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One bad apple spoils the barrel? Public good provision under threshold uncertainty

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Abstract
We report laboratory evidence on the voluntary provision of threshold public goods when the exact location of the threshold is not known. Our experimental treatments explicitly compare two prominent technologies, summation, and weakest link. Uncertainty in threshold location is particularly detrimental to threshold attainment under weakest link, where low contributions by one subject cannot be compensated by others. In contrast, threshold uncertainty does not affect contributions under summation. We demonstrate that non-binding pledges improve the chances of threshold attainment under both technologies, particularly under weakest link.

Keywords Public goods · Threshold uncertainty · Weakest link · Coordination · Experiment

JEL Classification C91 · H41 · Q54

1 Introduction

Economists have long highlighted the serious challenge that free-riding poses for the voluntary provision of public goods. In many settings, the level of the public good depends on the *sum* of voluntary contributions, which means that individuals

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may hope to free ride on the efforts of others (e.g., Zelmer, 2003). Yet, many public goods do not fit this framework of a summation technology. Rather, aggregation of individual contributions into public good provision may rely on more general technologies (e.g., Hirshleifer, 1983; Vicary & Sandler, 2002) including ones where individual contributions are complements rather than substitutes. A prominent example is the weakest-link technology, where the level of the public good depends on the *lowest individual contribution*. Such weakest links are present, e.g., when protecting against terrorist attacks such as airplane hijacking or when fighting contagious diseases (Barrett, 2016; Caparròs & Finus, 2020a; Vicary & Sandler, 2002). In these settings, the outcome critically depends on the minimum contribution level.[1]

Moreover, there are many situations where the link between effort (contributions) and the resulting amount of the public good is stochastic: the exact precautionary effort, e.g., the vaccination rate that prevents a given mutation or the security efforts that succeed in keeping terrorists out of high-security zones, is unknown. That is, additional effort will only increase the *chances* of preventing an adverse event. Despite the importance of uncertain thresholds in weakest-link settings, no study has yet explored their behavioral consequences. The main research question we address in this paper is how threshold uncertainty affects the provision of a public good under a weakest-link technology, particularly in relation to the same effect under the summation technology.

We conduct a lab experiment where subjects contribute to a public good, the benefits of which (in the form of avoiding a bad event) are generated only if some contribution threshold is passed. This design allows us to explicitly compare the likelihood of reaching the threshold under certain and uncertain thresholds and for both a summation and a weakest-link aggregation of contributions. With summation, total group contributions need to exceed the threshold, while the threshold under weakest link is a minimum level of contribution that all group members must achieve. Thus, the aggregation technologies we consider represent the polar cases of perfect substitutability and perfect complementarity among different players' contributions. We interact these investigations into the role of uncertainty and aggregation technology on contribution levels with a study of the role of (cheap talk) communication by allowing subjects to send messages on their intended contribution levels and making suggestions for the contributions by others.

Our paper contributes to diverse strands of the literature. Inspired by potential thresholds in the climate system (e.g., Steffen et al., 2018), a prominent discussion in the theoretical and experimental literature concerns how thresholds affect the provision of public goods under a summation technology (e.g., Barrett, 2013; Barrett & Dannenberg, 2012, 2014; Croson & Marks, 2000; Dannenberg et al., 2015; McBride, 2006). Thresholds provide a coordination mechanism and may increase contributions. Yet according to Barrett and Dannenberg (2012, 2014), uncertainty about the threshold level substantially reduces the chances of successful

[1] Other classical applications with a weakest-link structure include flood control (Hirshleifer, 1983), team production (Brandts and Cooper, 2006, 2007; Van Huyck et al., 1990), control of invasive species and pests (Meyer et al., 2022; Perrings et al., 2002), and coordination of tax policy (Holzinger, 2005).

coordination under summation. Intuitively, uncertainty about the threshold means that each individual is only able to impact the probability of threshold attainment at the margin. This increases the incentive to free ride compared with a known discontinuous threshold, making coordination equilibria more difficult to sustain. With this paper, we ask whether threshold uncertainty shows similar effects under a weakest-link technology.

