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Experts Playing the Traveler's Dilemma

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Abstract

We analyze a one-shot experiment on the traveler's dilemma in which members of the Game Theory Society, were asked to submit both a (possibly mixed) strategy and their belief concerning the average strategy of their opponents. Very few entrants expect and play the unique Nash equilibrium, while we observe a fifth playing the co-operative solution of the game, i. e. a strictly dominated strategy. The experimental data suggest to analyze the game as one of incomplete information. Most strategies observed are in the support of its Bayesian Nash equilibria. A notable exception is the Nash equilibrium strategy of the original game. (JEL C91, C72)

The traveler's dilemma was first described by Kaushik Basu (1994) at the conference of the American Economic Association in January 1994.[1] Basu proposed this game in order to demonstrate the conflict between intuition and game-theoretic reasoning in a one-shot game. We report the results of an experiment conducted on this game as a one-shot game participants being experts in game theory, in particular members of the Game Theory Society.

The parable for the traveler's dilemma (Basu, 1994, pp. 391) is the following: "Two travelers returning home from a remote island, where they bought identical antiques [...], discover that the airline has managed to smash these [...]. The airline manager [...] assures the passengers of adequate compensation. But since he does not know the cost of the antique, he offers the following scheme. Each of the two travelers has to write down on a piece of paper the cost of the antique. This can be any value between 2 units of money

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[1]Some month later, roughly the same game was presented in a philosophical journal under the title "The gingerbread game" (Martin Hollis, 1994).

and 100 units. Denote the number chosen by traveler i by n_i. If both write the same number, that is, $n_1 = n_2$, then it is reasonable to assume that they are telling the truth (so argues the manager) and so each of these travelers will be paid n_1 (or n_2) units of money. If traveler i writes a larger number than the other (i. e., $n_i > n_j$), then it is reasonable to assume (so it seems to the manager) that j is being honest and i is lying. In that case the manager will treat the lower number, that is, n_j, as the real cost and will pay traveler i the sum of $n_j - 2$ and pay j the sum of $n_j + 2$. Traveler i is paid 2 units less as penalty for lying and j is paid 2 units more as reward for being so honest in relation to the other traveler."

The resulting normal form game can be described by the following payoff-bimatrix, where $x, y \in \{2, \ldots 100\}$.

$$\text{(1)} \qquad \pi(x,y) = \begin{cases} (x+2, x-2) & \text{if } x < y \\ (x,x) & \text{if } x = y \\ (y-2, y+2) & \text{if } x > y \end{cases} .$$

If both players had to confine their choice to 2 or 3, the structure of the 2×2 payoff matrix of this reduced game would be identical with the prisoner's dilemma.

In this game, there is a unique Nash equilibrium, namely $(2,2)$. Furthermore, as Basu argues, $(2,2)$ is not only the unique Nash equilibrium, but also strict and the only rationalizable equilibrium.[2]

So it seems that game theoretic reasoning gives a clear cut answer to what should be expected in the traveler's dilemma. However, as Basu states: "All intuition seems to militate against all formal reasoning in the traveler's dilemma. Hence the traveler's dilemma seems to be one of the purest embodiments of the paradox of rationality in game theory because it eschews all unnecessary features, like play over time or the nonstrictness of the equilibrium" (Basu, 1994, p. 391).

The aim of our paper is twofold. First we investigate experimentally how experts actually play this game. Given that they did not act as predicted by Nash equilibrium, we then set out to find a theoretical argument which may explain the paradox.

Participants in the experiment reported on here were game theorists, in particular members of the Game Theory Society, who played one instance of a one-shot traveler's dilemma. We conducted the experiment eliciting the strategies participants chose in the one-shot traveler's dilemma and the beliefs they held about the average of the strategies played by the other participants. In the first part of this paper (Sections I. and II.), we describe

[2] An equilibrium is strict, if it is a combination of mutual unique best replies. Rationalizability was introduced independently by B. Douglas Bernheim (1984) and David G. Pearce (1984). Being the only rationalizable equilibrium means, that it is also the unique strategy combination surviving iterated elimination of strictly dominated strategies (Pearce, 1984, Lemma 3, p. 1048).

the experiment in detail. In the second part (Section III.) the results are confronted with the predictions we get from assuming equilibrium behavior in an incomplete information version of the traveler's dilemma. Finally, we discuss related literature and conclude with possible lines of further research.

I. Description of the Experiment

In order to generate a sample of 'experts', participation was limited to members of the Game Theory Society. An invitation to participate was emailed to all members five weeks before the closing date of July 15, 2002. The email referred recipients to a web site containing full details of the competition[3] and an online entry form. The site was protected, with the password given in the email. A reminder was sent two weeks before the closing date.

To ensure that participants were indeed members of the Game Theory Society they were required to disclose their name and email address, with the option to indicate whether they wanted their identity to be kept confidential. A list of all entrants was sent to the secretary of the Society who checked their eligibility.

Participants were required to submit their own strategy for the one-shot traveler's dilemma and their assessment of the average of the strategies submitted by the other participants, knowing that the other participants were also members of the Game Theory Society.

Specifying beliefs about the average strategy of the other players required specifying a probability distribution over the strategy space $\{2, 3, \ldots, 100\}$. To enable this, the online entry form provided 99 boxes labeled $2, 3, \ldots, 100$, in which the participant could write expected probability or frequency of each pure strategy. The instructions to participants said:

- There is no need to specify a probability weight for every cell. Missing entries are assumed to be zero.
- The probability weights do not have to sum to one. It suffices to assign an integer to each pure strategy in the support of your distribution, with the size of the integer proportional to its relative probability. We will normalize each distribution prior to computation.

A similar set of 99 boxes were provided for the participant to enter his or her strategy. A pure strategy could be specified by entering a single number in the appropriate box. A mixed strategy could be specified by entering probability weights to each pure strategy in the support, just as in specifying beliefs.

[3] It also included a reference to Basu (1994), since we assumed most potential participants to be aware of that paper, anyways. Consequently, we presented the game along with Basu's fable.

To facilitate the entry of beliefs (and mixed strategies), some simple tools were provided, enabling the participant

- to enter a constant value over any interval
- to linearly interpolate over any interval
- to shift the values over any interval either up or down by a specified amount.

Furthermore, the strategy and beliefs specified by the participant were depicted graphically, with plots showing the implied density and cumulative distribution functions. The tools could be used interactively, allowing the participant to modify his or her entry and view the resulting changes on the graphs.

When the participant indicated that he or she was satisfied with the specification by submitting their entry, the information provided was echoed back to the participant to enable him or her to confirm the entry before it was finally recorded.

To provide an incentive to think about beliefs as well as strategy, separate prizes were awarded for the accuracy of beliefs and the effectiveness of the strategy. Winners of both prizes were determined randomly, by drawing numbered balls from an urn.[4] We adopted random selection to avoid perverse incentive effects. For example, if we selected the winner of the belief prize on the basis of accuracy of his or her beliefs, we felt there was some chance that players might manipulate their strategies in an attempt to win the belief game. Similarly, if winning the strategy game depended on the effectiveness of the strategy, players might seek to maximize the probability of winning rather than maximize expected payoff. Transaction costs precluded the simple alternative of rewarding every participant with his average payoff.

