Climate negotiations under scientific uncertainty

Scott Barrett[a,b,c,1] and Astrid Dannenberg[a,d]

[a]Earth Institute and [b]School of International and Public Affairs, Columbia University, New York, NY 10027; [c]Princeton Institute for International and Regional Studies, Princeton University, Princeton, NJ 08544; and [d]Department of Economics, University of Gothenburg, 405 30 Gothenburg, Sweden

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How does uncertainty about "dangerous" climate change affect the prospects for international cooperation? Climate negotiations usually are depicted as a prisoners' dilemma game; collectively, countries are better off reducing their emissions, but self-interest impels them to keep on emitting. We provide experimental evidence, grounded in an analytical framework, showing that the fear of crossing a dangerous threshold can turn climate negotiations into a coordination game, making collective action to avoid a dangerous threshold virtually assured. These results are robust to uncertainty about the impact of crossing a threshold, but uncertainty about the location of the threshold turns the game back into a prisoners' dilemma, causing cooperation to collapse. Our research explains the paradox of why countries would agree to a collective goal, aimed at reducing the risk of catastrophe, but act as if they were blind to this risk.

Ever since the Framework Convention on Climate Change was adopted in 1992, negotiations over emission limits have been intertwined with efforts to identify a critical threshold for "dangerous anthropogenic interference with the climate system." A threshold finally was identified in the 2009 Copenhagen Accord: "the scientific view that the increase in global temperature should be below 2 degrees Celsius." However, the Copenhagen Accord relies on voluntary emission reductions to achieve this goal, and the amounts countries have pledged virtually guarantee that the 2 °C target will be missed (1). Identification of a threshold seems not to have helped the negotiations much at all.

Previous research suggests that this negative outcome is not inevitable but is largely a random occurrence, arising from a failure by negotiators to coordinate when the threshold is certain but the impact of crossing it is uncertain (2). Our research, which departs from the earlier literature in a number of ways (*SI Literature*), strongly questions this view. We provide experimental evidence suggesting that, if the threshold is known with certainty and the costs of avoiding it are low relative to the benefits, avoidance of the threshold is virtually assured whether or not the impact is uncertain, provided the negotiators can communicate (and if there is one thing negotiators can do it is communicate). Indeed, this finding may explain why the negotiations were framed around meeting a threshold and why negotiators wanted the threshold to be determined by "science" rather than by politics (only the former would be credible). Collective action fails, we show, because of uncertainty about the threshold. Far from being highly random, we show that failure is practically certain. Because the threshold is determined by Nature, and uncertainty about its value is substantially irreducible, our research suggests that negotiators should focus their attention on alternative strategies for collective action (3).

The scientific literature reveals not one but many scientific views about the temperature threshold for "dangerous" climate change (4–11), all of them uncertain. Even if a unique temperature threshold could be identified, countries can control only emissions directly, and the effect of emissions on temperature (mediated by the effect of emissions on atmospheric concentrations) is uncertain (12). Thresholds expressed in terms other than mean global temperature also are uncertain (13–16). One widely discussed paper identifies a unique "climate boundary" of 350 parts per million by volume (p.p.m.v.) atmospheric CO_2 "to ensure the continued existence of the large polar ice sheets," for which "there is a critical threshold between 350 and 550 p.p.m.v." (16). Our model can be interpreted as representing threshold uncertainty in this same way. Using the above reference values, our model suggests that countries can recognize that it is best to limit concentrations to 350 p.p.m.v. but still be compelled in this prisoners' dilemma to propose a higher target, to pledge less than is needed to meet this target, and then to contribute less than they pledged, with the consequence that concentrations ultimately exceed 550 p.p.m.v.

Although our paper was motivated by the climate problem, the participants in our experiment were not told of this motivation, making our results equally applicable to other situations in which collective action is needed to avoid a dangerous threshold. Examples range from the cascading effect of adding space debris beyond a critical level, rendering a key orbit unusable (17), to thresholds in antibiotic use, causing a disease to become drug resistant (18). Another example is the negotiation of fishery quotas—a routine task for the world's 17 regional fishery management organizations. For many species, there exists a critical minimum population level, but with unknown value. Making matters worse, fish stocks cannot be observed directly, and catch-per-unit-of-effort may fail to signal an impending crash, perhaps because of technological change (19) or the tendency of some species of fish to aggregate (20). When combined, these conditions can create a true tragedy of the commons. In all these situations, as in our game, countries have a collective incentive to avoid the far-reaching consequences of exceeding a threshold but also face individual incentives to free ride because of the inherent uncertainty about the location of the threshold.

Our underlying game-theoretic model assumes that there are N symmetric countries, each able to reduce emissions by up to $q^A_{\max}$ units using technology A and by up to $q^B_{\max}$ units using technology B. The per-unit cost of reducing emissions by these means are constant but different, with $c^A < c^B$. We can think of A as representing low-cost "ordinary abatement" and B as a high-cost technology for removing carbon dioxide from the atmosphere (21). Q denotes the total reduction in emissions by all countries using both technologies. Every unit of emission reduction gives each country a benefit, b, the marginal benefit of avoiding "gradual" climate change. Assuming $c^B > bN > c^A > b$ gives the classical prisoners' dilemma. For these parameter values, self-interest impels each country to abate 0, whereas collectively all countries are better off if each abates $q^A_{\max}$ units using technology A and 0 units using technology B.

Because climate thresholds can be related to cumulative emissions (22, 23), threshold avoidance can be expressed in terms of abatement from business as usual. Denote the threshold by $\overline{Q}$ and assume $N(q^A_{\max} + q^B_{\max}) > \overline{Q} > Nq^A_{\max}$. That is, avoidance of the threshold is technically feasible and requires using B in addition to A (air capture is needed to reduce concentrations

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[1]To whom correspondence should be addressed. E-mail: sb3116@columbia.edu.

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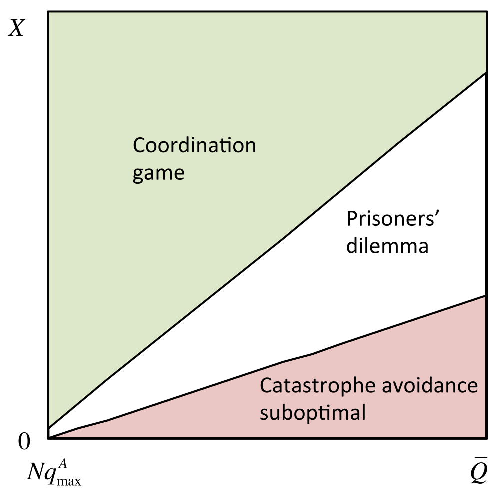

Fig. 1. Certainty model. Red area shows values for X and $\bar{Q}$ for which countries are collectively better off *not* avoiding catastrophe; here, $X < (c^B - bN)(\bar{Q}/N - q^A_{max})$. In the green area, catastrophe avoidance is a coordination game; here, $X \geq (c^B - b)\bar{Q}/N - (c^B - c^A)q^A_{max}$. In the white area, avoiding catastrophe is a prisoners' dilemma; here, if all other countries play $\bar{Q}/N$, each country prefers to abate 0. With certainty, a prisoners' dilemma arises only if $b > 0$.

from today's level to 350 p.p.m.v.). Abatement short of $\bar{Q}$ results in catastrophic loss of value X. We restrict parameter values so that when countries cooperate fully they can do no better than to abate $\bar{Q}$ precisely (Fig. 1), with technology A being fully deployed everywhere and technology B being used as a "top up" to make sure $Q = \bar{Q}$.

