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Voluntary Cooperation Based on Equilibrium Retribution - An Experiment Testing Finite-Horizon Folk Theorems

Lisa V. Bruttel*, Werner Güth†, Ulrich Kamecke‡, and Vera Popova§

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Abstract

Unlike previous attempts to implement cooperation in a prisoners' dilemma game with an infinite horizon in the laboratory, we focus on extended prisoners' dilemma games in which a second (pure strategy) equilibrium allows for voluntary cooperation in all but the last round. Our four main experimental treatments distinguish long versus short horizon and strict versus non-strict additional equilibrium compared to the control treatment, a standard prisoners' dilemma. Quite surprisingly, according to our results, only a strict additional equilibrium increases cooperation rate for a given time horizon. As expected a longer time horizon promotes cooperation.

JEL classification: C73, C91.

Keywords: Folk theorem, Finite horizon, Prisoners' dilemma, Experiment

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1 Introduction

One of the most influential insights of non-cooperative game theory is the potential conflict between social and individual rationality as exemplified in the two-person prisoners' dilemma game with two strategies, "defect" and "cooperate". It is well-known that this conflict can be solved if the game is repeated indefinitely, e.g. by threatening eternal play of "defect" in case of a defection from mutually profitable cooperation. However, if such games are played with a commonly known upper bound for the number of repetitions, their subgame perfect equilibria predict no cooperation at all. Nevertheless, there exists robust experimental evidence showing a high degree of fruitful voluntary cooperation (see, e.g., Andreoni and Miller, 1993) until approaching the known end of interaction (endgame). Although one cannot implement an infinite-horizon supergame in the lab (see Selten et al., 1997), ways to capture its illusion can enhance voluntary cooperation by limiting endgame non-cooperation (Dal Bó, 2005; Bruttel et al., 2007). Quite generally, this demonstrates how strong retributive emotions and inclinations¹ can maintain welfare enhancing voluntary cooperation even when such cooperation is not in line with equilibrium predictions based on common(ly known) opportunism (meaning that all know that all know... that all care only for their own material payoff).

The fact that retributive inclinations are strong enough to overcome (opportunistic) equilibrium incentives does not imply that welfare enhancing voluntary cooperation can be stabilized by equilibrium threats.² To allow for such equilibrium retribution, we extend the two-person prisoners' dilemma game with the original strategies "defect" and "cooperate" by a third strategy "avoid" whose mutual choice is a (non-)strict equilibrium of the one-shot extended prisoners' dilemma game. In the spirit of Benoit and Krishna (1985) we prove a finite horizon Folk Theorem-like result for finite repetitions of such games where we focus on parameter constellations allowing for equilibrium cooperation in all rounds except the last one.

¹Such findings are in line with punishment in ultimatum and finitely repeated public goods experiments as well as in one-shot interactions with an additional costly and arbitrary punishment option (see Camerer, 2003, for some survey).

²I.e., by retributive inclinations which can be justified by a subgame perfect equilibrium.

Our main experimental treatments rely on a two-by-two factorial design. One feature is the nature of the additional equilibrium of the one-shot (base) game - strict versus non-strict. The other feature is the commonly known finite number of repetitions where we distinguish between a short and a long horizon. Additionally, we explore a standard prisoners' dilemma game as a control treatment. We always rely on the same payoff parameters allowing equilibrium cooperation in all but the last round for all main treatments. Participants play such games repeatedly, similar to Selten and Stoecker (1986).

In section 2, we introduce a strong and a weak version of an extended prisoners' dilemma game and argue that the additional punishment option allows cooperative play in all but the last round although this is more convincing in the strong version of the game. The experimental protocol is described in section 3 together with some speculative hypotheses how retributive inclinations affect repeated play of base games with multiple equilibria, i.e. when and why voluntary cooperation can be expected. Section 4 presents the main findings and section 5 concludes.

2 Model analysis

2.1 The finite supergames

Let $i = 1, 2$ denote the players in the one-shot game. Each of them has three actions, C ("cooperate"), D ("defect"), and A ("avoid"). A pair of actions is denoted by $a = (a_1, a_2)$ where the action of player 1 is listed first and of player 2 second. We distinguish two symmetric payoff matrices of the one-shot interaction,

$i = 1 \backslash i = 2$	C	D	A
C	18, 18	0, 21	0, 0
D	21, 0	9, 9	0, 0
A	0, 0	0, 0	3, 3

EDP_s

and

$i = 1 \backslash i = 2$	C	D	A
C	18, 18	0, 21	3, 3
D	21, 0	9, 9	3, 3
A	3, 3	3, 3	3, 3

EDP_w

Clearly, the only pure strategy³ equilibria of both (base) games are (D, D) and (A, A) . However, (A, A) is an equilibrium in weakly dominated actions in EDP_w whereas it is

³In EDP_s there exists a mixed strategy equilibrium according to which both players use "defect" with probability 1/4 and "avoid" with probability 3/4.

strict and therefore in undominated actions in EPD_s . Correspondingly, we experimentally distinguish W-Treatments where participants play EPD_w and S-Treatments where they play EPD_s repeatedly with the same partner. S-Treatments feature situations where the alternative payoff of 3 can only be obtained by both players coordinating on “avoid”. W-Treatments capture situations where 3 is the conflict payoff resulting when at least one party uses “avoid”, i.e., where the avoid outcome does not require coordination.

In order to discuss these finite supergames we need some more notation. Let $T \geq 2$ denote the number of rounds of playing either EPD_w or EPD_s repeatedly with the same partner. In each game we observe histories $h_t \in H_t$ up to round t (a vector of length $2 \times T$ which, assuming appropriate information feedback between rounds, specifies all previous actions of the two players). A behavioral strategy profile $a : H \rightarrow \{C, D, A\} \times \{C, D, A\}$ specifies actions $a(h_t) = (a_1, a_2)(h_t)$ for all histories h_t of all rounds t .