The randomly chosen winner of the strategy game received twenty times the expected payoff of his or her strategy when pitted against the strategies submitted by the other contestants. The prize awarded to the randomly chosen winner of the belief game was proportional to the accuracy of his or her beliefs. We measured the accuracy of beliefs by summing the absolute differences between the player's estimated distribution function F and the actual distribution G of the strategies submitted by all other players, normalized to give a score between 0 and 1. Specifically, our measure of belief accuracy for each player is

$$\text{(2)} \qquad \mathbf{score} = 1 - \frac{\sum_{i=2}^{100} |F_i - G_i|}{98}$$

Since we did not know in advance what scores might be achieved, we determined the value of the prize as that fraction of \$1000 that the winner's score bore to highest score of all

[4]The draw was made by Hans-Peter Liebig, designated Rector of the University of Hohenheim on 26 July 2002. The actual prizes were \$970 and \$1693 respectively.

contestants. That is

$$\text{(3)} \quad \textbf{belief prize} = \frac{\textbf{score}}{\textbf{highest}} \times \$1000$$

where **score** is the belief accuracy of the prize-winner (chosen at random) and **highest** is the score of the contestant who has the most accurate beliefs.

In addition to the monetary prizes, all participants were promised that they would be personally informed of the results within two weeks of the closing date.

II. Results

A total of 51 entries were received.[5] 45 respondents submitted a pure strategy. Of these, three proposed the Nash strategy (s = 2) and 10 submitted the cooperative strategy (s = 100). The average strategy is illustrated in figure 1.

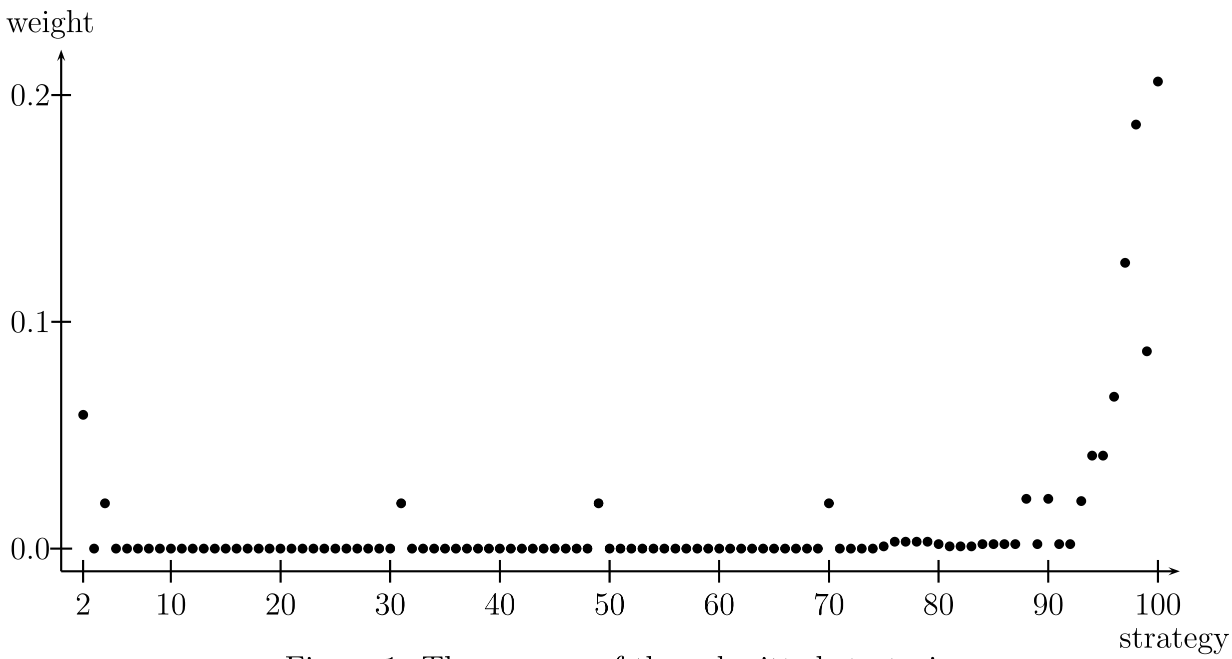

Figure 1: The average of the submitted strategies.

The peaks at 31, 49 and 70 are due to three players submitting pure strategies at these values. The full distribution of pure strategies is summarized in the following table.

The expected payoff to each pure strategy when playing against the average is shown in figure 2. We see that the best response to the average strategy is to play a pure strategy of 97. This was submitted by six entrants, giving an expected payoff of 85.09 (after removing the player's own strategy from the average). The average expected payoff over all strategies

[5] The invitation to participate was sent to all members of the Game Theory Society, which were around 300 at that time.

Table 1: Distribution of pure strategies played

Strategy	Entries	Strategy	Entries	Strategy	Entries
2	3	88	1	96	3
4	1	90	1	97	6
31	1	93	1	98	9
49	1	94	2	99	3
70	1	95	2	100	10

submitted was 75.23 with a standard deviation of 23.13. The worst payoffs went to the Nash strategy ($s = 2$), which earned a paltry 3.92 on average.

The actual winner in the strategy part of the experiment played the pure strategy 99, the payoff of which was 84.64, so he earned $\$1693 = 84.64 \cdot \$20$.

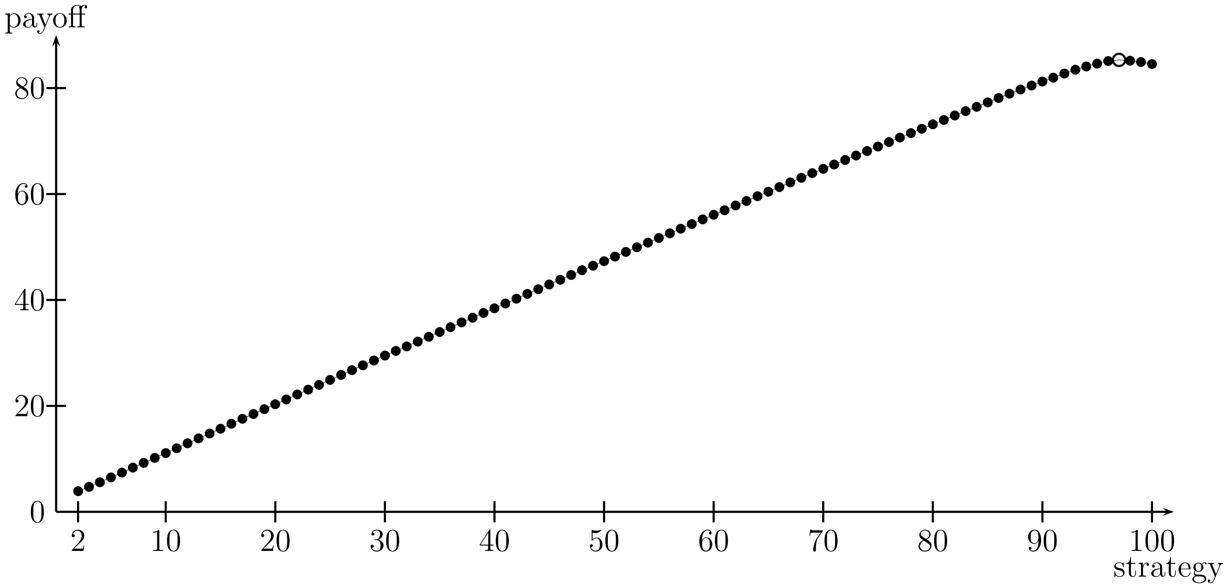

Figure 2: Payoffs against the average of the submitted strategies.

