta > \delta^*$, the correlation is overall positive and strong ($p \leq 0.018$). Players thus tend to cooperate as a first mover to almost the same extent that they conditionally cooperate as a second mover. We conjecture that this result is largely due to payoff maximizers having an incentive to cooperate in both roles, which makes them behave similarly to conditional cooperation types. The second finding is that no positive correlation is detected in treatment $\delta = 0.5, c = 32$, in which $\delta < \delta^*$. This result is consistent with the fact that payoff maximizers now have no incentive to conditionally cooperate as a second mover, nor to cooperate as a first mover. Any choice other than defection in $\delta = 0.5, c = 32$ can thus be attributed to behavior that differs from rational payoff maximization (such as, for example, other-regarding behavior or quantal responses). Given that as a first mover one is faced with higher strategic risk than as a second mover, there is no reason to expect that players who prefer to conditionally cooperate in $\delta = 0.5, c = 32$ as a second mover also prefer to cooperate as a first mover.

To further illustrate how players in $\delta = 0.5, c = 32$ make choices in different roles, we split up conditional cooperation types according to their behavior as a first mover. For simplicity, players are defined as conditional cooperation types if they conditionally cooperate more than half the time when encountering cooperation from the matched first mover. We find that 78% of them (14 out of 18) cooperate less frequently as a first mover than what is optimal and 17% (3 out of 18) cooperate more frequently than what is optimal. Among the other players, the percentages are 53% (19 out of 36) and 42% (15 out of 36), respectively, indicating a more balanced distribution. Although power is too low to provide conclusive statistical support, these findings suggest that conditional cooperation types tend to be more averse to disadvantageous inequality than other players.

IV. Conclusion

Failure to coordinate on efficient outcomes is largely due to individuals avoiding strategic risk (Van Huyck, Battalio and Beil, 1990, 1991). A similar logic applies with respect to cooperation in repeated games. Cooperation rates are highest in games where conditionally cooperative strategies involve little risk (Blonski, Ockenfels and Spagnolo, 2011; Dal Bó and Fréchette, 2011). We use this insight to predict that introducing sequentiality in games that are characterized by substantial strategic risk may facilitate cooperation by reducing that risk. The experiment we carry out shows that the prediction is borne out by the data. In games where it is difficult for players to achieve mutual cooperation — even though it can be supported in equilibrium — introducing sequentiality increases the cooperation rate by around 40 percentage points. In games where cooperation is not supported in equilibrium or where it is supported but strategic risk is particularly low, cooperation rates are close to zero or 100 percent respectively, independent of sequentiality. We thus conclude that individuals strongly react to sequentiality in environments with coordination problems that are the result of substantial strategic risk.

In modeling decision-making it is not always clear whether a simultaneous-move setting or a sequential-move setting is most appropriate. We show that behavior strongly depends on the setting, implying that possible policy implications may strongly depend on whether a simultaneous-move or sequential-move setting is ultimately chosen. The results also have implications for behavioral mechanism design. If a designer's goal is to achieve and sustain high efficiency levels, it is optimal that players decide sequentially and that second movers have information about the decision of the first mover. Consider, for instance, the issue of climate change, in which long-run incentives are arguably large enough for it to be optimal that countries engage in a cooperative mitigation of greenhouse gas emissions (Dutta and Radner, 2004; Calzolari, Casari and Ghidoni, 2018). If a country commits to a policy of reducing emissions in anticipation that other countries will follow suit, then those other countries will indeed have an increased incentive to do so because the risk of free-riding has been reduced. This may be good news for environmental policy makers because convincing one country or even a small group of countries to commit to environmentally-friendly actions is arguably easier to achieve than convincing all countries. Sequentiality might therefore help countries coordinate to achieve socially optimal outcomes. The same is true of other contexts, such as trade and employer-employee relations. Nevertheless, it is an open question as to whether the strong efficiency-enhancing effect of sequentiality is also achieved if the game's parameters are uncertain, which is a more realistic assumption in most applications. The result of Wilson and Vespa (2020) that cooperation does not predominate in a sequential-move setting with asymmetric information about payoffs suggests that this is not necessarily the case.