2.2 Subgame perfect equilibrium outcomes

Folk theorems are often used to justify why one observes cooperation so frequently although cooperative outcomes are just one possible equilibrium outcome. We follow this usual idea by first presenting how cooperation can be stabilized before exploring the whole spectrum of subgame perfect equilibrium outcomes.

Obviously constant play of actions (A, A) or (D, D) is a subgame perfect equilibrium outcome of both repeated games, EDP_s and EDP_w . It is also easy to see that the threat to continue with the payoff $(3, 3)$ instead of $(9, 9)$ can discourage myopically profitable deviations. In particular, one can prove that the (grim) strategy constellation (a^{grim}, a^{grim}) for T-Supergames with

$$a_t^{grim}(h_t) = \left\{ \begin{array}{ll} C_t & \text{if } t = 1, \dots, T-1 \\ D_t & \text{if } t = T \\ A_t & \text{otherwise} \end{array} \right\} \text{ and } (a_\tau, a_\tau) = (C_\tau, C_\tau) \text{ for all } \tau < t \quad (1)$$

is a subgame perfect equilibrium:

Clearly, after playing (C, C) in all rounds $\tau < T$, it does not pay to defect unilaterally from (a^{grim}, a^{grim}) in the last round $t = T$ since (D, D) is a strict equilibrium of the

one-shot interaction. Similarly, defecting alone from (a^{grim}, a^{grim}) in round $t < T$ after some violation of “ (C, C) for all $\tau < T$ ” does not pay since constant play of (A, A) is a subgame perfect equilibrium of the supergame. Thus, it only remains to establish that deviating unilaterally from (a^{grim}, a^{grim}) in round t after “ (C, C) for all $\tau < t$ ” does not pay. Now what a player can gain by such a deviation is an additional payoff of 3 since the best deviation is to “defect” when the other “cooperates”. But since $t < T$, this will lead to periodic payoff of 3 rather than 18 or 9 in all later rounds. Thus, even in case of $t = T - 1$, the additional gain of 3 in round $t = T - 1$ would cost 6 in round T .⁴ Thus, (a^{grim}, a^{grim}) is a subgame perfect equilibrium of the $T \geq 2$ supergame with base game EPD_w and EPD_s respectively.

Of course, there exist other subgame perfect equilibria. In the first section of Appendix I we show that the same argument justifies a large number of equilibrium outcomes. In rounds preceeding some outcome (D, D) the equilibrium payoffs are only restricted by feasibility and the condition that the number of rounds still to be played r ($r = T - t$) must guarantee the maximin-payoffs of $r \cdot (3, 3)$. This condition imposes a restriction only on the use of the outcomes $(0, 0)$, $(21, 0)$, and $(0, 21)$, and it leads to the following conclusion:

“Folk Theorem-like Result”: For $T \rightarrow \infty$ the set of average payoffs in a subgame perfect equilibrium of the finite supergames with $T (< \infty)$ commonly known rounds of play and base game EPD_w or EPD_s converges to a dense set on the individually rational attainable average payoffs in

$$\Omega = \{(\pi_1, \pi_2) \mid (\pi_1, \pi_2) \geq (3, 3) \text{ and } (\pi_1, \pi_2) \in \text{conv}((3, 3); (21, 0); (18, 18); (0, 21))\} \quad (2)$$

In particular, the subgame perfect equilibrium strategies (a^{grim}, a^{grim}) predict that both players will “cooperate” in all rounds except in the last round when they both “defect” so that the average periodic payoffs converge to $(18, 18)$ as $T \rightarrow \infty$.

⁴In our experiment and the corresponding theoretical analysis we concentrate on supergames in which the cumulative payoffs of all T rounds are paid after the last round. However, our arguments would also hold if the players discount their payoffs with some sufficiently large $\delta < 1$. The cooperative outcome, for instance, is obtained, whenever $\delta > 1/2$.

2.3 Refining rationality

We will now confront this Folk Theorem-like Result with stronger concepts of strategic rationality. In the base game such a refinement is straightforward. For EPD_w , the constellation (D, D) is the only strict equilibrium of the base game, while the equilibrium (D, D) uses dominated strategies. For EPD_s , one can justify (D, D) as the solution of the base game by payoff dominance - (D, D) yields higher payoffs for both players than (A, A) - or by risk dominance. (D, D) has a larger stability set than (A, A) in the reduced game with strategies “defect” and “avoid” neglecting “cooperate” since it is weakly dominated.⁵ Thus, backwards induction plus equilibrium selection by payoff or risk dominance among strict equilibria predict constant play of (D, D) for the supergames of both base games. Such selection requires considerably more “rationality” in EPD_s and can be considered to be much weaker and therefore less relevant when explaining the observed behavior. Neither of the approaches predicts (C, C) outcomes.

Rather than relying on backwards induction for the solutions of the base game, one can use the axiom of subgame consistency (Selten and Güth, 1982) to challenge the Folk Theorem-like result. Subgame consistency prescribes the same equilibrium for isomorphic games. The only state variable of our finitely often repeated games is r , the number of rounds still to be played, i.e., subgames with the same number r are isomorphically related⁶ implying that all subgames of infinitely repeated games have no state variable at all. This refinement would lead to those subgame perfect equilibria with both players distinguishing two sets of rounds r^D and r^A and playing the strategies

$$a_t(h_t) = \begin{cases} D & \text{for } r \in r^D \\ A & \text{for } r \in r^A . \end{cases} \quad (3)$$

This rules out the folk theorem but can neither distinguish⁷ between EPD_s and EPD_w nor justify (C, C) outcomes.

To equilibrate cooperation the players have to condition their equilibrium continuation on the history of the game, that is they must threaten to continue the game with (A, A) instead of (D, D) after some “unwarranted” experience. Such reactions, used to prove

⁵See Harsanyi and Selten (1988)

⁶Meaning that their rules can be transformed isomorphically, e.g. by affine utility transformations or renaming of strategies and/or players.