Of the 47 entrants who submitted both strategy and beliefs, many did an admirable job of estimating the average strategy. Measured as described in the previous section, accuracy scores ranged from 0.97 down to 0.12 with an average of 0.74 and standard deviation of 0.25. Although only 17 (out of 47) respondents played a best response to their own beliefs, 37 played a strategy which yielded a payoff not more than one unit below the payoff to their best response. The average strategy error was 0.99 with standard deviation of 2.86. Two players deviated significantly from a best response to their beliefs, sacrificing a significant fraction of their potential payoff.

The actual winner in the belief part of the experiment had a score of 0.94, which means he earned $\$968 = \frac{0.94}{0.97} \cdot \$1000$.

The average of the beliefs submitted is shown in figure 3 below.

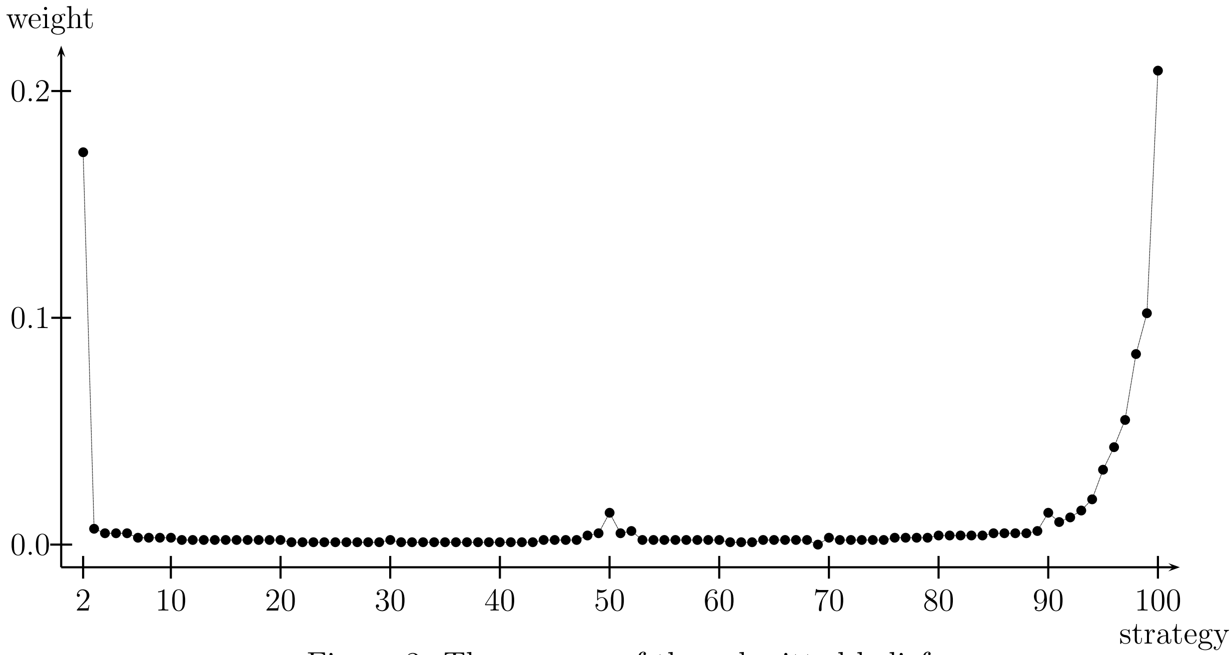

Figure 3: The average of the submitted beliefs.

III. Analysis of the Results

We will first describe how we arrive at modeling the traveler's dilemma as a game of incomplete information and state a number of results describing characteristics of Bayesian Nash equilibria in this model. Then we will numerically calculate such equilibria, in particular their support, for parameter values suggested by the experimental data and compare them with the experimental results.

A. The Traveler's Dilemma with Incomplete Information

Our analysis starts from two basic observations in the experimental data:

1. Most participants choice of strategy seems to be rational, i. e. follows a best response logic. Indeed, we observed 17 (out of 47) playing a best response to their belief and another 20 to get within 1 unit of what their best response would have yielded.

2. On the other hand, a substantial fraction, 10 participants, submitted the strategy 100 which cannot be explained as rational behavior in the traveler's dilemma, since it is strictly dominated (in fact it is the only such strategy in the game).

This suggests that it will be impossible to explain both patterns of behavior in the same way. So it seems to be crucial to explicitly consider heterogeneity in the participants. In our case, we are led to consider an incomplete information version of the traveler's dilemma in which there is an "irrational" type always playing $s = 100$. One might also think of this irrational type as a cooperative type, given that the strategy combination $(100, 100)$

corresponds to a cooperative approach to the game.[6] Hence $s = 100$ appears to be a second focal point (Thomas C. Schelling, 1960) in the traveler's dilemma, the unique Nash equilibrium strategy 2 being the first and most obvious.

So we assume that the population of participants consists of two different groups: While one of them is formed by rational players in the sense that they use a strategy forming a best response to their belief, the other consists of irrational players choosing a certain strategy for sure. As we have argued, the data lead us to consider at least one irrational type who always plays $s = 100$.

Of course, this approach means, that strictly speaking we do no longer analyze the traveler's dilemma but some different though related game of incomplete information. We do not see any way to avoid this, however, since not using a strictly dominated strategy is among the most direct consequences of assuming rationality. So while one might for example use the lack of common knowledge of rationality to construct models in which rational players use strategies other than the Nash equilibrium strategy 2, there is no hope to explain $s = 100$ being played.

An interesting exception are those entries playing the original game's Nash equilibrium strategy 2, of which we received three. Two of these gave full weight on $s = 2$ in their beliefs while the third put some minimal weight on $s = 3$, so that $s = 2$ is still the best reply to his belief. As will be demonstrated below, in the incomplete information version of the traveler's dilemma, 2 ceases to be a strategy that a rational player would use.

For this reason, and because we find it hard to accept to simply ignore the observations of the original game's Nash equilibrium strategies in our explanation, we assume that there are two irrational types. One always playing the cooperative strategy 100 and another always playing the Nash equilibrium strategy 2.[7]

It will become obvious, that the driving force behind our results is the assumption of the irrational cooperative type. Just a small probability for this type drastically changes the equilibrium behavior for the rational players breaking the Nash equilibrium of the full information game. Of course, assuming the existence of irrational 2 types, only, would not change anything: Both rational and irrational types would then play $s = 2$.

[6] All bargaining solutions satisfying Pareto-optimality and symmetry would agree on this solution. It is safe to assume that participants were aware of this fact. As an example, Joseph Mullat (2002) explicitly pointed out that the Nash bargaining solution would be an obvious candidate for what players would do in the game. Therefore, the term "irrational" should not be interpreted pejoratively. We use it in a technical sense simply meaning "not maximizing expected utility".