Our experimental design is inspired by Barrett and Dannenberg (2012, 2014), who explored uncertain thresholds with a summation technology. Subjects interact in groups of 10. Contributions generate payoffs that are linear in the sum of donations, and additionally, failure to reach a contribution threshold induces a discrete lump sum loss.[2] Threshold attainment under the weakest link technology requires all subjects to reach the threshold. Under summation, the sum of contributions reaches the (appropriately scaled) threshold in order to avoid the adverse event.

Weakest-link structures involve an element of coordination for the voluntary provision of public goods such that it is not worthwhile for an individual to contribute more than the smallest amount provided by another group member (Barrett, 2016). While this often gives rise to equilibria at contribution profiles other than the free-riding outcome, successful coordination is far from guaranteed (2020b; Anderson et al., 2001; Caparròs & Finus, 2020a; Caparròs et al., 2020; Devetag & Ortmann, 2007), not least because a single individual failing to coordinate is strongly detrimental to the outcome, thus confronting subjects with substantial strategic uncertainty.[3]

Anticipating this added vulnerability in weakest-link settings, we additionally explore the effect of communication on threshold attainment. Communication is implemented as a pledge, i.e., a truthful or non-truthful statement on the player's intended action (e.g., Cooper et al., 1992) combined with a suggestion for the action by group members (e.g., Weber, 2003) and thus follows closely the design in Barrett and Dannenberg (2014).

In previous work on cooperation games, the exact method of communication may similarly involve individual pledges by all group members or suggestions as to what other members should do. There is also variation in terms of whether all members can communicate or if only the messages of a single player are selected and broadcasted. Communication is typically efficiency enhancing (e.g. Barrett & Dannenberg, 2016; Brosig et al., 2003; Isaac & Walker, 1988), but may depend on the nature of communication. For example, pledges as simple numerical cheap talk had no net effect on contributions in Bochet et al. (2006) and Bochet and Putterman

[2] The presence of both a linear and a threshold benefit is consistent with many real-world public goods, including climate mitigation and vaccination against diseases (e.g., COVID-19). For the latter, national vaccination programs limit the spread of existing viral variants to other countries (the linear component) while also reducing the risk that new variants will emerge (the threshold component).

[3] In the literature, chances of successful coordination depend on communication opportunities prior to contribution decisions as well as the identity of contributors, heterogeneities among individuals, incentives to cooperate, and more (Barbieri and Malueg, 2019; Brandts and Cooper, 2006, 2007; Chaudhuri et al., 2009; Engelmann and Normann, 2010; Hamman et al., 2007; Harrison and Hirshleifer, 1989; Knez and Camerer, 1994; Lei et al., 2007; Riechmann and Weimann, 2008; Riedl et al., 2016).

(2009). Several extant studies consider the role of communication in weakest-link games or–more generally in coordination games. Cason et al. (2012a) study intra-group communication when two groups compete and thereby provide an example that communication can hurt efficiency (through the competition element).[4] Other studies have typically found efficiency-enhancing effects of communication, (e.g., Blume & Ortmann, 2007; Charness & Grosskopf, 2004; Cooper et al., 1992; Duffy & Feltovich, 2002, 2006; Smerdon et al., 2020; Van Huyck et al., 1993).

Most of these experiments involve smaller numbers of players in a group. While larger groups are typically found to lead to less or similar coordination levels in coordination games as smaller groups (e.g., Heinemann et al., 2009; Van Huyck et al., 1990), Feltovich and Grossman (2015) show that the beneficial effects of communication may be reduced in larger groups.

As such, it is an open question how threshold uncertainty functions in our ten-player weakest link setting and also whether or not communication can improve the coordination.