⁷One can, of course, require strictness in addition to subgame consistency.

the folk theorem, are eliminated by a simple dominance argument in the last round of EPD_w but not of EPD_s . Using this dominance argument iteratively eliminates all but the defective strategies in EPD_w because all strategies employing C or A after some history h_t are dominated by a strategy using $a_i(h_t) = D$ when all strategies satisfy $a_i(h_\tau) = D$ for all $\tau > t$.

Unfortunately, the result of iterated elimination of dominated strategies may depend on the order in which the strategies are eliminated.⁸ We can, however, use a backwards elimination argument to prove two alternative results in EPD_w which do not hold in EPD_s . In the second section of Appendix I we show that “always defect” is the unique proper equilibrium and the unique strictly perfect equilibrium of EPD_w . These game theoretic arguments suggest less cooperation in EPD_w than in EPD_s .

“Strong Rationality Refinement”: The set of strictly perfect (proper) equilibrium outcomes satisfies a Folk Theorem-like Result in a repeated EPD_s , while it contains only defective play $a_i(h_t) = D$ for all $h_t \in H$ in a repeated EPD_w .

Such results are informative but also conceptually debatable. In particular it is not clear to what extent they capture the behavioral aspect of retribution, that is, whether retribution is just an equilibrium selection device favoring payoff dominant strategically stable outcomes or whether it is an independent motive guiding individual decision making. Rather than discussing this abstractly we want to answer such questions empirically, more specifically experimentally, to learn which outcomes can actually be observed and how this supports or questions the different rationality postulates.

⁸Even though our backwards elimination employs only “nice” weak dominance in the sense of Marx and Swinkels (1997) we cannot apply their result, because their condition of “Transference of Decision Maker Indifference” does not hold for our repeated game.

3 Experiment

3.1 Design and procedures

We explored in a between-subjects design the four treatments $4W$, $16W$, $4S$, and $16S$ which differed in

- whether the base game is EPD_w or EPD_s and
- whether the number T of rounds is $T = 4$ or $T = 16$.

All participants played 32 rounds of either EPD_w or EPD_s . In $16W$ and $16S$ they played two supergames of 16 rounds each, with two different partners. In $4W$ and $4S$ they played 8 successive but rather short supergames with 4 rounds each. We relied on a random strangers design involving rematching groups of 4 participants with the additional guarantee that in the next round one would not confront the same participant again.

To provide comparisons with usual prisoners' dilemma experiments and since at least in the later supergame(s) only matching groups qualify as independent observations, we performed

- two control sessions of $4PD$ and $16PD$ each with participants playing the prisoners' dilemma without the "avoid" option either for 4 or for 16 rounds with changing partners when repeating this,
- two sessions of $16W$ and $16S$ each and
- two sessions of $4W$ and $4S$ each

where each session involved 32 participants. Altogether we ran 12 sessions, yielding 16 independent observations for each of the six treatments. 384 undergraduate students of the University of Jena took part in the experiment. On average, they earned 8.80 Euros and spent one hour in the laboratory of the Max Planck Institute of Economics in

Jena, Germany. Upon arrival in the lab, subjects were randomly assigned to a cubicle, where they individually read the instructions.⁹ After the instructions were also read aloud, participants were able to familiarize themselves with the experiment during two or three (depending on the treatment) test rounds. Hereafter they answered a questionnaire checking their understanding of the game rules. After that they participated in the computerized¹⁰ experiment.

3.2 Behavioral predictions

It is not obvious what behavior to expect in this experiment. Subgame perfection allows cooperative play in all but the last round for both repeated games, EPD_w and EPD_s . Stronger concepts of rationality show that this outcome is less credible in EPD_w , so that cooperation should be higher in EPD_s . It is, however, not clear whether such rationality concepts have descriptive content. Moreover, participants may perceive defecting and punishing in EPD_s as more risky since a possible punitive play of action A generates a coordination problem and may therefore lead to outcomes different from (A, A) with zero round payoffs for both players. Punishment in EPD_w does not exhibit this problem and is therefore less costly for the punisher in case of miscoordination on outcomes different from (A, A) . Thus, cooperation may even be higher in EPD_w .

Concerning the time horizon, the theoretic analysis in appendix I.1 demonstrates how the set of potential equilibrium outcomes increases for earlier rounds. For $T = 4$ (i.e. treatments 4W and 4S) considerable play of (D, D) throughout would therefore not be surprising. In the longer treatments, on the other hand, individual play is not restricted by strategic rationality so that participants' reaction to an early (t much smaller than T) deviation from (C_τ, C_τ) for all $\tau < t$ may not be "grim" in the sense of always playing A afterwards. Instead, players may punish by choosing strategy D since outcome (D, D) payoff-dominates (A, A) in the base games. Finally, in case of very early deviations from mutual cooperation (C, C) participants may even try to return to cooperation hoping for a forgiving opponent as illustrated by tit-for-tat rather than grim strategies.

All these behavioral speculations demonstrate that our design allows for a lot of variation in retributive behavior, not necessarily questioning the equilibrium character of retributive inclinations.

⁹For a translation of the instructions see Appendix II.

¹⁰We used Fischbacher's (2007) z-Tree software.

4 Results

4.1 Cooperation rates across treatments

Average¹¹ cooperation rates by treatment are depicted in Figure 1 and Table 1. Cooperation rates are higher when the horizon of the supergame is longer and the additional equilibrium is strict rather than weak. More specifically, cooperation rates monotonically increase from 4PD, over 4W, 4S, 16PD, and 16W toward 16S.