[7] It may sound confusing that playing the unique prediction of virtually any non-cooperative solution to the game is called irrational, but in the incomplete information game such is the case. Alternatively, one could think of these participants as playing the original traveler's dilemma without considering the possibility of other types playing high strategies. We prefer to stick to a game with incomplete information with common priors, though.

Formally, our model is as follows. There are three types of players, rational ones, irrational type 100 and irrational type 2 players. We assume that the common prior probability for the 2-type is p_2 and that of the 100-type p_{100}, hence a priori a player is rational with probability $p = 1 - p_2 - p_{100}$.

The rational types will never use the strictly dominated strategy 100. So we denote a mixed strategy for them by $r = (r_2, \ldots, r_{99})$. The resulting beliefs a rational player holds over the average strategy of her opponent (who may be rational or irrational) is denoted by $q = (q_2, \ldots, q_{100})$, with

$$(4) \quad q_j = \begin{cases} p_2 + (1 - p_2 - p_{100})\, r_j & \text{for } j = 2 \\ (1 - p_2 - p_{100})\, r_j & \text{for } j \in \{3, \ldots, 99\} \\ p_{100} & \text{for } j = 100. \end{cases}$$

From this we can derive a first result showing how the existence of the irrational 100 type leads rational players to use high strategies. The proof is deferred to Appendix B.

Claim 1 *In the traveler's dilemma with incomplete information pure strategy i is strictly dominated (by 99) for all*

$$(5) \quad p_{100} \; > \; \frac{3(1 - p_2)}{(102 - i)}$$

or put differently, given p_2 and p_{100} pure strategy i is dominated if and only if

$$(6) \quad i \; < \; 102 - \frac{3(1 - p_2)}{p_{100}}.$$

So pure strategy 2, the unique Nash equilibrium strategy in the traveler's dilemma with complete information, becomes dominated as soon as $p_{100} > 0.03$. In our experiment 10 of the 51 participants played the pure strategy 100, which corresponds to $p_{100} = 0.196$. This number is quite close to both the weight on 100 in the average strategy which is 0.206 and the weight on 100 in the average belief which is 0.209. In any case, for p_{100} corresponding to the experimental results, 2 is dominated. So, for the reasons given above, we introduce the 2-type. The three entrants who used pure strategy 2 correspond to $p_2 = 0.059$ which is also the weight of 2 in the average strategy.[8] Interestingly, the average belief puts a probability of 0.173 on 2 which is almost three times as high. We attribute this difference to the focal point character of 2, especially among game theorists. This argument lends further support to including the 2-type in the model.

From equation 6 above, we see that for the values $p_2 = 0.059$ and $p_{100} = 0.196$ all strategies $i \leq 87$ are dominated.[9] So for any assignments of the a priori probabilities of the two

[8]There was exactly one other entrant putting any weight on 2, this weight was 0.001.

[9]For the values from the average strategy ($p_2 = 0.059$ and $p_{100} = 0.206$) also pure strategy 88 becomes dominates and for the values from the average belief ($p_2 = 0.173$ and $p_{100} = 0.209$) all strategies less or equal to 90 are dominated.

irrational types which are in line with our data, our model suggests that the rational type should employ fairly high strategies, which means a drastic deviation from the complete information Nash equilibrium prediction that everybody plays $s = 2$.

We leave a detailed comparison of the experimental findings with the model's predictions to Subsection B. below. Here we briefly pause to check whether Claim 1 is consistent with our data. There remain 38 entrants we label rational players, because they played neither 2 nor 100. Of these 30 chose a strategy with support in the interval $[87, 99]$ (28 using a pure and two a mixed strategy). The average strategy of rational players puts a weight of 0.81 on the interval $[87, 99]$.[10] So both considerations indicate that the majority of rational players conform with Claim 1. Table 2 shows the frequencies of all pure strategies played. Values of undominated pure strategies are starred. The strategies of the two irrational types are framed.

Table 2: Pure strategies and number of entries

Strategy	Entries	Strategy	Entries	Strategy	Entries
$\boxed{2}$	3	88	1	96*	3
4	1	90	1	97*	6
31	1	93*	1	98*	9
49	1	94*	2	99*	3
70	1	95*	2	$\boxed{100}$	10

Therefore, it makes sense to consider the Bayesian Nash equilibria of our incomplete information game.[11] In fact, given the symmetry of the game, we concentrate on symmetric equilibria.

A necessary condition for $r = (r_2, \ldots, r_{99})$ to be a symmetric equilibrium is that the expected payoff of all strategies in the support of r is equal. We will denote the expected payoff of a strategy x given mixed strategy r by $\pi(x; r)$.

We are going to derive certain restrictions on the form such a strategy can take in our game. In particular, we will consider restrictions on the support of a (mixed) strategy r which forms part of a (symmetric) Bayesian Nash equilibrium, i. e. the set of all pure strategies in the equilibrium strategy with strictly positive weight.

[10] If we take the values $p_2 = 0.173$ and $p_{100} = 0.209$, so that all strategies $i \leq 90$ are dominated, there are 2 additional rational players using a dominated pure strategy (one 88 the other 90). The total weight of the average strategy of rational players on the interval $[91, 99]$ is 0.76.

[11] In fact, it looks as if only the rational type uses Bayesian updating and selects the optimal strategy given his information, while irrational types do not. This interpretation, is misleading however: If an irrational type always chooses the same strategy we do not have to assume he does not use Bayesian updating. Giving him the 'right' payoffs to make 'his' strategy dominant, results in him choosing it as optimal for any given belief, i. e. also for any possible result of Bayesian updating.

The first follows from Claim 1 above. Since dominated strategies cannot be in the support of an equilibrium strategy, this result gives a lower bound for the support. The following claim shows that by introducing the 100-type with sufficiently high a priori probability p_{100} means that very high strategies, namely 97, 98 or 99, have to be in the equilibrium support which is also in line with experimental evidence. Again, the proof can be found in Appendix B.

Claim 2 *For $p_{100} \geq \frac{3(1-p_2)}{100}$ the support of a Bayesian Nash equilibrium must contain 97, 98 or 99.*

Our empirical values for p_{100} and p_2 satisfy the conditions of Claim 2 even if we take the lowest values for $p_{100} = 0.196$ (the percentage of participants playing pure strategy 100) and $p_2 = 0.059$ (the percentage of participants playing pure strategy 2).

There are multiple symmetric equilibria in the game. Here we shall focus on one particular equilibrium, however, which has the following properties.

- The support is connected, i. e. an interval.
- The equilibrium is Pareto optimal among those with interval support.

It turns out that it follows from these requirements that the support of the equilibrium strategies has to contain 99.

Claim 3 *For any Pareto optimal Bayesian Nash equilibrium with interval support, the support contains 99.*

B. Equilibrium Behavior Compared to Experimental Results

Since we conducted a one-shot experiment, the only clear cut test of whether a reported strategy is consistent with a Bayesian Nash equilibrium strategy is to check whether its support is contained in the support of the equilibrium strategy. In particular, any pure strategy from the support could be interpreted as the result of drawing from the equilibrium mixed strategy.

The support of the Pareto efficient interval equilibrium strategy is the interval $[94, 99]$. This strategy, or more precisely the resulting frequencies of pure strategies chosen by the rational and the irrational types, is depicted in figure 4.