Our experiment reveals the importance of the aggregation technology. Importantly, thresholds in the weakest-link setting imply quite different behavioral patterns depending on whether the threshold is certain or uncertain. When the threshold level is certain, the threshold provides a highly successful coordination device. In contrast, groups are almost guaranteed *not* to reach the threshold if the level is uncertain. Thus, we conclude that the role of strategic uncertainty is further enhanced when the threshold becomes uncertain, leading to considerably lower success rates.

Under summation, we find that uncertainty regarding the threshold does not significantly affect contributions or the probability of threshold attainment. This highlights the contrast with weakest link, where threshold attainment hinges on all subjects contributing a sufficient amount, and high contributors are unable to compensate for low contributions by other group members.

The results for summation are also in stark contrast to Barrett and Dannenberg (2012, 2014), who identified a strong negative effect of threshold uncertainty. One explanation for the different results is that we find subjects largely adhering to their non-binding pledges, which was not the case in the earlier studies. Another explanation might be minor differences in how the experiment was implemented in our paper compared to the Barrett and Dannenberg papers: specifically, they had subjects play five practice rounds such that subjects obtained information about the behavior of other potential group members before playing the actual experiment, while our experimental implementation does not give feedback and thus is more in line with a one-shot interaction. While we thus cannot give a definitive answer to the

[4] More generally, group contests invove strategic uncertainty regarding the choices of the opposing group and thus bear similarity with our uncertain threshold games where the threshold uncertainty is implemented through a random device (e.g.,2011b; Cason et al., 2012b; Sheremeta, 2011a). Similar features are present in voting games where again the voter turnout of the opposing party is uncertain (for a review, see Palfrey, 2009; Großer, 2020).

drivers of these differences, our experiment is designed to compare weakest links and summation technologies under threshold uncertainty.[5]

Finally, regarding the role of pre-play communication, the chances for threshold attainment in all of our treatments turn out to heavily hinge on subjects being able to announce intended behavior (pledges) and/or make proposals for how other group members should act. A lack of communication prior to contribution decisions particularly handicaps threshold attainment under weakest link. Exploring the mechanisms through which such opportunities to communicate affect contributions, we find that the non-binding nature of the pledge induces individuals to make larger contribution announcements. These promises are more likely to be kept if other people have made similar pledges.

The paper is structured as follows: Sect. 2 discusses the experimental design, before we provide some theoretical predictions in Sect. 3. Section 4 discusses our results regarding threshold attainment, individual contribution decisions, and the role of pledges. Section 5 concludes.

2 Experimental design

The games played in our experiment are variants of the voluntary public good paradigm. In this section, we first provide general definitions and then describe our treatments and experimental protocols, which (in the summation case) are highly similar to those of Barrett and Dannenberg (2012, 2014). Theoretical analysis is conducted in Sect. 3.[6]

The games are played in groups of 10 players $i \in \{1, \ldots, 10\}$, following Barrett and Dannenberg (2012). There is mixed evidence regarding the relationship between contributions in a public good game and group size (see e.g., Zelmer, 2003; Diederich et al., 2016). For weakest-link games, coordination is clearly more difficult to achieve with larger group sizes (Riedl et al., 2016).

Each player is endowed with 20 experimental tokens. The contribution to the common pool is denoted $q_i \in \{0, 1, \ldots, 20\}$. Each player's opportunity cost of contributing is piecewise linear and convex, and given by

$$C(q_i) = \begin{cases} c_L q_i, & \text{for} 0 \le q_i \le 10 \\ 10c_L + c_H(q_i - 10), & \text{for } 11 \le q_i \le 20 \end{cases}$$

[5] We note that it is unclear why this (minor) design difference should drive the differences in the findings. If it were essential, the qualitative results in Barrett and Dannenberg (2012, 2014) would be highly susceptible to variation in experimental implementation.