Acting independently, each country will maximize its own payoff, taking as given the abatement choices of other countries. We restrict parameter values so that there are two symmetric Nash equilibria in pure strategies. In one, every country abates 0, and the threshold is exceeded. In the other, every country abates q^A_{max} using technology A and $\bar{Q}/N - q^A_{max}$ using technology B, ensuring that the threshold is narrowly avoided. By our restrictions, the latter equilibrium is universally preferred. The game thus involves players coordinating to support this mutually preferred equilibrium (Fig. 1).

With threshold uncertainty, $\bar{Q}$ is assumed to be distributed uniformly so that the probability of avoiding catastrophe is 0 for $Q < \bar{Q}_{min}$, $(Q - \bar{Q}_{min})/(\bar{Q}_{max} - \bar{Q}_{min})$ for $Q \in [\bar{Q}_{min}, \bar{Q}_{max}]$, and 1 for $Q > \bar{Q}_{max}$. We assume $N(q^A_{max} + q^B_{max}) \geq \bar{Q}_{max} > \bar{Q}_{min} \geq Nq^A_{max}$ and restrict parameters so that when countries cooperate fully they abate $\bar{Q}_{max}$ collectively, eliminating threshold uncertainty, and when countries choose their abatement levels noncooperatively, they do nothing to limit their emissions, making it inevitable that the threshold will be crossed. Our experiment also assumes a uniform distribution for impacts, which means X must be replaced by its expected value in our analytical model.

Our experiment involved 400 participants (*Materials and Methods* and *SI Materials and Methods*): 10 games per treatment × 4 treatments × 10 players per game. At the start of each game, every subject was given "working capital" of €11, distributed between Accounts A (€1) and B (€10). Contributions to the public good consisted of poker chips (abatement) purchased from these accounts. Chips purchased from Account A cost €0.10 each ($c^A = 0.1$), and there were 10 chips ($q^A_{max} = 10$). Chips paid for out of Account B cost €1.00 each ($c^B = 1$), and again there were 10 chips ($q^B_{max} = 10$). Every subject also was given an endowment fund of €20, allocated to Account C. This fund could not be used to purchase chips; it was included only to ensure that no player could be left out of pocket.

After the game was played, each subject received a payoff equal to the amount of money left in his or her three accounts, after making two further adjustments. First, each subject was given €0.05 for every poker chip contributed by the group (b = 0.05). Second, each subject's payoff was reduced by an amount X unless $\bar{Q}$ or more chips were contributed. In the *Certainty* treatment, X = €15 and $\bar{Q} = 150$. Under *Impact Uncertainty*, X was distributed uniformly between €10 and €20. Under *Threshold Uncertainty*, $\bar{Q}$ was distributed uniformly between 100 and 200. In the *Impact-and-Threshold Uncertainty* treatment, X and $\bar{Q}$ were both distributed uniformly as above.

The game was played in stages. In the communication stage, every subject pledged an amount he or she intended to contribute individually and also proposed a contribution target for the group. It was common knowledge that proposals and pledges were nonbinding. Once every member of a group had made these choices, all members were informed about these values. In the contributions stage, subjects chose their actual contributions. Then the players were informed about everyone's individual and collective contributions.

For the uncertainty treatments, "Nature" chose the impact and/or the threshold in a third stage. Probabilities can be difficult for people to comprehend and so must be communicated with care (24). In our game, a volunteer was invited to activate a computerized "spinning wheel," with the "ends" of the wheel at 12 o'clock representing the minimum and maximum values of the range [(€10, €20) for X and (100, 200) for $\bar{Q}$]. Every subject was able to observe the wheel being spun and see where the arrow came to rest, determining the value for the impact and/or the threshold. After completing a follow-up questionnaire, participants were paid their earnings in cash. Answers to the survey indicate that the players understood the games and the probabilities determined by the spinning wheel (*SI Materials and Methods*).

Results

Our main hypotheses are that catastrophe will be avoided in the *Certainty* and *Impact Uncertainty* treatments but not in the *Threshold Uncertainty* and *Impact-and-Threshold Uncertainty* treatments. Our main results strongly support both hypotheses (Fig. 2). The difference in the frequency of catastrophe between *Certainty* and *Impact Uncertainty*, on the one hand, and *Threshold Uncertainty* and *Impact-and-Threshold Uncertainty,* on the other,

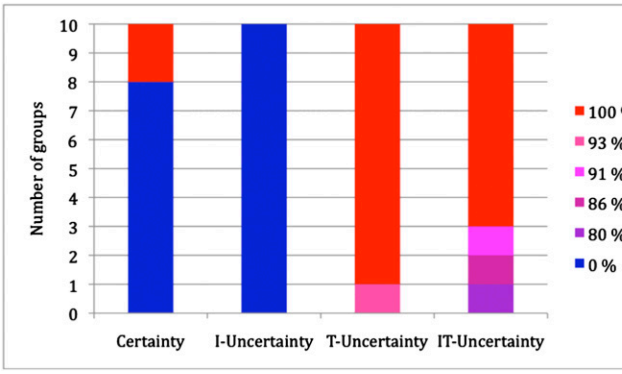

Fig. 2. Probability of catastrophe by treatment. Catastrophe was avoided 8 of 10 times in the *Certainty* treatment and 10 of 10 times under *Impact Uncertainty* (I-Uncertainty). In contrast, the probability of catastrophe was reduced below 100% (to 93%) by only 1 of 10 groups under *Threshold Uncertainty* (T-Uncertainty) and by only 3 of 10 groups (to 91, 86, and 80%, respectively) under *Impact-and-Threshold Uncertainty* (IT-Uncertainty). In the four cases where the probability of catastrophe was reduced below 100%, the spinning wheel determined that the threshold was crossed every time.