Excluding the three playing 2 (2-type) and the ten using the cooperative strategy (100-type), we regard the remaining 38 as the "rational" players. Of these, 25 used a pure

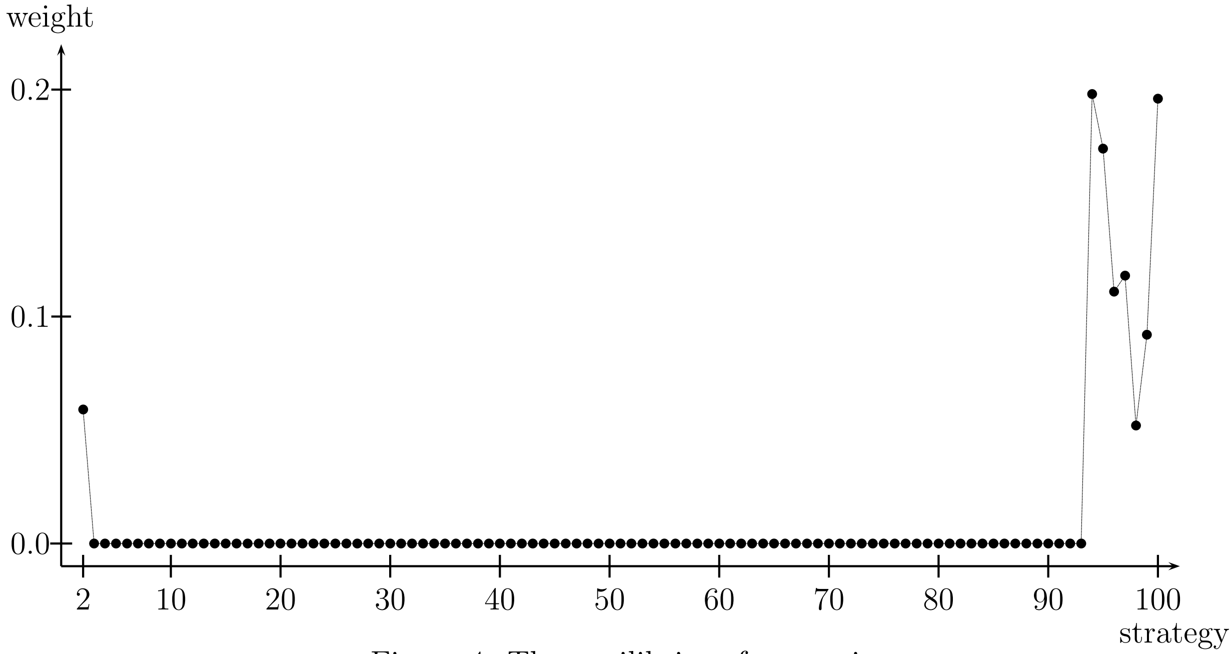

Figure 4: The equilibrium frequencies

strategy in the interval $[94, 99]$ and 2 used a mixed strategy with support $[94, 99]$. Overall, our model is consistent with the behavior of 27 of the 38 rational entrants.

Three of the remaining 11 used undominated strategies. We regard the remaining players as outliers of some sort, and feel that our model does quite well to explain the behavior of the rational participants.

Another question is whether the reported beliefs support our modelling of the game. So far we have used beliefs just to argue that most participants were playing rationally in following a best response logic albeit for many of them the strategies were just approximately best responses. Considering the average belief, there is a higher weight on 2 than should follow from prior beliefs according to strategy choices (0.173 as opposed to 0.059). The weight on 100 almost coincides (0.206 in average strategy or 0.196 in percentage of participants using pure strategy 100 against 0.209 in the average belief). There is, however, an aggregate weight of 0.281 outside the equilibrium support $[94, 99]$ and still 0.219 outside $[87, 94]$ the set of strategies which are not dominated.

Beliefs are more problematic. While the aggregate belief does not necessarily contradict the model, individual beliefs are very heterogeneous. To support an equilibrium, it is not enough that beliefs have the right support. While one can argue that any pure strategy in the support can be the result of a random draw according to the equilibrium distribution, if this is how participants arrived at their strategy choices, they should have reported beliefs that are equilibrium beliefs.

So our reading of the experiment is that average beliefs are much closer to model predictions than individual ones. Despite beliefs not fitting the equilibrium predictions of the model, individual behavior can be explained quite well by it.

IV. Connections with Related Literature

One participant, Nimrod Megiddo (2002), pointed out that the traveler's dilemma can be viewed as a form of finitely repeated prisoner's dilemma. From this perspective, our model of an incomplete information version of the traveler's dilemma seems to directly translate to the model of David M. Kreps et. al. (1982) for the prisoner's dilemma. Their basic idea is to explain the high number of rounds with cooperation by rational players in 100 repetitions of the prisoner's dilemma by introducing an irrational cooperative type, which makes it rational to imitate this type until quite near the end of the game leading to the cooperative payoff. However, even if the basic modeling strategy is the same, the economic interpretation is different, since imitation cannot occur in a one shot game.

Robert J. Aumann's shows that in the 100-times repeated prisoner's dilemma, allowing for a breakdown in the mutuality of knowledge of players' rationality at some level can account for keeping up cooperative behavior "until at least the 85th or the 90th stage, and even beyond" (Aumann, 1992, p. 222). While this appears to be related to our result that the strategies chosen by most rational players are in the high nineties, it cannot explain the ten entries using the strictly dominated pure strategy 100.

C. Monika Capra et. al. (1999) run a repeated traveler's dilemma as a laboratory experiment with students from economic classes in order to investigate, whether average claims are affected by the (theoretically irrelevant) changes in the penalty/reward parameter. Their work shows that the Nash equilibrium strategy solution is a rather bad predictor of how people play the repeated traveler's dilemma. Exploiting the dynamic structure of the repeated game, they develop a logit learning model in which players are assumed to start with a uniform prior and use a simple counting rule to update their beliefs. These beliefs determine expected payoffs and these in turn determine players choice probabilities. This model seems to be able to reproduce the qualitative features of observed adjustment patterns in the multi-stage game and the inverse relationship between the penalty/reward parameter and average claims. It is important to stress that the focus in their work is very different from ours. While they are mainly interested in learning during repeated plays of the game and hence do not have to take the initial uniform prior too seriously, we focus on the one shot game and thus our explanation hinges on players initial beliefs.

The logit learning model is complemented by considering the quantal response equilibrium proposed by Richard D. McKelvey and Thomas R. Palfrey (1995) and advocated in Jakob K. Goeree and Charles A. Holt (1999) which has been successfully used to explain data from many different experiments. An analogous concept for games continuous strategy spaces is the logit equilibrium developed by Simon P. Anderson et. al. (2002). Goeree et. al. (2004) have proposed regular quantal response equilibria. Philip A. Haile et. al. (2003) have questioned the empirical content of quantal response equilibrium claiming that by choosing appropriate parameters it can explain any possible behavior. Of course, our explanation is subject to the same general criticism. By choosing the right irrational types with appropriate probabilities, it could also explain any given data.

Capra et. al. (2003) study one-shot traveler's dilemma games using an introspective procedure that is similar in spirit to the idea behind the quantal response equilibrium. They also show, that this approach can also explain data of treatments in which players receive a common advice which becomes common knowledge.