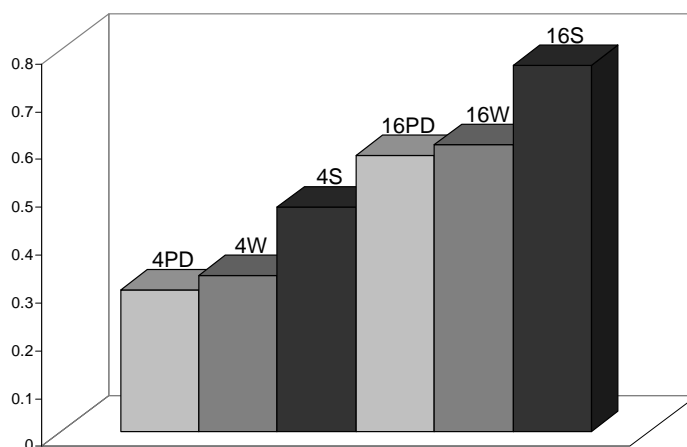


Figure 1: Mean cooperation rates by treatment

Treatment	4PD	4W	4S	16PD	16W	16S
Mean cooperation rate	0.296	0.327	0.470	0.578	0.599	0.765

Table 1: Mean cooperation rates by treatment

Within the same horizon, only the strict game triggers significantly more cooperation. The effect between the weak treatment and the pure PD is not statistically significant for both horizons, i.e., multiplicity of equilibria alone does not inspire more cooperation. Across horizons, cooperation is significantly higher for the longer horizon for all game types (PD, W, S). The results of pairwise comparisons between treatments with respect to means using a Wilcoxon rank-sum test are summarized in Table 2.

¹¹Results the following analysis do not substantially change when considering medians instead of means. Therefore, we do not discuss them separately.

Treatment	16S vs. 16W	16S vs. 16PD	16W vs. 16PD
p values	0.036	0.030	0.706
Treatment	4S vs. 4W	4S vs. 4PD	4W vs. 4PD
p values	0.065	0.048	0.650
Treatment	16PD vs. 4PD	16S vs. 4S	16W vs. 4W
p values	0.004	0.001	0.002

Table 2: Wilcoxon rank-sum p values for means; null hypothesis: two independent samples are from populations with the same distribution

Figure 2 captures the evolution of cooperation over time, on the left hand side for the short horizon and on the right hand side for the long horizon. Vertical lines indicate the last period of an interaction with the same partner. The figure shows that the results above hold not only at the aggregate level but also for most rounds. When performing Wilcoxon rank-sum tests, based on pairwise comparisons between treatments for each round in almost all rounds cooperation rates for the strict game lie above those for the other games. For the short horizon, cooperation in the strict treatment is significantly higher than cooperation in the weak and in the PD treatment in 75% of the rounds (see Table 7, Appendix). Interestingly, even in the last round, there is a pronounced difference between the strict treatment and the other two. For the long horizon cooperation in the strict game is higher than that in the weak game in 75% of the rounds. Cooperation in the strict game is above cooperation in the PD in 81% of all rounds (see Table 8, Appendix). In case of the long horizon we do not observe a significant game effect in the last round.

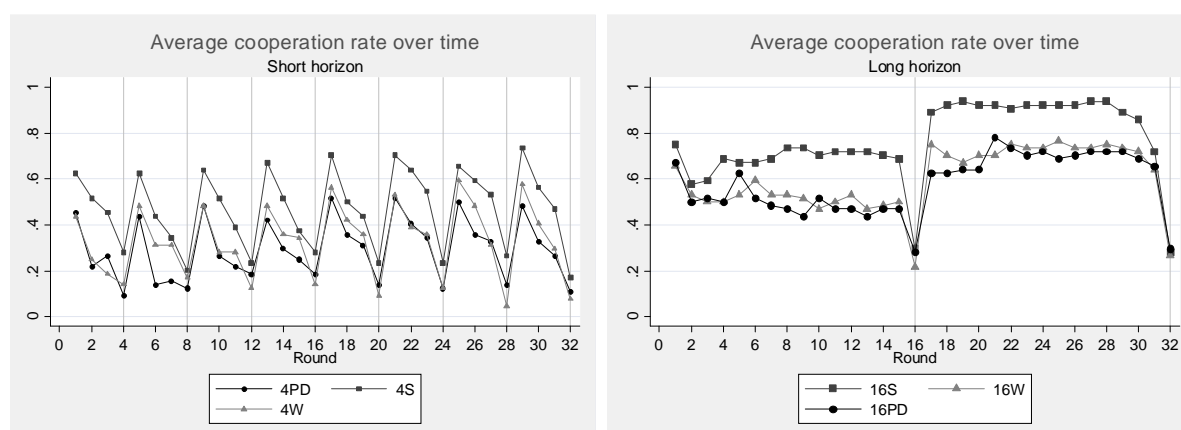


Figure 2: Average cooperation rates over time

From Table 2 and Figure 3 we conclude that regardless of the game there is always more cooperation when participants face the longer horizon.

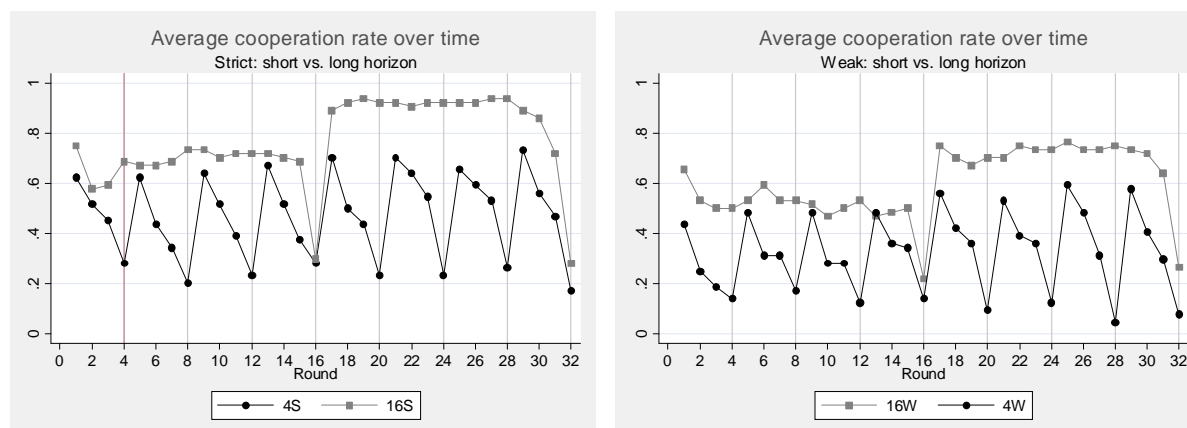


Figure 3: Long vs. short horizon over time

Neglecting the first 12 rounds in case of the long horizon we can compare the remaining four rounds with the four rounds of the short-horizon games. The findings do not change. Cooperation rates for the long horizon remain significantly higher (see Table 3) suggesting the following results.