[6] The experimental design and analysis plan were formally registered with the American Economic Association's registry for randomized controlled trials (AEARCTR-0005175), and approved on December 11, 2019.

Table 1 Experimental treatments

Treatments	Aggregation technology	Threshold support	N
T1: WL, certainty	Weakest link: $q_i^{min} \geq \overline{Q}$	$\overline{Q} = 15$	100
T2: WL, uncertainty	Weakest link: $q_i^{min} \geq \overline{Q}$	$\overline{Q} \in \{10, \dots, 20\}$	100
T3: WL, small uncert	Weakest link: $q_i^{min} \geq \overline{Q}$	$\overline{Q} \in \{14, \dots, 16\}$	80
T4: Sum, certainty	Summation: $\sum_{i=1}^{n} q_i \geq \overline{Q}$	$\overline{Q} = 150$	100
T5: Sum, uncertainty	Summation: $\sum_{i=1}^{n} q_i \geq \overline{Q}$	$\overline{Q} \in \{100, \dots, 200\}$	100
T6: Sum, small uncert	Summation: $\sum_{i=1}^{n} q_i \geq \overline{Q}$	$\overline{Q} \in \{140, \dots, 160\}$	100

where $c_L = €0.1$ and $c_H = €0.5$.[7] One interpretation of this cost structure is that there are two technologies available to each player: one low-cost technology (L) and one high-cost technology (H). By design, and as further described below, the upper limit for the low-cost technology lies in the threshold support only if this is relatively wide.

Contributions to the common pool have two effects: (i) they generate a public-good return $r = €0.05$ to each group member per token contributed by any player, and (ii) they (weakly) increase the probability that the group reaches a threshold contribution level $\overline{Q}$, which is uniformly distributed on integers $\{a, a+1, \dots, b-1, b\}$, with $b \geq a > 0$. Total returns from contributing (after resolving the uncertainty in $\overline{Q}$) are

$$r\left(\sum_{i=1}^{10} q_i\right) - f\left(q_1, \dots, q_{10}, \overline{Q}\right)X$$

where f is a discontinuous function of the contributions and the threshold level, while $X = €15$ is a fixed cost of failing to reach the threshold.

Our treatments differ in the mapping of individual contributions onto threshold attainment. Under a weakest-link technology, the cost of €15 is paid unless *all* group members contribute at least $\overline{Q}$. That is, the contribution by the player with the smallest contribution needs to reach the threshold, so $f = I\left(q^{min} < \overline{Q}\right)$, where $q^{min} = \min_i\left(q_i\right)$ and I is the binary indicator function. Under a summation technology, the cost of €15 is paid by all players unless the group sum of contributions reaches at least $\overline{Q}$; formally, $f = I\left(\sum_{i=1}^{10} q_i < \overline{Q}\right)$.

Table 1 lists the six between-subject treatments included in the experiment. We use a 2-by-3 design that explores, first, the effect of technology, i.e., whether threshold attainment is based on weakest link or summation aggregation. Second, we vary

[7] In the experiment, the piecewise linear cost scheme was implemented as follows: Of each participant's 20 tokens, half were framed as belonging to a low-value "Account A" and the other half to a high-value "Account B." We hardcoded contributions to draw from account B only once account A had been exhausted. In addition to the endowment of tokens (worth €6 if retained) and any net earnings from the game, subjects were also given a fixed show-up fee of €15.

whether the location of the threshold is certain ("certainty"), or alternatively exhibits uncertainty in a broad ("uncertainty") or narrow range ("small uncertainty").[8] We include the small uncertainty case as there is theoretical support that small uncertainty can actually *increase* contributions in a summation public good game (Barrett & Dannenberg, 2014); we return to this point in Sect. 3. To make symmetric equilibria and per-person contributions as comparable as possible across technologies, weakest-link threshold ranges are obtained by dividing the corresponding ranges for summation by 10, the group size.