Of course, quantal response equilibrium is not the only explanation that has been put forward to explain experimentally observed behavior in the traveler's dilemma. Closest to ours is Mathias Erlei (2004), who in a broader context proposes to consider what he calls heterogeneous social preferences. In addition to rational players (SE-players in his terminology) he considers inequity averse (IE) and welfare oriented (WP) players. In the traveler's dilemma with small penalty/reward as considered by Goeree and Holt (2001, p. 1405–06)[12], he finds that there exists a Bayesian Nash equilibrium in which WP-Players play 300 while rational players use a mixed strategy with support in the upper end of the strategy space $[291, 299]$. All types using the lowest strategy available is another Bayesian Nash equilibrium, however (cf. Erlei, 2004, Result 2, p. 16).

Goeree and Holt (2004) propose yet another approach to analyze behavior, namely noisy introspection. Their idea is somewhat related to the idea to consider limited levels of mutual knowledge of rationality. Their model puts some noise in the process of iterated formation of conjectures about each others' decisions and beliefs.

Finally, to return to the source of the traveler's dilemma, Basu (1994) in his discussion of the paradox described three possible 'lines of attack'. Our model probably suggests to further study the second one, which is to analyze where the two assumptions of rational behavior in the sense of best response and common knowledge of rationality "may by themselves be inconsistent" (Basu, 1994, p. 394). At least, introducing the 100-type and therefore dispensing common knowledge of rationality (in the original full information game) helped to explain observed behavior.

V. Conclusions

What distinguishes our experiment from other experiments on the traveler's dilemma reported in the literature is that the participants were experts in game theory. Therefore, the fact that our results confirm the general findings that the behavior in experiments is far from the Nash equilibrium prediction indicates that these findings should not be attributed to any lack of understanding the game but rather represent a robust pattern of behavior.

[12] They take the strategy space to be $\{180, \ldots, 300\}$ and consider a version with small penalty/reward (5) and one with high penalty/reward (180).

Our analysis shows that introducing incomplete information allows for a fairly good explanation of the data from our experiment. This would seem to partially contradict the claim by Goeree and Holt (2001) that standard game theory cannot explain the data from experiments on the one-shot traveler's dilemma with small claims. However, this is not strictly true, since what we analyze is not Basu's original traveler's dilemma but rather a game of incomplete information in which most players have the payoff matrix of the traveler's dilemma.

What we cannot explain at all using classical game theoretic analysis, however, is the motivation of those 'irrational' participants who chose the strictly dominated strategy 100. This choice cannot be explained either, by invoking some kind of breakdown in the mutuality of knowledge of rationality as in Aumann (1992). It is however a robust feature of all experiments on the traveler's dilemma, that with a comparable size of the reward/penalty, the cooperative strategy is used quite often (cf. Ariel Rubinstein, 2004).

It may be interesting to note that the irrational 100-types provide a kind of public good to all players in the game: Without them, everybody would end up in the Nash equilibrium with payoff 2, while the payoffs to all types are much higher in the Bayesian Nash equilibrium of the incomplete information game. This clearly distinguishes the traveler's dilemma from the prisoner's dilemma.

The main feature of our results is the heterogeneity of players. Only the experimental evidence that a number of participants played a strictly dominated strategy led us to introduce the irrational 100-type. Similarly, a sufficiently large fraction of players who use any other high strategy, say $s = 99$, would lead to qualitatively the same results by inducing Bayesian Nash equilibria with support in the high end of the strategy space. At the same time, using such a strategy could be reconciled with rationality in the sense of playing a best response by considering heterogeneity in the beliefs. To arrive at these however, we cannot assume all players to continue the chain of reasoning prescribed by the concept of rationalizability. However, assuming they stop at a certain level (cf. Rosemarie Nagel, 1995, Dale O. Stahl II, 1993, and Stahl and Paul W. Wilson, 1994, 1995) can generate different beliefs. Again, just a certain fraction of players who are not infinitely rational would suffice to explain a markable deviation from Nash equilibrium behavior by the others.

Appendix A: Playing all others versus playing their average

We evaluated entrants strategies by computing their expected payoff against the average strategy of their opponents. This section just reminds that this is equivalent to assigning to each strategy the expected payoff from a round robin tournament.

Let the set of participants be $I = \{1, 2, \ldots, n\} \subset \mathbb{N}$.

In the game there are two players, 1 and 2; their roles are filled by the participants in a tournament, i. e. each participant having given a strategy for role of player 1 is matched exactly once with any other participant in the role of player 2.

We are comparing the average of her payoffs in those matches against playing once against a strategy for player 2 that is the average of the other participants' strategies for that role.

Denote the pure strategies for player 1 by $K = \{1, \dots \bar{k}\} \subset \mathbb{N}$. and those for player 2 by $L = \{1, \dots \bar{l}\} \subset \mathbb{N}$.

In the traveler's dilemma, we have $\bar{k} = \bar{l}$, so actually in our case both strategy sets are equal.

Payoffs for a pair (k, l) of pure strategies are denoted by $\pi(k, l) = (\pi_1(k, l), \pi_2(k, l))$.

Each participant $i \in I$ submits a vector we interpret as either a mixed strategy for player 1, $p^i = \left(p_1^i, p_2^i, \dots, p_{\bar{k}}^i\right)$ or for player 2, $q^i = \left(q_1^i, q_2^i, \dots, q_{\bar{l}}^i\right)$ (in general, of course, entries would have to consist of a pair of strategies, one for player 1, and one for player 2).

We pick a participant $\hat{\imath} \in I$ who is player 1. Let $J_{-\hat{\imath}} \subseteq I$ denote the subset of participants we consider as possible opponents, i. e. all participants who could fill player 2's role, when $\hat{\imath}$ is player 1 (typically, $J_{-\hat{\imath}} = I$ or, as in our case, $J_{-\hat{\imath}} = I \setminus \{\hat{\imath}\}$).

The average mixed strategy of the members in $J_{-\hat{\imath}}$ is given by

$$(7) \quad \bar{q}^{-\hat{\imath}} = \frac{1}{|J_{-\hat{\imath}}|} \sum_{j \in J_{-\hat{\imath}}} q^j.$$

If $\hat{\imath}$ as player 1 plays against this average mixed strategy her expected payoff is

$$\begin{aligned}
\pi &= \sum_{k \in K} p_k^{\hat{\imath}} \sum_{l \in L} \bar{q}_l^{-\hat{\imath}} \, \pi_1(k, l) \\
&= \sum_{k \in K} p_k^{\hat{\imath}} \sum_{l \in L} \frac{1}{|J_{-\hat{\imath}}|} \sum_{j \in J_{-\hat{\imath}}} q^j \, \pi_1(k, l) \\
&= \frac{1}{|J_{-\hat{\imath}}|} \sum_{k \in K} \sum_{l \in L} \sum_{j \in J_{-\hat{\imath}}} p_k^{\hat{\imath}} \, q_l^j \, \pi_1(k, l).
\end{aligned}$$

If on the other hand, she plays against each one of her possible opponents, the average payoff from this is

$$\begin{aligned}
\tilde{\pi} &= \frac{1}{|J_{-\hat{\imath}}|} \sum_{j \in J_{-\hat{\imath}}} \sum_{k \in K} p_k^{\hat{\imath}} \sum_{l \in L} q_l^j \, \pi_1(k, l) \\
&= \frac{1}{|J_{-\hat{\imath}}|} \sum_{j \in J_{-\hat{\imath}}} \sum_{k \in K} \sum_{l \in L} p_k^{\hat{\imath}} \, q_l^j \, \pi_1(k, l) \\
&= \frac{1}{|J_{-\hat{\imath}}|} \sum_{k \in K} \sum_{l \in L} \sum_{j \in J_{-\hat{\imath}}} p_k^{\hat{\imath}} \, q_l^j \, \pi_1(k, l).
\end{aligned}$$

Therefore $\pi = \tilde{\pi}$.