Table 1. Summary statistics: Mean values across groups per treatment

Treatment	Mean proposal	Mean pledge	Mean group contribution	Range of group contribution
Certainty	151.9 (1.57)	14.7 (0.51)	150.9 (7.69)	136–159
Impact Uncertainty	149.1 (4.98)	14.4 (0.80)	155.5 (2.92)	152–161
Threshold Uncertainty	166.3 (9.85)	15.8 (1.69)	77.2 (16.67)	55–107
Impact-and-Threshold Uncertainty	167.0 (10.40)	15.5 (2.07)	79.9 (26.90)	44–120

SDs are given in parentheses. Under threshold uncertainty, players propose that *more* be contributed, compared with the threshold certainty treatments, but end up contributing *less*. Variability in proposals, pledges, and especially contributions also is greater for the threshold uncertainty treatments.

is statistically significant (Fisher's exact test, $n = 20$, $P < 0.05$ each). In the two threshold certainty treatments, catastrophe was avoided 18 of 20 times. (In each of the two cases in which catastrophe was not avoided, the reason was a sharp deviation from the pledged and expected behavior of a single individual; see below.) In the two threshold uncertainty treatments, catastrophe occurred with certainty in 16 of 20 cases and with a probability of at least 80% in the other four cases.

As predicted, group contributions are significantly lower in the treatments with threshold uncertainty than in those without threshold uncertainty (Table 1, Mann–Whitney–Wilcoxon test, $n = 20$, $P < 0.05$ each; *SI Results*). The former also exhibit greater variability (Levene test, $n = 20$, $P < 0.05$ each). There are no statistically significant differences within these pairs of treatments. That is, impact uncertainty has no significant effect on collective action.

In both the *Certainty* and *Impact Uncertainty* treatments, group contributions are relatively close to the predicted 150. In both treatments the most frequent individual contribution is 15, the obvious focal point (25). Fifty-six percent of subjects chose this contribution level in *Certainty*. Fifty percent did so in *Impact Uncertainty*.

The prediction of zero contributions in the two threshold uncertainty treatments, on the other hand, is clearly rejected (one-sided t test, $n = 10$, $P = 0.00$ each). Zero individual contributions were common (30% in *Threshold Uncertainty* and 32% in *Impact-and-Threshold Uncertainty*), but contributions of 10 were slightly more common (36% in *Threshold Uncertainty*, 39% in *Impact-and-Threshold Uncertainty*). These subjects contributed from their low-cost account to lessen the well-known conflict between collective and individual interests (26–28).

Communication is the essence of negotiation, and it is striking how the players used their proposals and pledges differently depending on threshold uncertainty. When the threshold was known, players communicated so as to coordinate to the threshold. When the threshold was unknown, communication was more strategic. Mean proposals for the *Certainty* and *Impact Uncertainty* treatments are very close to 150 (Table 1), with 83% of subjects in *Certainty* and 94% in *Impact Uncertainty* proposing precisely this amount. Mean proposals in *Threshold Uncertainty* and *Impact-and-Threshold Uncertainty* were significantly larger (Mann–Whitney–Wilcoxon test, $n = 20$, $P < 0.05$ each), with 29% of subjects in *Threshold Uncertainty* and 35% in *Impact-and-Threshold Uncertainty* proposing 200. Why did not more participants propose the collectively optimal 200? Answers to questions in our follow-up questionnaire provide a strong clue. Participants perceived their proposals as serving to motivate other students to contribute; they thought that a proposal below 200 was more credible and so was more likely to stimulate contributions by others.

Fig. 3 shows the relationship between pledges and actual contributions. In *Certainty* and *Impact Uncertainty*, almost all players (98% in both treatments) contributed at least as much as they pledged. Two of 200 contributed substantially less than they pledged, causing the two breakdowns in collective action in the

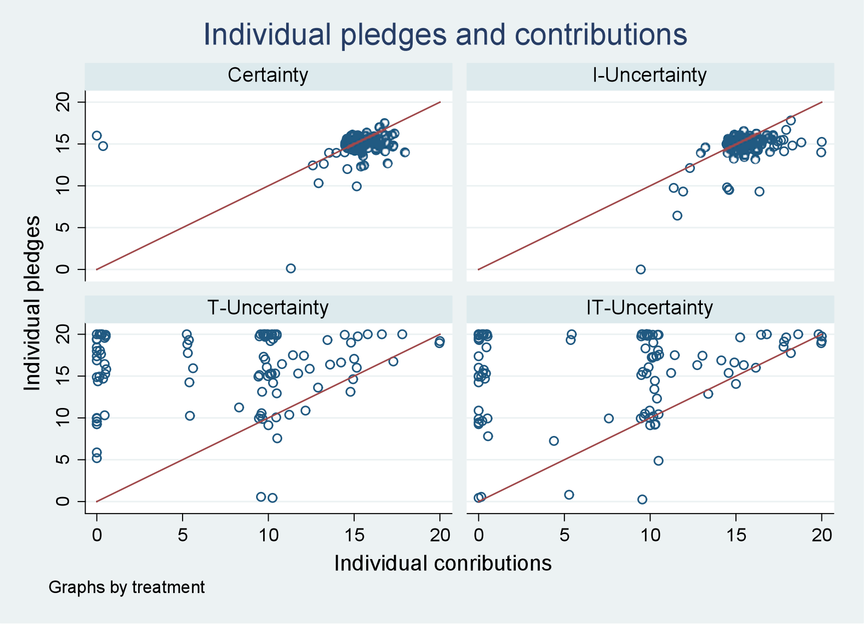

Fig. 3. Pledges and actual contributions by treatment. In the *Certainty* and *Impact Uncertainty* treatments, pledges and contributions are tightly bunched, with contributions usually exceeding pledges. In the *Threshold* and *Impact-and-Threshold Uncertainty* treatments, values vary widely, with contributions usually falling far short of pledges. A small noise (3%) has been inserted to make all data points visible.

Certainty treatment. By contrast, in the *Threshold Uncertainty* and *Impact-and-Threshold Uncertainty* treatments, most (82 and 75%, respectively) contributed less than they pledged, indicating that pledges, like proposals, were used strategically.

Our follow-up questionnaire revealed that the reason for these differences had to do with the context in which decisions were made. Fairness and trust were more important considerations for the coordination games than for the prisoners' dilemmas. Players were more trusting in the *Certainty* and *Impact Uncertainty* treatments because each recognized that the others had a strong incentive to be trustworthy in these situations.

A final observation concerns attitudes toward risk, which can play a crucial role in the analysis of collective best outcomes (29). Our theory assumes that people are risk-neutral. Our questionnaire reveals that a majority of subjects are risk averse, but statistical analysis shows that whether a person is risk averse has no discernable influence on behavior (*SI Results*). Once again, the context of these games seems to shape how people behave.

Discussion

There is universal agreement among countries that global emissions should be limited so as to prevent "dangerous interference" with the climate system. Our research strongly suggests that if a threshold for catastrophic climate change could be identified with certainty, free-riding behavior would be disciplined; countries very likely would propose a collective target certain to avoid catastrophe, would pledge to contribute their fair share to the global effort, and would act so as to fulfill their promises. Scientists have endeavored to support this negotiation strategy by identifying a "red line" for collective action, but thresholds for "abrupt and catastrophic" climate change are inherently uncertain. Our research suggests that, under these circumstances, countries are very likely to propose to do less collectively than is needed to avert catastrophe, pledge to contribute less than their fair share of the amount proposed, and end up contributing even less than their pledge. The climate change game is a prisoners' dilemma, but not for the reasons usually given. What makes it a prisoners' dilemma is not just the need for collective action but uncertainty about the threshold for dangerous climate change.