Last 4 rounds of treatments	4S vs. 16S	4W vs. 16W	4PD vs. 16PD
<i>p</i> values	0.0898	0.026	0.038

Table 3: Wilcoxon rank-sum *p* values; null hypothesis: two independent samples are from populations with the same distribution.

Result 1 *For all three base game types PD, W, and S cooperation is significantly higher in the supergames with the longer time horizon.*

Result 2 *For the same time horizon only an additional **strict** equilibrium **significantly increases** cooperation rates compared to the prisoner's dilemma game.*

Result 3 *An additional **weak** equilibrium **does not increase** cooperation rates for both time horizons compared to the prisoner's dilemma game.*

Results 2 and 3 are very much in line with the theoretical prediction of the “Strong Rationality Refinement” that only the strict additional equilibrium should allow for higher cooperation rates. From a behavioral point of view, however, it is rather surprising that an additional weak equilibrium of the stage game does not at all increase cooperation.

4.2 Actual use of the additional action A

Decision	16S	16W	4S	4W
C	76.46%	59.86%	47.17%	32.62%
D	22.41%	37.45%	51.07%	65.92%
A	1.12%	2.69%	1.76%	1.46%

Table 4: Relative frequency of decisions by treatment; C : “cooperate”, D : “defect”, A : “avoid”

When justifying cooperation the main purpose of action A is to discourage deviations from cooperation, i.e., the additional action is mainly chosen off the equilibrium path. Hence, its actual use should be rare or at least become rare with experience. Table 4 lists the relative frequency of the three actions C , D , and A by treatment. A ’s relative frequency is less than 3% supporting the idea that action A is not supposed to be used.

Absolute frequency of A -choices after ...	4S	4W	16S	16W
own C and other’s C	0	0	0	0
own C and other’s D	14	9	9	9
own C and other’s A	0	0	0	0
own D and other’s C	1	2	3	6
own D and other’s D	11	15	5	23
own D and other’s A	1	0	1	1
own A and other’s C	1	0	0	0
own A and other’s D	8	4	5	16
own A and other’s A	0	0	0	0

Table 5: Absolute frequency of decision A after a given outcome in the previous period by treatment; C : “cooperate”, D : “defect”, A : “avoid”

Table 5 illustrates when players use action A . Most of the time subjects select A after the partner has played D in the previous period, i.e., after outcomes (C, D) , (D, D) , or (A, D) . Option A seems to be just a punishing device.

Table 6 provides evidence on how players react when their partner uses A in the previous round. Do “punished” subjects become more cooperative in the next round? In fact, only a few start cooperating. Most subjects continue playing D . Punishment seems to be ineffective.

Reaction after the other has played A	4S	4W	16S	16W
C after own C and other's A	2	0	4	4
C after own D and other's A	8	3	2	5
C after own A and other's A	0	0	1	3
D after own C and other's A	2	1	1	1
D after own D and other's A	21	22	9	38
D after own A and other's A	0	0	1	1
A after own C and other's A	0	0	0	0
A after own D and other's A	1	0	1	1
A after own A and other's A	0	6	0	0

Table 6: Absolute frequency of decisions C , D , or A after outcomes (C, A) , (D, A) , or (A, A) by treatment; C : “cooperate”, D : “defect”, A : “avoid”

Result 4 *The additional action A is mainly used as a punishment device. In the rare cases when subjects play A , they do so when the partner has not chosen C before. This “punishment”, however, is ineffective since only a few partners subsequently switch to C .*

5 Conclusion

With multiple equilibria in the base game Folk Theorem-like results do not require an infinite horizon as established by the theoretical results in section 2. According to the Folk Theorem, the existence of multiple equilibria in the base game suffices for subgame perfect equilibrium cooperation in all rounds except the commonly known last round of interaction. By refining subgame perfection one can, however, distinguish whether the additional equilibrium of our extended prisoners’ dilemma games is strict or not. Our experimental results reveal that behaviorally this is the dividing line between base games yielding cooperative or non-cooperative outcomes except for the last round(s).

As expected a longer horizon promotes cooperation even when also the short horizon is sufficient for subgame perfect equilibrium cooperation. Such a horizon effect could be predicted by reputation equilibria (Kreps et al., 1982) where, however, for base games with multiple equilibria the necessary type of incomplete information is far from obvious.

There exist intermediate games with bimatrix representation

$i = 2 \backslash i = 1$	C	D	A	or	$i = 2 \backslash i = 1$	C	D	A
C	18, 18	0, 21	0, 0		C	18, 18	0, 21	3, 3
D	21, 0	9, 9	0, 0		D	21, 0	9, 9	3, 3
A	3, 3	3, 3	3, 3		A	0, 0	0, 0	3, 3

which could sharpen our understanding of how retributive motivation affects behavior in social dilemma games with additional punishment options. In the left-hand diagram, A is undominated for player 1 but not for player 2 and vice versa in case of the right-hand table above. When comparing EPD_s with EPD_w , one could argue that the retributive threat A in EDP_w is either strengthened by higher payoffs for unilateral play of strategy A or weakened by rendering it weak. The two intermediate games could reveal whether the first argument depends on who is the only one using strategy A . However, in order not to overburden our experimental design, we left them for future research.

Appendix I: equilibrium predictions

I.1 The Folk Theorem

Let us give up symmetry and explore the payoff space which can be justified by any pure strategy subgame perfect equilibrium as it is usually done when establishing Folk Theorems.

Suppose EPD_w is repeated T times so that the number of rounds left to be played is $r = T \dots 1$. In each round r both players i select a stage game action $a_i \in \{C, D, A\}$.

In the last round ($r = 1$) we have two pure subgame equilibrium strategies, (D, D) and (A, A) with additional subgame payoffs $(9, 9)$ and $(3, 3)$ respectively.