The experiment was conducted at the laboratory of the Vienna Center for Experimental Economics, using the lab's associated subject pool of university students. A total of 29 experimental sessions were conducted, each with 20 subjects (two groups) belonging to the same treatment.[9]

The sessions progressed as follows. First, subjects were randomly assigned to one of the groups and acquainted with the game rules.[10] There were no practice rounds: instead, exhaustive examples and control questions were included to ensure that subjects understood the game.[11] We did not allow for practice rounds since we did not want subjects to learn anything about other players' behavior, particularly in relation to their proposed group contributions and pledges (see below).[12] Subjects were also informed that there were two rounds, one of which would be randomly chosen for payment at the end of the session. Subjects then played a first round of the game variant corresponding to their treatment. Importantly, this initial one-shot round was not followed by feedback of any kind.

Next, group composition was re-shuffled, with subjects informed that a second round would now take place among the new groups. Our main analysis is based on this second round. Immediately prior to it, subjects were asked to make a pair of non-binding announcements to the other members of their group. Subjects submitted, first, a proposal for how many tokens the group as a whole should contribute to the joint project, and second, a pledge to personally contribute some number of tokens in the coming round. All proposals and pledges made in a group were then

[8] Under "uncertainty", the upper limit of the low-cost technology coincides with the lower bound of the threshold support; under "small uncertainty", the upper limit is outside the threshold support. Thus, another difference between these treatments is the cost requirement for avoiding the threshold (with some probability).

[9] Our pre-registered initial plan included 120 subjects (12 groups) in each treatment. However, due to the onset of the COVID-19 pandemic, we could not conduct some of the planned sessions, leaving us with the sample sizes reported in Table 1. Before preregistration, we conducted power calculations based on the findings by Barrett and Dannenberg (2012). While these were not reported during preregistration, they are simple to verify. The likelihood of reaching the threshold was 80% and 10% in their main treatments. With a power of 0.8, the required sample size is 7 groups per treatment. In our experiment, the smallest number of groups is 8. If we instead look at individual contributions, mean (s.d.) for the two main treatments were 150.9 (7.69) and 77.2 (16.67). With a power of 0.8, the required sample is 3 subjects per treatment. This is of course considerably lower than the actual number of subjects in each treatment, where the lowest number of subjects is 80.

[10] The experiment was programmed using the zTree software (Fischbacher, 2007).

[11] Instructions, examples, and control and survey questions are provided in Appendix A.

[12] This is an important difference from Barrett and Dannenberg (2012), who included 5 practice rounds prior to the actual pay-off relevant games. We return to this point in Sect. 4.3.

Table 2 Symmetric Nash equilibria by treatment

Treatment	Symmetric Nash equilibria (all i)	
	Zero contribution	Coordination/cooperation
T1. Weakest link, certainty	$q_i = 0$	$q_i = 15$
T2. Weakest link, uncertainty	$q_i = 0$	$q_i = q \in \{10, \dots, 20\}$
T3. Weakest link, small uncertainty	$q_i = 0$	$q_i = q \in \{14, \dots, 16\}$
T4. Summation, certainty	$q_i = 0$	$q_i = 15$
T5. Summation, uncertainty	$q_i = 0$	–
T6. Summation, small uncertainty	$q_i = 0$	$q_i = 16$

displayed on screen to all members immediately before the subjects made the second-round contribution decision.

To summarize, there was no interaction among group members in the first round, no feedback after round 1 (and no practice rounds), and also reshuffling between rounds. Because of this, our design arguably allows us to identify the effect of communication by comparing outcomes across the two rounds. Of course, it is difficult to fully rule out that some possibility for learning or experience (and hence confounding order effects) may remain: Weber (2003) found learning in a competitive guessing game over 10 rounds played with no feedback. However, our experiment only includes two rounds, and unlike the guessing game, there are multiple equilibria requiring coordinated behavior. Also, the often-observed pattern of declining contributions in public good games is not likely to hold without any information feedback between rounds (Neugebauer et al., 2009). Therefore, we do not believe that learning should be of any concern here, and thus we will compare across rounds in Sect. 4.3.