Our analysis is consistent with how the climate negotiations have played out so far. Concern about climate thresholds has reinforced the need to limit emissions so as to reduce, if not eliminate, the risk of dangerous interference, without having any noticeable effect on how countries behave. As in our experiment, countries have pledged to do less than is needed to meet their stated collective goals. We will not know until 2020 if the Copenhagen Accord pledges will be met, but if our experimental results are a reliable guide, countries may end up emitting more than they pledged—with potentially profound and possibly irreversible consequences.

Our research thus underscores the need to pursue alternative negotiation strategies for transforming the prisoners' dilemma. Collective action can succeed, we have shown, when the underlying prisoners' dilemma game is transformed into a coordination game. Although threshold uncertainty spoils this transformation, previous research shows that strategic treaty design can bring about a similar transformation. One way is by the use of trade restrictions against nonparticipating countries. If the loss from the trade restrictions exceeds the gains from free riding, every country will want to participate in a treaty, so long as each is assured that others will participate; this is how the Montreal Protocol enforced restrictions on the production and consumption of chlorofluorocarbons to protect the ozone layer (3). Another way to make abatement a coordination game is by the use of technology standards when these exhibit network externalities—that is, when the returns to each country of adopting a standard increase with the number of other countries that adopt the standard (30); this is how the MARPOL treaty limited releases of oil into the sea by tankers (3). Climate change is a more complex challenge, but our research suggests that strategies like these will be more successful than relying exclusively on the fear of dangerous climate change.

Materials and Methods

The experimental sessions were held in a computer laboratory at the University of Magdeburg, Germany, using students recruited from the general student population. In total, 400 students participated in the experiment, 100 per treatment. At the beginning of a session, subjects were seated at computers, which were linked to enable structured communication during the game (see *SI Materials and Methods* for further details and software). Written instructions, including several numerical examples and control questions, were handed out. The control questions tested the subjects' understanding of the game to ensure that they were aware of the implications of making different choices. Subjects then were assigned randomly to 10-person groups and played five practice rounds, with the membership of each group changing after each round. After a final reshuffling of members, each group played the game itself. To ensure anonymity, the members of each group were identified by the letters A through J. Subjects first announced a contribution target for the group and an amount they intended to contribute themselves. After being informed about everyone's proposals and pledges, subjects chose their actual contributions. The decisions in both stages were made simultaneously and independently. Players were informed about all the decisions at the end of the game. They also were informed about individual expected payoffs contingent on the probability of the loss and the expected value of the loss. After the game, subjects were asked to complete a short questionnaire, giving a picture of their reasoning, emotions, and motivation during the game. Then they were paid their earnings in cash.

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Supporting Information

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SI Materials and Methods

Experimental Design and Procedure. As is conventional practice in the literature, our experiment involved students as participants (all but one of the 20 studies listed in Table S3 used students). The experimental sessions were held in a computer laboratory at the University of Magdeburg, Germany, with 400 students recruited from the general student population (using the recruiting software Orsee; ref. 1). The four treatments were run in a between-subjects design. One hundred subjects were assigned randomly to each treatment. In each session, 20 subjects were seated randomly at linked computers (using the game software Ztree; ref. 2). Before the subjects received the experimental instructions and practiced playing the game, they were invited to use and become familiar with the computerized "spinning wheel" (Fig. S1). Then written instructions, including several numerical examples and control questions, were handed out. The instructions assumed a neutral frame for the context and language of the experiment to avoid any potential bias (there was no mention of "climate change"). Control questions tested the subjects' understanding of the game to ensure that they were aware of the implications of different choices. An oral presentation highlighted the key features of the game and provided further numerical examples. After the game was explained and questions about it were answered privately, subjects were assigned randomly to one of two 10-person groups and played a practice round. The players were shuffled again and played another practice round. In all, every player played five practice rounds, each time with a different group. After a final reshuffling, each group played the game "for real." Table S1 summarizes the experimental design; Table S2 shows the corresponding hypotheses derived from the analytical model.

Experimental Instructions. The instructions below are for the *Impact Uncertainty* treatment, translated from German. The instructions for the other treatments are nearly identical.

Welcome to our experiment!

1. General information

In our experiment you can earn money. How much you earn depends on the gameplay, or more precisely on the decisions you and your fellow coplayers make. You will receive €20 for your participation, but note that a loss during the experiment will be deducted from that amount, whereas a gain will be added. For a successful run of this experiment, it is essential that you do not talk to other participants. Now, read the following rules of the game carefully. If you have any questions, please give us a hand signal. It is important that you read up to the STOP sign only. Please wait when you get there, because we will give you a brief oral presentation before we continue.

2. Game rules

There are 10 symmetric players in the game, meaning you and nine other players. Each player is faced with the same decision problem. All decisions in the experiment are anonymous. For the purpose of anonymity, you will be identified by a letter (between A and J), which you will see in the lower left corner of your display.

At the beginning of the game, you will receive 20 poker chips, which are credited to two personal accounts, Account A and Account B. During the experiment, you can use the poker chips in your accounts to contribute to a joint project, or you can leave these chips untouched. Chips from Account A are cheap; they cost €0.10 each. However, you can contribute no more than 10 chips from Account *A*. Chips from Account B are more expensive; they cost €1.00 each. You can contribute at most 10 chips from Account *B*. So, overall you can contribute any integer amount of chips between 0 and 20 to the joint project: 10 chips from Account A and 10 chips from Account B.

At the end of the game, the amount of chips you have left in Accounts A and B will be paid to you in cash: €0.10 for each chip in Account A and €1.00 for each chip in Account B. There are two further adjustments: First, you will get €0.05 for every poker chip contributed to the joint project, irrespective of who contributed the chip and whether the chip was purchased from Account A or B. Second, if the group as a whole contributes fewer than 150 poker chips to the joint project, every player will lose a certain amount of money. The loss is the same for each player, but it is uncertain; it ranges from €10.00 to €20.00. The loss will be determined at the end of the experiment by the "spinning wheel" you can see on your display. Note that each value between €10.00 and €20.00 has the same probability of being selected. If the group contributes 150 or more poker chips to the joint project, no player will lose any money.

Before you and the other players decide how many chips to contribute, everyone will be given an opportunity to make two nonbinding announcements: First, each player will make a proposal for how many chips the group as a whole should contribute to the joint project. Second, each player will make a pledge for how many chips he or she intends to contribute to the joint project. All the proposals and pledges made by the players will be displayed before you and the others decide how much to contribute.

The game will be played and paid out only once. You should think carefully about how to decide in the game. Before playing the game itself, five trial rounds will be played so that you and the other players can become familiar with the game. The people with whom you play will change in each trial round and in the real round, so you will never play more than one round with the same group of people.

3. Example

Here, you can see a (hypothetical) example of the decisions made by the 10 players.