In the second last round ($r = 2$) the continuations are sufficient to discourage deviation from cooperation so that (C, C) is supported as equilibrium outcome with continuation (D, D) and the threat to select (A, A) instead after a deviation. For the same reason the (less interesting) actions (D, A) and (A, D) can occur in equilibrium. Thus, the additional subgame payoffs $\Pi_2 = \{(27, 27), (18, 18), (12, 12), (6, 6)\}$ are realized by the corresponding

subgame equilibrium strategies. In this round coordination failure (C, D) and (D, C) and the actions (C, A) and (A, C) are never chosen in equilibrium, because the corresponding potential gains of 9 and 15 after a deviation cannot be compensated by equilibrium retribution in the last round.

A round earlier ($r = 3$) this is no longer true, because the threat to continue with $(18, 18)$, $(12, 12)$ or $(6, 6)$ instead of $(27, 27)$ or with $(6, 6)$ instead of $(18, 18)$ discourages deviations. Similarly, the remaining asymmetric actions (C, A) and (A, C) can be stabilized in this round if the players continue with an equilibrium payoff $(6, 6)$ instead of $(27, 27)$. Thus, all nine action combinations may occur in an equilibrium in rounds $r \geq 3$ when the feasible continuations are restricted as described above. The resulting asymmetric and symmetric additional subgame payoffs are then

$$\begin{aligned} \Pi_3 &= \{(48, 27), (27, 48), (39, 18), (18, 39), (45, 45), (36, 36), (30, 30)\} \\ &\cup \{(27, 27), (21, 21), (15, 15), (9, 9)\}. \end{aligned} \quad (4)$$

The resulting restrictions on the action combinations can be summarized as follows¹²:

Theorem 1 *A combination of actions (a_1, a_2) in round r of the repeated weak extended prisoners' dilemma game is compatible with a subgame perfect equilibrium if and only if $r \geq 3$, or $r = 2$ and $(a_1, a_2) \in \{(C, C), (D, D), (D, A), (A, D), (A, A)\}$, or $r = 1$ and $(a_1, a_2) \in \{(D, D), (A, A)\}$.*

In earlier rounds ($r = 4, 5 \dots$) the equilibrium strategies also allow all nine action combinations. The corresponding set equilibrium payoffs is generated by adding the potential stage payoffs $\{(18, 18), (21, 0), (0, 21), (9, 9), (3, 3)\}$ to the set of equilibrium payoffs in the following round whenever the difference to the strongest potential punishment is sufficient to deter deviations. To construct the next stage equilibrium payoffs we therefore have to split the subgame equilibrium payoffs starting in the following round $r - 1$ into the following three (non-disjoint) sets

$$\Pi_{r-1}^1 = \Pi_{r-1} \cap \{(\pi_1, \pi_2) \mid \pi_1 \geq 3r \text{ and } \pi_2 \geq 3r\} \quad (6)$$

$$\Pi_{r-1}^2 = \Pi_{r-1} \cap \{(\pi_1, \pi_2) \mid \pi_1 \geq 3r + 6\} \quad (7)$$

$$\Pi_{r-1}^3 = \Pi_{r-1} \cap \{(\pi_1, \pi_2) \mid \pi_2 \geq 3r + 6\} \quad (8)$$

¹²Of course, not all actions can be combined to an equilibrium history so that there are further restrictions on the set of equilibrium strategies.

and then add the continuation payoffs as follows:

$$\Pi_r = (\Pi_{r-1} + \{(9, 9), (3, 3)\}) \cup (\Pi_{r-1}^1 + \{(18, 18)\}) \cup (\Pi_{r-1}^2 + \{(21, 0)\}) \cup (\Pi_{r-1}^3 + \{(0, 21)\}) \quad (9)$$

This construction algorithm guarantees that the unstable stage game payoffs $(18, 18)$, $(21, 0)$ and $(0, 21)$ are only added if they can be stabilized by subsequent deviations to the worst equilibrium continuation which always gives $(3(r-1), 3(r-1))$. For $r = 4$ (after eliminating double elements) this yields the set of possible additional subgame payoffs

$$\Pi_4 = \{(57, 36), (51, 30), (36, 57), (30, 51), (48, 27), (27, 48), (36, 36)\} \quad (10)$$

$$\cup \{(30, 30), (24, 24), (18, 18), (12, 12)\} \quad (11)$$

$$\cup \{(63, 63), (54, 54), (48, 48), (45, 45), (39, 39), (33, 33)\} \quad (12)$$

$$\cup \{(69, 27), (60, 18), (66, 45), (57, 36), (51, 30), (48, 27), (42, 21)\} \quad (13)$$

$$\cup \{(27, 69), (18, 60), (45, 66), (36, 57), (30, 51), (27, 48), (21, 42)\} \quad (14)$$

It is straightforward that a folk theorem holds for the resulting average equilibrium outcomes:

Theorem 2 *The set of average equilibrium payoffs Π_r/r converges to a dense set on the individually rational attainable average payoffs in*

$$\Omega = \{(\pi_1, \pi_2) \mid (\pi_1, \pi_2) \geq (3, 3) \text{ and } (\pi_1, \pi_2) \in \text{conv}((3, 3); (21, 0); (18, 18); (0, 21))\}. \quad (15)$$

To show this limit result we approximate every interior point of Ω as a rational convex combination $\alpha \cdot (3, 3) + \beta \cdot (21, 0) + \gamma \cdot (18, 18)$ or $\alpha \cdot (3, 3) + \beta \cdot (0, 21) + \gamma \cdot (18, 18)$. Let us choose T such that $\alpha T \in \mathbb{N}$, $\alpha T \geq 4$, $\beta T \in \mathbb{N}$ and $\gamma T \in \mathbb{N}$, and let the players use $(\alpha T - 1)$ times $(3, 3)$, βT times $(21, 0)$ or $(0, 21)$ respectively, γT times $(18, 18)$ and $(9, 9)$ once. This payoff scheme can be realized as an equilibrium outcome because it ends with equilibrium payoffs and because individual rationality $(\pi_1, \pi_2) \geq (3, 3)$ restricts the use of $(21, 0)$ sufficiently to allow the necessary threat for equilibrating such behavior.