After the conclusion of the second round, subjects filled out an end-of-session survey with questions on risk, time, and social preferences based on Falk et al. (2018), as well as demographic variables.[13] We also asked subjects to (i) explain their reasoning behind pledging a certain contribution, (ii) rate how much they trusted the pledges of other group members, and (iii) judge whether the pledges and proposals of others made them change their own contribution level. Finally, subjects were informed of the outcome of both game rounds, including their own associated potential and actual earnings in each round.

[13] We report the data on these survey questions in the Appendix Table C7. We also explored their impact on contribution decisions and pledges, finding that they do not have any explanatory power. Thus, we do not further discuss these preferences and variables in this paper.

3 Characterization of symmetric Nash equilibria

In Appendix B, we derive the best responses and characterize associated Nash equilibria within each treatment. Some simplifying assumptions are applied: first, the analysis limits attention to symmetric equilibria. Second, players are assumed to be risk neutral throughout. Finally, we do not include the proposals and pledges made prior to the second round. Table 2 summarizes the results obtained under these conditions.

The symmetric equilibrium where each player has $q_i = 0$ is supported in all treatments. However, options for symmetric coordination at higher contribution levels vary substantially across treatments.

Under weakest link, there is a coordination equilibrium at $q_i = 15$ when the position of the threshold is known with certainty (T1). Introducing uncertainty creates a range of equilibria at *every* integer within the support of $\overline{Q}$ (T2 and T3). This is because the weakest-link structure leaves each player relatively pivotal to threshold attainment even in the presence of uncertainty. Thus, if every other player j has chosen to contribute some $q_j = q$ in the interior of that support, then for the parameters used in our experiment, the remaining player i will always prefer $q_i = q$ to $q_i < q$ (and will certainly not contribute $q_i > q_j$, since doing so would not change the outcome).

In summation under certainty (T4), there is a single symmetric equilibrium at the threshold (Isaac et al., 1989). This payoff (Pareto) dominant equilibrium disappears under large uncertainty (T5), as stressed by Barrett and Dannenberg (2012) and Barrett (2013). The reason is that, as uncertainty is added, each player becomes less pivotal to threshold attainment since they can now only influence the probability that $\sum_{i=1}^{n} q_i \geq \overline{Q}$ at the margin. Under small uncertainty, however, the threshold support is small enough, and each player correspondingly pivotal enough, that a non-zero equilibrium survives (Barrett & Dannenberg, 2014) at the upper bound of the support of $\overline{Q}$. Kotani et al. (2014) obtain a similar result for a game with binary contributions.

Taken at face value, the main conclusion from Table 2 is that contributions in T5, where no "upper" equilibrium exists, might be expected to be lower than in all other treatments. Importantly, the effect of introducing large uncertainty differs substantially between the two aggregation technologies: cooperation collapses under summation but not necessarily under weakest link.

3.1 Equilibrium selection and strategic uncertainty

Because all treatments except T5 involve multiple equilibria, further predictions will inevitably need to invoke some rule for equilibrium selection. For example, in our experiment, payoff dominance consistently implies selecting the equilibrium with the highest contribution levels. Then, except for T5, threshold uncertainty would be predicted to increase rather than decrease contributions.

However, most experiments on coordination games with multiple Pareto-ranked equilibria have found that payoff dominance is a poor predictor of actual play (see Devetag & Ortmann, 2007 for a review). The main alternative criterion for equilibrium selection in the literature is risk dominance (Harsanyi & Selten, 1988). However, deriving clear-cut predictions in this regard requires a full treatment of multi-player, multi-action risk dominance in the context of our game, which is beyond the scope of this paper. That being said, developing intuition related to risk and strategic uncertainty may still be useful for interpreting results. We summarize our conclusions here; the underlying analysis is presented in full in Appendix B.3.