An alternative instrument that can in principle reduce strategic uncertainty is pre-play communication (see, for example, Arechar et al., 2017) and it appears that sequentiality can overcome some of its disadvantages. First, given that communication is not consequential on monetary payoffs, it has no effect on predictions based on equilibrium refinements or on concepts such as the basin of attraction of a particular strategy (Crawford, 1998). In contrast, sequentiality does affect monetary payoffs because it allows the second mover to avoid the sucker payoff. Second, the efficacy of communication in increasing coordination appears to be quite sensitive to the communication protocol, which makes implementation less straightforward than introducing sequentiality (see, for example, Cooper et al., 1992; Andersson and Wengström, 2012, for evidence from simple coordination games).[27]

Our results have implications for the interpretation of behavior in PD games played in (quasi-)continuous time (see, for example, Friedman and Oprea, 2012; Bigoni et al., 2015). Cooperation rates in (quasi-)continuous time are typically very high but the reasons are not entirely understood. These games differ in at

[27] That said, it also holds that pre-play communication can trigger behavioral responses that go beyond removing strategic uncertainty and can foster cooperation even if this is not an equilibrium outcome, for example by appealing to honesty (Gneezy, 2005) or inducing guilt aversion (Charness and Dufwenberg, 2006). To illustrate, pre-play chat has been shown to increase cooperation in one-shot interactions (see Balliet, 2010, for a meta-analysis) or in repeated simultaneous games in which cooperation cannot be sustained in equilibrium (Kartal and Müller, 2018).

least three respects from discrete-time simultaneous PDs: (a) the frequency of the (albeit shorter) interactions is higher in each repeated game; (b) players move *de facto* sequentially, i.e. they observe the partner's choice before making a choice; and (c) players choose the timing of their moves. Friedman and Oprea (2012) show that frequency of interaction increases the cooperation rate in discrete-time PDs; however our experiment shows that sequentiality on its own may also lead to a substantial increase in cooperation, provided that cooperation is sustainable in equilibrium. The sequential-move nature of games played in (quasi-)continuous time may thus be one of the structural characteristics that leads to the higher cooperation rate. This is consistent with the results of an experiment in which strategic uncertainty is removed by freezing choices for a few seconds, which is shown to increase cooperation (Calford and Oprea, 2017). Strategically, a sequential PD is similar to a simultaneous PD in which the choice of one of the players is frozen for one period.

Our analysis builds on a framework in which it is assumed that payoff-maximizing players choose between always defecting and conditional cooperation under common knowledge. This makes it possible to construct a simple measure of the degree of strategic uncertainty and helps to formalize the difference between sequential-move and simultaneous-move PDs. Thus, the approach is not meant to provide an accurate description of how individuals play. There are at least two ways in which behavior can be plausibly expected to deviate from the assumptions. First, players may follow strategies other than always defect or conditional cooperation. Results of strategy estimations show that by far the majority of the cooperative strategies involve conditional cooperation à la grim trigger or tit-for-tat (see Section E in the Appendix).[28] This, and the fact that we are dealing with relatively short games, gives us confidence that the simplification of the repeated games to binary-choice games is not overly simplistic.[29]

Second, players may not all be perfect payoff maximizers with common knowledge. We have shown that some form of heterogeneity is needed in order to explain all aspects of the data. To do so, we have used an example on other-regarding preferences but a similar intuition holds if there is heterogeneity in risk preferences or in the strength of quantal responses.[30] A key element is that the heterogeneity introduces individual-specific trade-offs between a conditional cooperation strat-

[28] An exception is the strategy to first defect and then switch to tit-for-tat (D-TFT), which is particularly popular among first movers and to some extent in the case of simultaneous moves, in the game in which cooperation cannot be sustained in equilibrium. We speculate that this may have to do with the fact that D-TFT protects a player from the sucker payoff if matched with a defecting partner and at the same time achieves mutual cooperation if the partner is lenient.

[29] One might argue that the finding that the conditional cooperation rate of second movers is well below 100% even if $\delta > \delta^*$ is related to the beliefs of second movers. In particular, if the second mover believes that the first mover either always defects or always cooperates, then it would be optimal for her to always defect. However, given that in the treatments with $\delta > \delta^*$ and intermediate gains from cooperation less than 2% of the first movers is estimated to always cooperate, holding such a belief would be largely irrational. We therefore feel that this is not a sufficient explanation.

[30] For example, risk-averse (risk-seeking) players will prefer conditional cooperation less (more) than always defect.

egy and an always-defect strategy, which introduce smoothness into the aggregate effect of the game's parameters on the cooperation rate, even in sequential-move games with $\delta > \delta^*$. A promising model that incorporates strategic risk and at the same time predicts smoothness is that of Kartal and Müller (2018). The model provides a micro-economic foundation for strategic uncertainty by assuming that players have heterogeneous and unobservable tastes.

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