In the strict extended prisoners' dilemma game EPD_s the situation is more complicated as the additional payoff $(0, 0)$ is more difficult to reach in an equilibrium. However,

since this payoff is below the maxmin stage game payoff¹³ this additional cell is only of limited relevance. In the last round there is no difference since the set of equilibrium payoffs coincides with those in the weak game. In the second last round ($r = 2$) the stage payoffs $(0, 0)$ can be added to $(9, 9)$ and $(18, 18)$, because the threat to move on with $(3, 3)$ instead is sufficient to stabilize the corresponding actions. Thus, $\Pi_{2,strict} = \{(27, 27), (18, 18), (12, 12), (9, 9), (6, 6)\}$ contains one element more than $\Pi_{2,weak}$. This trick allows to fill the gaps between the average payoffs faster, but it does not change the limit result in theorem 2, since it never affects the smallest average payoff $(3, 3)$. The equilibrium actions are a bit more restricted than above:

Theorem 3 *A combination of actions (a_1, a_2) in round r of the repeated strict extended prisoners' dilemma game is compatible with a subgame perfect equilibrium if and only if $r \geq 4$, or $r = 3$ and $(a_1, a_2) \notin \{(A, C), (C, A)\}$, or $r = 2$ and $(a_1, a_2) \in \{(C, C), (D, D), (A, A)\}$, or $r = 1$ and $(a_1, a_2) \in \{(C, C), (D, D)\}$.*

1.2 Properness as a refinement

In this subsection we need additional notation. We denote by α_i mixed behavioral strategies with probabilities $\alpha_{ia}(h)$ for the three possible actions $a \in \{C, D, A\}$ after history $h \in H$. The normal form pure (mixed) strategies are denoted by s (σ), σ^ε is a sequence of completely mixed strategies with $\varepsilon \rightarrow 0$ and with $\sigma_i^\varepsilon(s_i) \geq \varepsilon$ for every pure strategy s_i , $(\sigma \mid s_i)$ is the strategy vector in which the (mixed) strategy σ_i is replaced by the (pure) strategy s_i , $\pi(\sigma) = (\pi_1(\sigma), \pi_2(\sigma))$ is the expected payoff realized if the strategies σ are played, and the payoff $\pi_i^h(\sigma)$ is the expected payoff of a mixed strategy conditional on the fact that history h has been reached (which is always well-defined for completely mixed strategies).

It is easy to see that the folk theorem above holds in EDP_s also if we restrict the attention to strictly perfect equilibria, that is to equilibria which are stable with respect to every perceivable uniform tremble. In EDP_w the situation is drastically different. There the simple argument holds only for the defective equilibrium in which the players select the strategies $a_i(h_t) = D$ for all $t = 1 \dots T$. All other equilibria can be excluded by backwards induction in the form of repeated elimination of dominated strategies sketched above: let

¹³If one chooses, for instance, D with probability $1/4$ and A with probability $3/4$, one is sure to receive at least an expected payoff of $3/4$ regardless of what the other does.

players tremble such that future mistakes matter much less than present ones; from the requirement that (agent normal form) perfect equilibria must not use dominated behavioral strategies follows that players will not use dominated actions in the last round; so assume that the players select only behavioral strategies $a_i(h_t) = D$ for all $t > \hat{t}$, then $a_i(h_{\hat{t}}) = D$ is the unique best reply after any $h_{\hat{t}} \in H_{\hat{t}}$ to a completely mixed strategy, because potential gains from future trembles are negligible compared to the present gains. Thus, we can conclude that this tremble structure justifies only the defective action as equilibrium behavior:

Theorem 4 *Defective play $a_i(h_t) = D$ for all $h_t \in H$ is the unique strictly perfect equilibrium in the agent normal form of EDP_w .*

The concept of strict perfection is not accepted in the literature for both technical and conceptual reasons. We therefore use the concept of proper equilibrium (Myerson, 1978) to defend the uniqueness of defective play in EDP_w . To impose rationality also in unreached decision nodes we restrict our attention to normal form proper equilibria in behavioral strategies which are approximated by ε -proper equilibria as proposed by van Damme (1987, p.119) to prove

Theorem 5 *Defective play $a_i(h_t) = D$ for all $h_t \in H$ is the unique strategy which can be approximated by the normal form strategies of an ε -proper equilibrium of EDP_w .*

We show that the behavioral strategies concentrate on an ‘always defect’ continuation, that is $\alpha_{iD}^\varepsilon(h) \geq \varepsilon \alpha_{ia}^\varepsilon(h)$ for both actions $a \in \{C, A\}$ and for all histories $h \in H$ so that ‘always defect’ is the unique proper equilibrium which can be approximated by corresponding induced ε -proper behavioral equilibrium strategies.

We proceed by backwards induction. Suppose the claim is true for all histories of length $\rho < r$. Take an arbitrary history $h_r \in H_r$ of length $T - r$ and assume that the outcomes in period r are not concentrated on (D, D) , that is the limit distribution induced by $\alpha^\varepsilon(h_r)$ on the nine states puts a positive limit probability on some state $(a_1, a_2) \neq (D, D)$ as $\varepsilon \rightarrow 0$. Let $D_i(h_r)$ be the set of player i ’s defective continuations of h_r , that is the pure strategies which follow h_r and select defect (D) in all following decision nodes. Our induction assumption implies that both players concentrate on defective continuations

$d_i \in D_i(h_r, (a_1, a_2))$, no matter which state (a'_1, a'_2) is realized after h_r . So if $(a_1, a_2)(h_r) \neq (A, A)$ (at least) one of the players can improve his payoff by a deviation to a $d_i \in D_i(h_r)$: if $a_j \neq A$ player $i \neq j$ gets a larger payoff after h_r while the outcomes in the rest of the game are $(9, 9)$ with probability $(1 - \varepsilon)^{T-r} \rightarrow 0$. Thus, the expected outcome difference in the remaining periods becomes negligible as compared to the gain after h_r .