Our starting point is to perform a set of pairwise risk-dominance comparisons across all symmetric equilibria in a given treatment (as in Riedl et al., 2016). To this effect, we consider a set of two-player games, where each player chooses between two strategies that each form symmetric equilibria in Table 2. The higher-contribution equilibrium turns out to be risk dominant in *all* pairwise comparisons of this kind: thus, risk and payoff dominance fully coincide.

However, our games involve ten players, not two. As the number of players grows, concerns with strategic uncertainty increasingly favor non-cooperation, since each player will only be willing to cooperate if enough other players do so as well, and this becomes increasingly unlikely the more players there are. The situation is particularly severe under weakest link, where deviations from high-contribution equilibria strongly reduce the marginal effect of contributions on the probability of threshold attainment, leaving players unable to compensate for low-contribution behavior by others.

Cooperating is also generally riskier in the treatments with threshold uncertainty. The reason is that (i) fully eliminating threshold risk in these treatments requires higher contributions than under certainty (e.g., everyone contributing 20 instead of 15), and (ii) in the weakest-link treatments, coordinating at some equilibrium that does *not* fully eliminate threshold risk is (even) less valuable, and thus riskier, than fully eliminating threshold risk.

Thus, at some point, players' risk calculus is likely to shift to favor low contributions. Indeed, this is not only due to the expectation that other players may try to coordinate on such low-contribution equilibria, but also due to possible off-equilibrium behavior from, e.g., mistakes (see Caparrós et al., 2020). No matter the cause, the resulting strategic uncertainty can be expected to favor low contributions, especially with many players (as in our experiment), and under weakest link and/or uncertainty. However, our analysis does not yield clear-cut predictions on whether risk concerns will dominate in any given treatment.

4 Results

First, in Sect. 4.1 and 4.2, we discuss second-round threshold attainment and contribution decisions, respectively. That is, we focus first on contributions following non-binding contribution pledges and proposals for how many tokens the group should contribute. Here, we also compare our results under the summation technology to

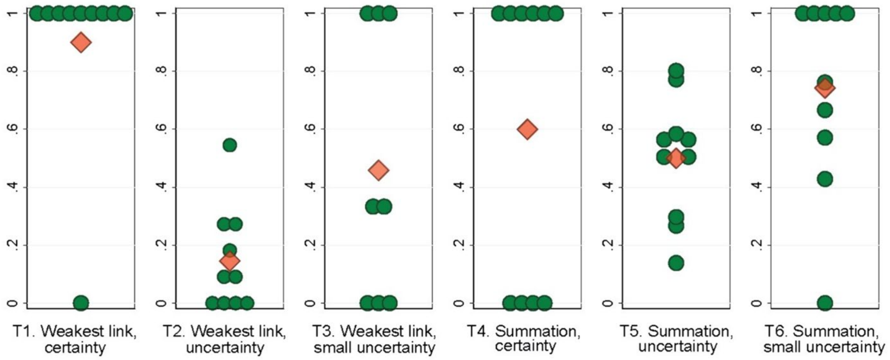

Fig. 1 Probability of reaching a threshold in each treatment with pledges. Each green circle represents the outcome in one experimental group. The red diamonds give the average probability of success (reaching the threshold) across all groups in a given treatment

Barrett and Dannenberg (2012, 2014). Then, in Sect. 4.3, we explore the mechanisms through which communication affects contribution decisions. For this, we investigate how individual pledges compare to decisions in the initial game round, and whether subjects follow through with their pledges or renege on them.