Appendix B: Proofs of the claims

This section gathers the proofs of Claims 1, 2, and 3.

Proof of Claim 1:
Claim 1 states that in the traveler's dilemma with incomplete information pure strategy i is strictly dominated (by 99) for all

$$(8)\quad p_{100} > \frac{3(1-p_2)}{(102-i)}$$

or put differently, given p_2 and p_{100} pure strategy i is dominated if and only if

$$(9)\quad i < 102 - \frac{3(1-p_2)}{p_{100}}.$$

To see this, let r be the rational types' strategy and q the resulting beliefs. The payoff of strategy i is given by

$$(10)\quad \pi(i) = \begin{cases} q_2 \cdot 2 + \sum_{j=3}^{99} q_j \cdot 4 + p_{100} \cdot 4 & \text{if } i = 2, \\ \sum_{j=2}^{i-1} q_j \cdot (j-2) + q_i \cdot i + \left(\sum_{j=i+1}^{99} q_j + p_{100}\right) \cdot (i+2) & \text{if } i \in \{3, \dots, 99\}. \end{cases}$$

Therefore the payoff difference between the strategy 99 and pure strategy 2 is

$$(11)\quad \begin{aligned} &\pi(99) - \pi(2) = \\ &- q_2 \cdot 2 + \sum_{j=3}^{98} q_j \left[(j-2) - (2+2)\right] + q_{99}\left[99 - (2+2)\right] + p_{100}\left[(99+2) - (2+2)\right]. \end{aligned}$$

The payoff difference between the strategy 99 and pure strategy $i = 3, \dots 98$ is

$$(12)\quad \begin{aligned} \pi(99) - \pi(i) &= q_i\left[(i-2) - i\right] + \sum_{j=i+1}^{98} q_j \left[(j-2) - (i+2)\right] \\ &\quad + q_{99}\left[99 - (i+2)\right] + p_{100}\left[(99+2) - (i+2)\right]. \end{aligned}$$

So in general the payoff difference between the strategy 99 and pure strategy $i = 2, \dots 98$ can be written as

$$(13)\quad \pi(99) - \pi(i) = -2q_i + \sum_{j=i+1}^{98} q_j(j-i-4) + q_{99}(97-i) + p_{100}(99-i).$$

Pure strategy i is dominated by 99 if and only if the payoff difference in equation 13 is positive for all admissible q, i. e. for all possible mixed strategies r of the rational type.

For all $i \in \{2, \dots, 97\}$ we see from equation 13, that $\pi(99) - \pi(i)$ is minimal for maximal q_{i+1}, because the coefficient for q_{i+1} is -3 which is less than any other. This means $r_{i+1} = 1$ is the rational types strategy most favorable for strategy i resulting in $q_{i+1} = (1 - p_2 - p_{100})$. So for 99 to dominate i we must have

$$\begin{aligned}
& (1 - p_2 - p_{100}) \cdot (-3) + p_{100} \cdot (99 - i) \ > \ 0 \\
\iff \quad & -3 + 3p_2 + (102 - i)p_{100} \ > \ 0 \\
\iff \quad & p_{100} \ > \ \frac{3(1-p_2)}{(102-i)} \qquad \iff \qquad i \ < \ 102 - \frac{3(1-p_2)}{p_{100}}.
\end{aligned} \tag{14}$$

For the strategy 98, the most favorable situation is not to have all weight on $98+1 = 99$ but rather to have it on 98 itself. This is because 99 earns 99 against itself so that the payoff difference in favor of 98 is just 1, while it is 2 against 98 itself (it earns 98 while 99 is penalized and earns $98 - 2 = 96$). Hence 99 dominates 98 if

$$\begin{aligned}
& (1 - p_2 - p_{100}) \cdot (-2) + p_{100} \ > \ 0 \\
\iff \quad & -2 + 2p_2 + (101 - 98)p_{100} \ > \ 0 \\
\iff \quad & p_{100} \ > \ \frac{2(1-p_2)}{(101-98)}.
\end{aligned} \tag{15}$$

Since

$$\frac{2(1-p_2)}{(101-98)} = \frac{2(1-p_2)}{3} = \frac{3(1-p_2)}{4.5} < \frac{3(1-p_2)}{4} = \frac{3(1-p_2)}{102-98}, \tag{16}$$

the general condition 14 implies the condition 15 and thus ensures strategy 98 to be dominated.

From this observation, it may seem that it is easier for 99 to dominate 98 than 97. This is not the case, as a comparison of the threshold values for p_{100} guaranteeing strategies 97 and 98, respectively, to be dominated by 99. For 97 it is $p_{100} > \frac{3(1-p_2)}{5}$ and for 98 it is $p_{100} > \frac{2(1-p_2)}{3}$. Since

$$\frac{2(1-p_2)}{3} = \frac{3(1-p_2)}{4.5} > \frac{3(1-p_2)}{5}, \tag{17}$$

whenever 98 is dominated by 99 so is 97.

Proof of Claim 2:
The statement of this claim is that for $p_{100} \geq \frac{3(1-p_2)}{100}$ the support of a Bayesian Nash equilibrium must contain 97, 98 or 99.

For values of p_{100} below the given threshold, there is a unique equilibrium, namely every rational player playing 2, i. e. the Nash equilibrium of the complete information game remains.

Let r be the (rational players') strategy in the symmetric equilibrium and q the resulting beliefs. Let $X \subseteq \{2, \ldots, 99\}$ be the support of r and let $y = \max(X)$ and $z = \max(X \setminus \{y\})$.

Suppose $y \leq 96$. For this to be the case, we must have $\pi(99, q) - \pi(y, q) \leq 0$. From our calculations in the proof of Claim 1 above and the observation that $q_{97} = q_{98} = q_{99} = 0$ by assumption, we see that this means

$$(18) \quad -q_y \cdot 2 + p_{100}(99 - y) \leq 0 \qquad \Longleftrightarrow \qquad q_y \geq \frac{99 - y}{2} p_{100}.$$

Also we must have $\pi(z, q) - \pi(y, q) = 0$ from the fact that both are in the support of the equilibrium strategy. Taking into account that $q_j = 0$ for $j \in \{z+1, \dots y-1\} \cup \{97, \dots, 99\}$ this leads to

$$(19) \quad q_z \cdot 4 + q_y \cdot (z + 2 - y) + p_{100}(z - y) = 0 \qquad \Longleftrightarrow \qquad q_z = \frac{y - z - 2}{4} q_y + \frac{(y - z)}{4} p_{100}.$$

If $z = y - 1$ equation 19 becomes

$$(20) \quad q_z = \frac{-1}{4} q_y + \frac{1}{4} p_{100}.$$

Together with equation 18 this implies

$$(21) \quad q_z \leq \frac{-1}{4} \frac{99 - y}{2} p_{100} + \frac{(1)}{4} p_{100} = \frac{2 - (99 - y)}{8} p_{100} = \frac{y - 97}{8} p_{100}.$$

Since q_z has to be strictly positive, this implies $y > 97$.