[Screenshot, see Fig. S2]

The leftmost column ("Proposals") shows every player's proposal for the collective contribution target. The column next to it ("Pledges") shows each player's pledge for his or her own contribution. The next column ("Contributions") displays each player's actual contribution. The rightmost column ("Expected Payoffs") shows the corresponding EXPECTED payoff levels, i.e., the payoffs when the loss equals the expected loss (€15). Note that your ACTUAL payoff will be based on the actual loss (between €10 and €20), which will be determined by the spinning wheel at the end of the experiment. When you have played the game, you will see this information displayed.

[STOP sign]

Please wait for the oral description of the game.

4. Control questions

Please answer the following control questions.

a. Take a look at the hypothetical example in part 3 above. Are the collective contributions of the group as a whole sufficient to avoid the loss?

○ Yes ○ No

b. How many chips does each player have to contribute, on average, if the group were to contribute 150 chips in total?

○ 0 ○ 5 ○ 10 ○ 15 ○ 20

c. Assume that the group as a whole has contributed fewer than 150 chips and the loss is to be determined by the spinning wheel. What is the smallest possible loss and what is the greatest possible loss for each player?

Smallest possible loss: €__________

Greatest possible loss: €__________

d. Assume that the group as a whole has contributed fewer than 150 chips and the loss is to be determined by the spinning wheel. What is the probability of the loss being greater than €15.00?

○ 0% ○ 25% ○ 50% ○ 75% ○ 100%

e. Assume that the group as a whole (including yourself) has contributed 0 chips to the joint account. The spinning wheel determines the loss to be €18.50. What would be your payoff (excluding the participation fee)?

○ – €7.50 ○ – €2.00 ○ €1.50 ○ €10.00 ○ €12.50 ○ €17.50

d. Assume that the group as a whole (including yourself) has contributed 100 chips to the joint account. Assume also that you have contributed 10 chips from Account A and 0 chips from Account B. The spinning wheel determines the loss to be €13.50. What would be your payoff (excluding the participation fee)?

○ – €7.50 ○ – €2.00 ○ €1.50 ○ €10.00 ○ €12.50 ○ €17.50

e. Assume that the group as a whole (including yourself) has contributed 150 chips to the joint account. Assume also that you have contributed 10 chips from Account A and 5 chips from Account B. What would be your payoff (excluding the participation fee)?

○ – €7.50 ○ –€2.00 ○ €1.50 ○ €10.00 ○ €12.50 ○ €17.50

f. Assume that the group as a whole (including yourself) has contributed 150 chips to the joint account. Assume also that you have contributed 10 chips from Account A and 0 chips from Account B. What would be your payoff (excluding the participation fee)?

○ – €7.50 ○ – €2.00 ○ €1.50 ○ €10.00 ○ €12.50 ○ €17.50

g. Assume that the group as a whole (including yourself) has contributed 200 chips to the joint account. Assume also that you have contributed 10 chips from Account A and 10 chips from Account B. What would be your payoff (excluding the participation fee)?

○ – €7.50 ○ – €2.00 ○ €1.50 ○ €10.00 ○ €12.50 ○ €17.50

Please use the pocket calculator to calculate other examples! Give us a hand signal after you have answered all the control questions. We will come to you and check that you have answered all of the questions. The game will begin after we have checked the answers of all of the players and answered any questions you may have. Good luck!

SI Literature

Linear public goods games (variants of the prisoners' dilemma) have been studied extensively in experimental settings. In these games, there is a unique, Pareto-inefficient Nash equilibrium. Cooperation typically starts out relatively high but declines steadily with repeated play (for reviews, see refs. 3 and 4). In threshold public goods games, the incentives are different. In these games, the public good is provided only if the sum of contributions reaches a predetermined threshold, and there exist two sets of Nash equilibria (in pure strategies), one of which is efficient. In these games, provision can succeed, and full cooperation be sustained, depending on the cost–benefit ratio of provision and the experimental design (for a review, see ref. 5).

Threshold public goods experiments with uncertainty about the threshold or the impact of missing the threshold have been conducted within three different contexts; for an overview see Table S3. The climate catastrophe literature has focused so far on impact uncertainty. These studies assume that impact uncertainty obeys a Bernoulli distribution, with climate catastrophe occurring with given probability if the players' climate protection efforts fall short of a certain threshold. Threshold uncertainty has been analyzed in the context of discrete public goods and common pool resources. In the latter literature, players are allowed to claim any amount of a collectively owned resource, but they are unaware of the precise resource size and receive a payoff of zero if the total quantity claimed exceeds the resource stock. A key result of this literature is that increasing resource uncertainty causes participants to overestimate resource size and, as a consequence, request more.

Our paper departs from this literature (Table S3 and refs. 6–25) in a number of ways. Impact uncertainty in our model is represented by a continuous uniform distribution; rather than uncertainty as to whether there will be an impact, our model expresses uncertainty about the value of the impact. Contributions in our model alleviate "gradual" climate change, not only "abrupt and catastrophic" climate change; players have two ways of reducing emissions, rather than one, each achieved at a different marginal cost. Most importantly, in addition to having a certainty treatment, we examine both threshold and impact uncertainty. Our experiments are played by 10 players, significantly more than in previous studies. A greater number of players should amplify free-rider incentives while making coordination more difficult. Finally, we place great emphasis on communication, a possibility ignored by all but one previous study in all three literatures. Specifically, we allow players not only to make pledges but also to propose group contributions.

From a theoretical viewpoint, costless preplay communication that does not directly affect payoffs is "cheap talk." Communication nevertheless matters, because it affects payoffs indirectly through the players' beliefs. However, it does not guarantee efficiency. Even given an unlimited chance to negotiate, agents may not be able to reach a good outcome or escape a bad one. Cheap talk is credible and therefore is presumed to work, if it is self-committing (i.e., if, when a pledge is believed by others, the person making the pledge has an incentive to fulfill it) and self-signaling (i.e., the person making the pledge only pledges to do what she truly wants to do) (26–28). Previous experiments have shown that communication among players can increase cooperation, although the effects generally depend on the nature of the game and the communication medium. In a nutshell, although communication often works in coordination games, it works much less reliably in cooperation games. Coordination experiments show that communication greatly facilitates coordination on the Pareto efficient equilibrium, even if communication is limited to the exchange of written messages and is not self-signaling (29–35). Cooperation experiments show that communication may work when it is entirely incredible (i.e., neither self-committing nor self-signaling), but the positive effect of communication is not robust; it depends, for example, on the specific medium. Communication generally works best when it is face-to-face among a small group of players, allowing them to discuss their problem and to make and elicit ethically binding promises (for reviews, see refs. 36–38). It also has a positive effect when combined with punishment (39).

SI Results

Table S4 shows the significance of differences in proposals, pledges, and contributions between treatments. It shows that threshold uncertainty leads to significantly different behavior, whereas impact uncertainty has virtually no significant effect.