So let $(a_1, a_2) = (A, A)$ and compare player 1's payoff $\pi_1^h(\sigma^\varepsilon | d_1)$ after a defective continuation $d_1 \in D_1(h_r)$ and player 1's payoff $\pi_1^h(\sigma^\varepsilon | \hat{s}_1)$ after any pure strategy \hat{s}_1 which continues with at least one later deviation from D after some history $(h_r, (A, A) \dots)$. Both payoffs contain the same constant value which is realized up to h_r . In round r player 1 gets more than 3 if player 2 trembles to C or D while $(\sigma^\varepsilon | \hat{s}_1)$ leads to a payoff of 3. In later rounds player 1 may gain or lose from further trembles if he continues with $(\sigma^\varepsilon | d_1)$, while $(\sigma^\varepsilon | \hat{s}_1)$ generates a loss of at least 6 against 2's regular strategy at least once. Thus, we get that $\pi_h(\sigma^\varepsilon | d_1) - \pi_h(\sigma^\varepsilon | \hat{s}_1) \geq \varepsilon(21(T - r)) + 6 \cdot (1 - \varepsilon) > 0$ for ε sufficiently small so that the requirement of ε -proper trembles implies that player 1's trembles satisfy $\sigma_1^\varepsilon(d_1) \geq \varepsilon \cdot \sigma_1^\varepsilon(\hat{s}_1)$.

Finally, we use this condition to compare player 2's defective continuations $d_2 \in D_2(h_r)$ with the pure strategy $\hat{s}_2 \in D_2(h_r, (A, A))$ on which he is supposed to concentrate. The defective continuation d_2 gives a higher payoff than \hat{s}_2 ($\pi_2^h(\sigma^\varepsilon | d_2) > \pi_2^h(\sigma^\varepsilon | \hat{s}_2)$) if player 1 trembles after h_r and it may give less (or more) if player 1 trembles in later rounds. The condition $\sigma_1^\varepsilon(d_1) \geq \varepsilon \cdot \sigma_1^\varepsilon(\hat{s}_1)$ implies that later trembles are much less likely so that the resulting expected present gains dominate potential future losses for small ε . This implies that strategies which put a positive weight on the action $a_i(h_r) = A$ cannot be best replies to σ and are therefore by van Damme's (1987, p.30) Lemma 2.3.2 incompatible with an ε -proper equilibrium.

Appendix II: instructions

Welcome and thank you for participating in this experiment. Please read the instructions carefully. From now on we ask you to remain seated and to stop communicating with other participants. If you have any questions, please raise your hand. We will come to your place and answer your questions in private. It is very important that you follow these rules. Any violation will lead to your exclusion from the experiment and any payment.

The instructions are identical for all participants.

You will participate in the following sub-experiment two [eight]¹⁴ times. Every sub-experiment consists of 16 [four] rounds. Within the same sub-experiment you will be interacting with the same participant. Whenever a sub-experiment is finished, the other participant will be replaced. [It is possible that you interact with a participant you have already interacted with. However it is impossible that you interact with the same other participant for two consecutive sub-experiments.]

In each round, you and the other participant will be simultaneously asked to choose one of three {two} alternatives A, B, or C {A, or B}.¹⁵ Depending on your own decision and the decision of the other participant, your earnings are given by the following table.¹⁶ ¹⁷

¹⁴In brackets: short horizon.

¹⁵In curly brackets: PD treatments.

¹⁶In parentheses: weak game. The table for the PD game consists only of the cells that include choices A and B.

¹⁷ECU = Experimental Currency Units

My decision	The decision of the other participant	My earnings in ECU	The earnings of the other participant in ECU
A	A	18	18
A	B	0	21
A	C	0(3)	0(3)
B	A	21	0
B	B	9	9
B	C	0(3)	0(3)
C	A	0(3)	0(3)
C	B	0(3)	0(3)
C	C	3	3

If you, for example, choose A, while the other participant chooses B, you will earn 0 ECU and the other will earn 21 ECU. If you choose B and the other chooses A, you will receive 21 ECU and the other 0 ECU. At the end of each round you will be informed about

- your own decision
- the decision of the other participant
- your earnings from the current round
- your total earnings from the current sub-experiment

Your earnings from the two [eight] sub-experiments will be added up and paid to you in cash at the end of the experiment. The exchange rate is 66 ECU per 1 Euro. Additionally, you will receive a show-up fee of 2.50 Euros.

After reading these instructions, you can familiarize yourself with the experiment during three {two} test rounds. The test rounds are not relevant for your earnings. Then you will be asked to answer some control questions. Hereafter the experiment will start. In the end we will ask you to fill in a brief questionnaire.

Appendix III: tables

Round	4S vs. 4W	4S vs. 4PD	4W vs. 4PD
1	0.09	0.05	0.56
2	0.08	0.02	0.40
3	0.13	0.17	0.64
4	0.01	0.05	0.77
reject equality in % of rounds	75%	75%	0%

Table 7: Wilcoxon rank-sum tests by period for the short horizon; null hypothesis: two independent samples are from populations with the same distribution

Round	16S vs. 16W	16S vs. 16PD	16W vs. 16PD
1	0.09	0.01	0.41
2	0.14	0.01	0.39
3	0.04	0.02	0.69
4	0.02	0.01	0.77
5	0.06	0.44	0.27
6	0.16	0.07	0.57
7	0.05	0.04	0.77
8	0.03	0.01	0.69
9	0.04	0.00	0.30
10	0.02	0.06	0.82
11	0.02	0.01	0.80
12	0.04	0.02	0.59
13	0.03	0.03	0.84
14	0.03	0.03	0.89
15	0.19	0.19	0.92
16	0.36	0.86	0.43
reject equality in % of rounds	75%	81%	0%

Table 8: Wilcoxon rank-sum tests by period for the long horizon; null hypothesis: two independent samples are from populations with the same distribution

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