If $z \leq y - 2$ we must have $\pi(y - 1, q) - \pi(y, q) \leq 0$ so

$$(22) \quad q_y \cdot 1 + p_{100} \cdot (-1) \leq 0 \qquad \Longleftrightarrow \qquad q_y \leq p_{100}.$$

Together with equation 18 this implies

$$\begin{aligned} & p_{100} \geq q_y \geq \frac{99 - y}{2} p_{100} \\ \Longleftrightarrow\ & 1 \geq \frac{99 - y}{2} \\ (23) \quad \Longleftrightarrow\ & y \geq 97. \end{aligned}$$

Proof of Claim 3:
The claim we want to prove is that the support of any Pareto optimal Bayesian Nash equilibrium with interval support contains 99.

Since for interval equilibria we are in the first case of the proof of Claim 2, it is clear, that the support must contain 98.

Suppose r is an equilibrium with support $[x, 98]$ that is an interval not containing 99. Then there is a corresponding equilibrium with support $[x + 1, 99]$ and equilibrium strategy r' given by $r'_i = r_{i-1}$ (which also means $q'(i) = q(i - 1)$ for all $i \in [x + 1, 99]$).

To see this consider the conditions for r being an equilibrium with support $[x, 98]$. These are two, namely that all strategies in the support give the same payoff, i. e. for all $i \in [x, 98]$

$$\pi(i) - \pi(98) = 0 \quad \iff \quad q_i \cdot 4 + \sum_{j=i+1}^{97} q_j(i - j + 4) + q_{98}(i + 2 - 98) = 0. \tag{24}$$

and that the payoff to all strategies below x is less or equal to that of x, i. e. for all $j < x$

$$\pi(j) - \pi(x) \leq 0 \quad \iff \quad q_x \cdot 2 + \sum_{i=x+1}^{98} q_i(j - x) + p_{100}(j - x) \leq 0. \tag{25}$$

Now consider r' defined above. It follows for all $i' \in [x + 1, 99]$ that

$$\pi(i') - \pi(99) = q'_{i'} \cdot 4 + \sum_{j=i'+1}^{98} q'_j(i' - j + 4) + q'_{99}(i' + 2 - 99)$$

$$\iff q_{i'-1} \cdot 4 + \sum_{j=i'+1}^{98} q_{j-1}(i' - j + 4) + q_{98}\big((i' - 1) + 2 - 98\big)$$

$$\iff q_{i'-1} \cdot 4 + \sum_{j=(i'-1)+1}^{97} q_j\big((i' - 1) - j + 4\big) + q_{98}\big((i' - 1) + 2 - 98\big) \tag{26}$$

But equation 26 is just equation 24 as can be seen by replacing $i' - 1$ with i.

Similarly, for all $j' < x + 1$ we have

$$\pi(j') - \pi(x + 1) = q'_{x+1} \cdot 2 + \sum_{i=(x+1)+1}^{99} q'_i\big(j' - (x + 1)\big) + p_{100}\big(j' - (x + 1)\big)$$

$$\iff q_x \cdot 2 + \sum_{i=x+1}^{98} q_i\big((j' - 1) - x)\big) + p_{100}\big((j' - 1) - x\big) \tag{27}$$

But equation 27 is just equation 25 as can be seen by replacing $j' - 1$ by j.

Considering the payoff to pure strategy 98 with beliefs q generated by r and that of 99 with beliefs q' generated by r' one immediately sees that r' yields a higher payoff than r.

$$\begin{aligned}
\pi(99, q') &= p_2 \cdot 0 + \sum_{i'=x+1} 98 q'_{i'}(i' - 2) + q'_{99} \cdot 99 + p_{100} \cdot 101 \\
&= p_2 \cdot 0 + \sum_{i=x} 98\big[q_i\big((i - 2) + 1\big) + q_{98}(98 + 1) + p_{100}(100 + 1) \\
&= p_2 \cdot 0 + \sum_{i=x} 98\big[q_i(i - 2) + q_{98} \cdot 98 + p_{100} \cdot 100 + 1(1 - p_2) \\
&= \pi(98, q) + 1(1 - p_2).
\end{aligned}$$

Appendix C: Calculation of Bayesian Nash equilibria

In general, there are many Bayesian Nash equilibria of the traveler's dilemma with incomplete information. We select the Pareto optimal interval equilibrium as a focal point, since it can be computed by a simple recursive system.

By Claim 3, the support of the Pareto optimal interval equilibrium contains 99. Let x denote the lower element of the support. Since it is an interval equilibrium, every pure strategy between x and 99 must have the same payoff. That is, the equilibrium strategy r must satisfy the following system of equations

$$\begin{aligned}
&\pi(99,r) = \pi(98,r) \\
&\pi(98,r) = \pi(97,r) \\
&\vdots \\
\text{(28)}\quad &\pi(x+1,r) = \pi(x,r)
\end{aligned}$$

which is equivalent to the system

$$\begin{aligned}
&p_{100} = 2\,q_{98} + q_{99} \\
&p_{100} = 2\,q_{97} + q_{98} - q_{99} \\
&p_{100} = 2\,q_{96} + q_{97} - q_{98} - q_{99} \\
&\vdots \\
\text{(29)}\quad &p_{100} = 2\,q_x + q_{x+1} - q_{x+2} \cdots - q_{96} - q_{97} - q_{98} - q_{99}
\end{aligned}$$

Given a value for q_{99}, this system can be solved recursively for q_{98}, q_{97}, and so on. Put differently, once q_{99} has been determined, the remaining non-zero probabilities follow inexorably from the requirement to maintain indifference between adjacent strategies. Further note that the first equation puts a restriction on q_{99}, namely

$$\text{(30)}\quad q_{98} > 0 \implies q_{99} < p_{100}$$

The cumulative distribution function is

$$\text{(31)}\quad F(x) = p_{100} + \sum_{i=x}^{99} q_i.$$

Substituting the above recursion, it can be shown that the distribution function reduces to

$$\text{(32)}\quad F(x) = a_x p_{100} + b_x q_{99}$$

with $0 < a_{99} < a_{98} < \ldots$ and $0 < b_{99} < b_{98} < b_{97} < b_{95} < b_{94} \ldots \ldots$ (The omission of b_{96} from the previous inequality is deliberate.)

It follows that, for given p_{100}, there are unique values of x and $q_{99} < p_{100}$ such that

(33) $F(y) < 1$, for every $y > x$ and q_{99} and $F(x) = 1$.

These values define the Pareto optimal interval equilibrium. The remaining probabilities in the support can be computed from the previous recursive system.

For the values $p_2 = 0.059$ and $p_{100} = 0.196$ this yields $q_{94} = 0.198$, $q_{95} = 0.174$, $q_{96} = 0.111$, $q_{97} = 0.118$, $q_{98} = 0.052$, $q_{99} = 0.092$, resulting in the equilibrium payoff 89.940 whereas the payoff to pure strategy 93 is 89.395.

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