Table S5 presents the subjects' responses to our follow-up questionnaire. In general, whenever the questions are about general attitudes, responses vary little across treatments. This uniformity indicates that the random allocation of participants into treatment cells worked well and that participants' experience in the game did not significantly affect their responses to these questions.

Subjects' risk aversion (see question 10), for example, is similar among treatments, with the percentage of risk-averse subjects ranging from 58–65% (Fisher's exact test, $P > 0.05$ each). Moreover, within each treatment, there is no significant correlation between individual risk aversion and individual contributions or between the number of risk-averse members in a group and group contributions (Spearman's correlation test, $P > 0.05$ each). Thus, we cannot reject the hypothesis that risk aversion and behavior in the game are statistically independent.

Averages of point estimates for the threshold and impact (see questions 11 and 12) do not differ significantly from their corresponding expected values (t test, $P > 0.05$ each); nor do they differ significantly among treatments (Mann–Whitney–Wilcoxon test, $P > 0.05$ each). This measure suggests that our participants understood the probability distribution for each parameter and that a higher degree of uncertainty (i.e., the combination of impact uncertainty and threshold uncertainty compared with only one type of uncertainty) did not bias subjects' perception of these distributions. It also suggests that when collective action collapsed in our experiment, the reason was not a misperception of risk, as has been observed in common pool resource experiments (20–22).

In contrast, responses to the questions about subjects' reasoning and emotions during the game vary greatly between the treatments with and without threshold uncertainty. Subjects in the threshold certainty treatments were more contented with the game's outcome. Fairness and trust played a more important role in decision-making for these treatments. Proposals and pledges were found to be more helpful than under threshold uncertainty. Interestingly, the majority of subjects in all of the treatments did not feel betrayed by other members of their group, nor did they regret the choices they had made. This outcome suggests that the elicited behavior is likely to be stable.

Table S6 presents subjects' responses to the open-ended questions about their motivation for making proposals, pledges, and contributions. The responses were classified and assigned to certain response categories. A large majority in *Certainty* and *Impact Uncertainty* stated that the joint group payoff was the most important reason for their proposal. Most subjects in the threshold uncertainty treatments stated that they wanted to propose a realistic target or to stimulate others' contributions. A large majority in the *Certainty* and *Impact Uncertainty* treatments used the pledges to signal truthfully their intended contribution and to create trust within the group. In contrast, most subjects in the *Threshold Uncertainty* and *Impact-and-Threshold Uncertainty* treatments used the pledge to stimulate others' contributions. As for the contribution decision, responses indicate that subjects in the threshold certainty treatments either wanted to contribute their fair share of the burden or to compensate for potentially missing contributions. Most subjects in the threshold uncertainty treatments stated that they chose their contribution level because they wanted to maximize their own payoff, because they distrusted their coplayers, or simply because the contributed chips were cheap. Combining subjects' responses to these questions and their actual behavior in the game reveals that in the threshold certainty treatments the most frequently stated reason for deviating from the own pledge was to compensate for potentially missing compensations. Thus, when people deviated from their pledge, they generally contributed more than they pledged. In contrast, in the threshold uncertainty treatments, people often deviated from their pledge by contributing less. The reason was that they often used the pledge to stimulate others' contributions, but they chose their contributions to maximize their own payoff.

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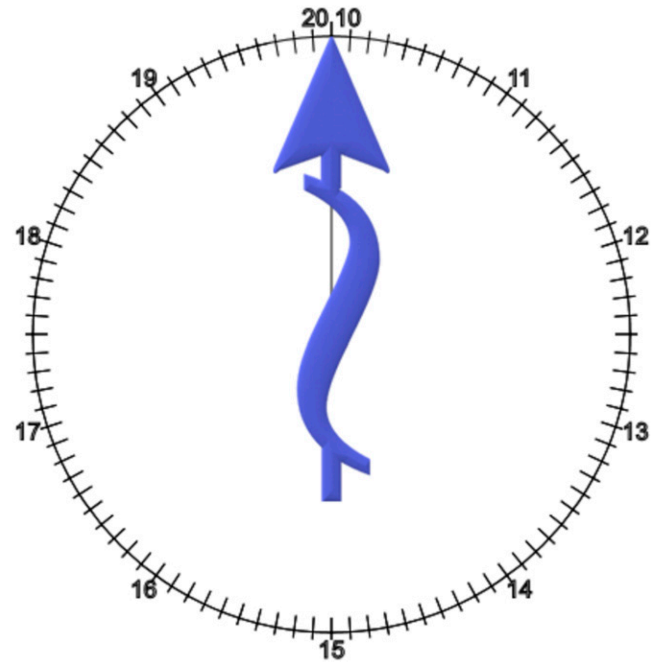

Fig. S1. At the end of the experiment, a volunteer was invited to activate a computerized spinning wheel with the "ends" of the wheel at 12 o'clock representing the minimum and maximum values of the range [(€10, €20) for X and (100, 200) for $\overline{Q}$]. Every subject was able to observe the wheel being spun and see where the arrow came to rest, determining the value for the impact or the threshold. The selected value also was displayed next to the wheel. The wheel generated random numbers (rounded to two decimal places), i.e., it was not possible to manipulate the outcome. All participants had 15 min to play with and become familiar with the wheel before the rules of the game were explained. To spin the spinner, players had to click on the spinner and swipe to the side, away from the spinner.

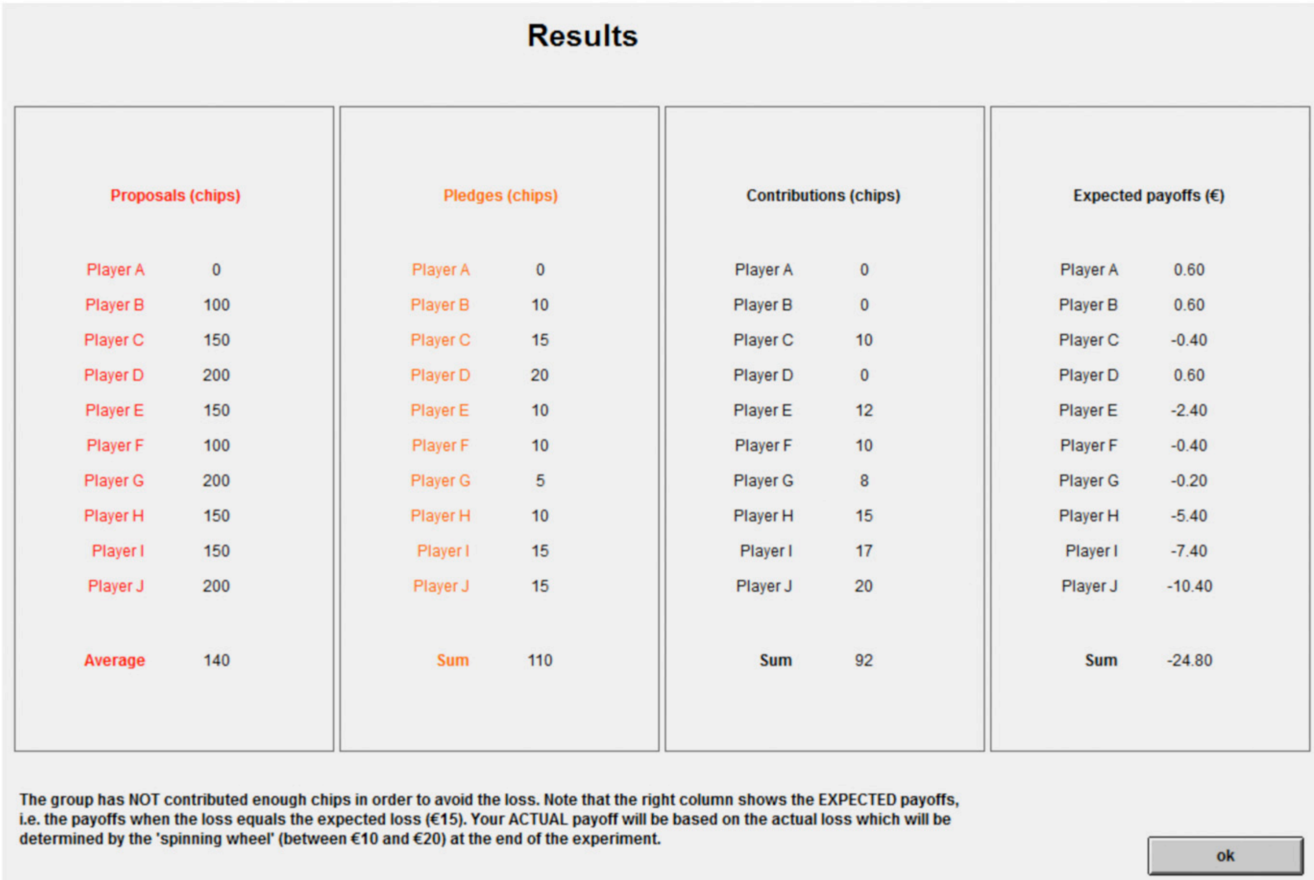

Fig. S2. Screenshot shown in the experimental instructions: a *hypothetical* example of the decisions made by the 10 players. The leftmost column ("Proposals") shows each player's proposal for the collective contribution target. The column next to it ("Pledges") shows each player's pledge for his or her own contribution. The next column ("Contributions") displays each player's actual contribution. The rightmost column ("Expected payoffs") shows the corresponding expected payoff levels.

Table S1. Experimental design

Treatment	N	Endowment [chips]	Marginal costs [€]	Marginal benefit [€]	Impact [€]	Threshold [chips]
Certainty	10	$q^A_{max} = 10, q^B_{max} = 10$	$c^A = 0.10, c^B = 1.00$	$b = 0.05$	15	150
Impact Uncertainty	10	$q^A_{max} = 10, q^B_{max} = 10$	$c^A = 0.10, c^B = 1.00$	$b = 0.05$	[10, 20]	150
Threshold Uncertainty	10	$q^A_{max} = 10, q^B_{max} = 10$	$c^A = 0.10, c^B = 1.00$	$b = 0.05$	15	[100, 200]
Impact-and-Threshold Uncertainty	10	$q^A_{max} = 10, q^B_{max} = 10$	$c^A = 0.10, c^B = 1.00$	$b = 0.05$	[10, 20]	[100, 200]

Subjects' initial endowment of €31.00 is divided among three separate accounts: €1.00 in Account A (10 chips at €0.10 each), €10.00 in Account B (10 chips at €1.00 each), and €20.00 in Account C. Subjects can use any amount of chips from Accounts A and B but are not allowed to touch Account C.

Table S2. Hypotheses

Treatment	Catastrophe avoided	Group contribution
Certainty	Yes	150
Impact Uncertainty	Yes	150
Threshold Uncertainty	No	0
Impact-and-Threshold Uncertainty	No	0

The analytical model predicts that with threshold certainty players will be able to avoid catastrophe, but with threshold uncertainty players will be unable to sustain full cooperation. A stronger hypothesis would be that the players contribute 150 in total under threshold certainty and nothing under threshold uncertainty.

Table S3. Threshold public goods experiments with impact or threshold uncertainty

Study (ref.)	Contributions	Uncertainty test and rounds	Benefits	Marginal costs	*N*	*Certainty* treatment	*Impact Uncertainty* treatment	*Threshold Uncertainty* treatment	*Impact-and-Threshold Uncertainty* treatment	Communication
Climate change experiments										
This paper	Simultaneous; discrete [0, 20]	Between-subject test; one-shot	Continuous and discontinuous	Stepwise constant	10	Yes	Yes; continuous uniform distribution	Yes; continuous uniform distribution	Yes; continuous uniform distribution	Yes; proposals and pledges
Hasson et al., 2010 (6)	Simultaneous; binary {0, 10}	No test; one-shot	Discontinuous	Constant	4	No	Yes; Bernoulli distribution	No	No	No
Hasson et al., 2012 (7)	Simultaneous; binary {0, 10}	Between-subject test; one-shot	Discontinuous	Constant	4	Yes	Yes; Bernoulli distribution	No	No	No
Milinski et al., 2008 (8)	Simultaneous; {0, 2, 4} per round	Between-subject test; one-shot in 10 successive rounds	Discontinuous	Constant	6	No	Yes; Bernoulli distribution	No	No	No
Milinski et al., 2011 (9)	Simultaneous; {0, 2, 4} per round	No test; one-shot in 10 successive rounds	Discontinuous	Constant	6	No	Yes; Bernoulli distribution	No	No	No
Tavoni et al., 2011 (10)	Simultaneous; {0, 2, 4} per round	No test; one-shot in 10 successive rounds	Discontinuous	Constant	6	No	Yes; Bernoulli distribution	No	No	Yes; pledges
Discrete public goods experiments										
Au 2004 (11)	Sequential; binary {0, 10}	Between-subject test; x rounds in 38 min	Discontinuous	Constant	5	Yes	No	Yes; discrete uniform distribution	No	No
Gustafsson et al., 2000* (12)	Simultaneous; [0, 2000]	Within-subject test; 2 x 8 rounds	Discontinuous	Constant	5	No	No	Yes; sequence of numbers with different variances	No	No
McBride 2010 (13)	Simultaneous; binary {0, 1}	Within-subject test; 2 × 15 rounds	Discontinuous	Constant	5	Yes	No	Yes; discrete uniform distribution	No	No
Suleiman et al., 2001 (14)	Simultaneous; discrete [0, 5]	Within-subject test; 3 x 8 rounds	Discontinuous	Constant	5	Yes	No	Yes; discrete uniform distribution	No	No
Van Dijk et al., 1999* (15)	Simultaneous; discrete [0, 75]	Between-subject test; one-shot	Discontinuous	Constant	4	Yes	Yes; continuous uniform distribution	No	No	No
Wit/Wilke 1998* (16)	Sequential; discrete [0, 15]	Between-subject test; one-shot	Discontinuous	Constant	100	No	No	Yes; continuous uniform distribution	No	No
Common pool resource experiments										
Budescu et al., 1990 (17)	Simultaneous; any request	Within-subject test; 3 × 10 rounds	Discontinuous	Constant	5	Yes	No	Yes; continuous uniform distribution	No	No
Budescu et al., 1995a (18)	Simultaneous and sequential; any request	Within-subject test; 5 × 4 rounds	Discontinuous	Constant	5	No	No	Yes; continuous uniform distribution	No	No
Budescu et al., 1995b (19)	Simultaneous and sequential; any request	Within-subject test; 3 × 10 rounds	Discontinuous	Constant	2; 3; 5	Yes	No	Yes; continuous uniform distribution	No	No
Gustafsson et al., 1999a* (20)	Simultaneous; any request	Within-subject test; 6 × 4 rounds	Discontinuous	Constant	5	No	No	Yes; continuous uniform distribution	No	No
Gustafsson et al., 1999b* (21)	Simultaneous; any request	Within-subject test; 2 × 8 rounds	Discontinuous	Constant	5	No	No	Yes; sequence of numbers with different variances	No	No
Rapoport et al., 1992 (22)	Simultaneous; any request	Within-subject test; 5 × 4 rounds	Discontinuous	Constant	5	Yes	No	Yes; continuous uniform distribution	No	No
Rapoport et al., 1993 (23)	Sequential; any request	Within-subject test; 3 × 10 rounds	Discontinuous	Constant	5	Yes	No	Yes; continuous uniform distribution	No	No
Suleiman et al., 1996 (24)	Sequential; any request	Within-subject test; 3 × 5 rounds	Discontinuous	Constant	5	Yes	No	Yes; continuous uniform distribution	No	No
Walker and Gardner 1992 (25)	Simultaneous; discrete [0, 25]	20 rounds with probabilistic prior destruction	Continuous and discontinuous	Constant	8	No	Yes; Bernoulli distribution	No	No	No

*Participants in these experiments were given false information about the game and paid an amount that was unrelated to how they and others actually played.

Table S4. Significance of differences between treatments

Treatment	*Certainty*			*Impact Uncertainty*			*Threshold Uncertainty*		
	Proposal	Pledge	Contribution	Proposal	Pledge	Contribution	Proposal	Pledge	Contribution
Impact Uncertainty	0.0226 (0.2362)	0.4688 (0.3507)	0.1478 (0.0598)						
Threshold Uncertainty	0.0002 (0.0052)	0.0638 (0.0170)	0.0002 (0.0137)	0.0001 (0.0624)	0.0371 (0.0701)	0.0002 (0.0003)			
Impact-and-Threshold Uncertainty	0.0024 (0.0114)	0.0340 (0.0273)	0.0002 (0.0064)	0.0010 (0.0849)	0.0230 (0.0739)	0.0002 (0.0010)	0.7051 (0.9913)	0.7912 (0.7355)	1.0000 (0.1956)

P values from a Mann–Whitney–Wilcoxon rank-sum test of treatment differences in mean values; *P* values from a Levene test of treatment differences in variances are given in parentheses.

Table S5. Responses to the ex post questionnaire

Question	Response	*Certainty*	*Impact Uncertainty*	*Threshold Uncertainty*	*Impact-and-Threshold Uncertainty*
1. Were you generally satisfied with the game's outcome?	Very much	63	66	10	10
	Somewhat	18	33	31	38
	Little	5	1	26	34
	Not at all	14	0	33	18
2. Knowing how the game was played, with the benefit of hindsight, do you wish you had made a different contribution?	Very much	2	2	11	8
	Somewhat	19	19	17	24
	Little	27	24	22	20
	Not at all	52	55	50	48
3. Did fairness play a role for your contribution decision?	Very much	61	65	24	23
	Somewhat	16	23	10	28
	Little	11	6	21	17
	Not at all	12	6	45	32
4. Did trust play a role for your contribution decision?	Very much	58	56	18	33
	Somewhat	22	32	12	20
	Little	9	7	23	13
	Not at all	11	5	47	34
5. Do you agree with the statement that the exchange of proposals was helpful?	Very much	49	49	6	15
	Somewhat	27	23	28	23
	Little	13	19	34	33
	Not at all	11	9	32	29
6. Do you agree with the statement that the exchange of pledges was helpful?	Very much	68	80	10	17
	Somewhat	24	16	30	28
	Little	5	4	27	34
	Not at all	3	0	33	21
7. Generally speaking, do you trust other people?	Very much	25	24	21	27
	Somewhat	60	65	60	55
	Little	13	10	17	14
	Not at all	2	1	2	4
8. Did you trust the other players to make the contributions they pledged?	Very much	47	56	10	11
	Somewhat	43	35	23	24
	Little	8	8	26	27
	Not at all	2	1	41	38
9. Knowing how the game was played, with the benefit of hindsight, do you feel, that some of the other players betrayed your trust in them?	Very much	10	0	16	14
	Somewhat	12	28	21	21
	Little	37	29	23	25
	Not at all	41	43	40	40
10. Please imagine the following situation in another unrelated experiment: You have an initial endowment of €40. There is a 50% possibility that you will lose your €40. However, you can avoid this loss by paying €20 up front. Would you rather pay this amount and get €20 for certain or would you rather accept the risk of losing the €40 with probability 50%?	€40 uncertain	15	19	25	17
	Indifferent	27	16	13	18
	€20 certain	58	65	62	65
11. The contribution threshold will soon be determined by the spinning wheel. What single value do you estimate for the threshold?	Mean estimation			150.71	153.49
12. The loss will soon be determined by the spinning wheel. What single value do you estimate for the loss?	Mean estimation		15.12		15.41

Numbers are percentages of subjects per treatment (except for questions 11 and 12, which show mean values).

Table S6. Responses to the ex post open-ended questions

Question	Response category	*Certainty*	*Impact Uncertainty*	*Threshold Uncertainty*	*Impact-and-Threshold Uncertainty*
1. What was the most important reason for your proposal for the group contribution?	Joint payoff maximization	82	88	22	23
	Fairness	3	4	1	1
	Safety	8	2	0	0
	Stimulation of others' contributions	2	0	31	24
	Realistic target	0	1	39	41
	Other reason	5	5	7	11
2. What was the most important reason for your pledge for your own intended contribution?	Signaling of intended contribution/ creation of trust	71	67	24	32
	Stimulation of others' contributions	17	17	66	56
	Safety	5	10	4	4
	Other reason	7	6	6	8
3. What was the most important reason for your contribution?	Fair share to reach target/own pledge	56	62	12	19
	Compensation of potentially missing contributions/safety	33	31	0	0
	Own payoff maximization	10	5	24	29
	Resignation/distrust	0	0	30	32
	Cheap chips/compromise between group and own interest	0	1	33	17
	Other reason	1	1	1	3

Subjects' responses were classified by keyword search. Numbers are percentages of subjects per treatment.