4.1 Threshold attainment

We begin by examining threshold attainment across treatments. Rather than reporting observed success rates among the subject groups (which depend on the actual random draw of the level of the threshold), we calculate each group's probability of reaching the threshold according to the cumulative distribution of $\overline{Q}$. Fig. 1 reports the distribution of the resulting probabilities (green circles) in each of the six treatments. For each treatment, we also report the average probability (red diamond) among subject groups. In the certainty treatments, these averages equal the observed success rates. The probabilities underlying Fig. 1 are also summarized in Table C1 of Appendix C.

Starting with the weakest-link technology, we find that 9 out of 10 groups reach the threshold under certainty (T1). Under uncertainty (T2), by contrast, the average success probability is 15 percent. Using a rank-sum test of success probabilities against the certainty case and treating each group as an independent observation, we find significant differences (T2 vs. T1, $p < 0.001$, $n = 20$). Under uncertainty (T2), 40 percent of the groups are certain to fail to reach the threshold as at least one player contributes less than the lower bound of the threshold distribution. This pattern is also present with the smaller range of uncertainty (14–16) in treatment T3, where again there is a considerable drop in the average probability of reaching the threshold (46%) compared with certainty (rank-sumtest of success probabilities, T3 vs. T1: $p = 0.033$, $n = 20$).

For the summation technology, only 6 out of 10 groups reach the threshold under certainty. Under uncertainty, no group achieves threshold attainment for sure, yet this is not surprising given that doing so would require every group member to contribute all of their tokens. It is noteworthy that all groups reach the threshold with some positive probability. In fact, the average probability of reaching the threshold under uncertainty is 50 percent. Again using a ranksum test against the certainty case, we cannot reject the hypothesis of equal distributions (T5 vs. T4, $p = 0.442$, $n = 20$).

This result diverges from the experimental findings of for example Barrett and Dannenberg (2012), where contributions and the probability of reaching the threshold are strongly negatively impacted by threshold uncertainty (e.g., 80% threshold achievement under certainty vs. 7% under uncertainty, compared to 60% vs. 50% in our data). There is a similar departure from earlier results for the smaller range of uncertainty (140–160) in treatment T6, for which Barrett and Dannenberg (2014) also identified a significant drop (to 0%) in the probability of reaching the threshold relative to the certainty case. In our experiment, the average probability is 0.74, i.e., even higher than under certainty, although a rank-sum test between certainty and small uncertainty gives nonsignificant results (rank-sum test, T6 vs. T4, $p = 0.802$, $n = 20$). Thus, our results are not in line with the findings by Barrett and Dannenberg (2014). Interestingly, the difference appears to be driven by different adherence to pledges, as will be explored in Sect. 4.3.

In summary, we conclude that threshold uncertainty negatively impacts the probability of threshold attainment under a weakest-link technology, but not under summation. As such, the technology through which the public good is generated importantly interacts with the degree of threshold uncertainty.

These results are inconsistent with payoff dominance among the symmetric Nash equilibria in Table 2, as well as with similar previous studies (Barrett & Dannenberg, 2012, 2014), but may be broadly consistent with concerns with strategic uncertainty as outlined in Sect. 3.1.

4.2 Individual contributions

To better understand the above patterns of threshold attainment, we now consider individual contributions. Table C2 reports descriptive statistics on contributions across the six treatments. For both weakest link and summation, average contributions are very similar across the certainty and uncertainty treatments. Table C3 reports results from Tobit models with left-censoring at 0 and right-censoring at 20. We include dummy variables for the two treatments with uncertainty, and thus the certainty treatment is the reference case. The two dummy variables for the treatments with uncertainty are statistically insignificant in both the weakest-link and summation games. Thus, for both aggregation technologies, average contributions do not differ between certainty and uncertainty or small uncertainty.

Yet, it is essential to gain more detailed insight into the distribution of contributions since a single player who contributes little can be devastating for the chances of reaching the threshold. The full distribution of contributions under the different treatments is given in Fig. 2. For weakest link, the modal contribution is 15 in both the certainty and the uncertainty treatment, and 16 under small uncertainty. For

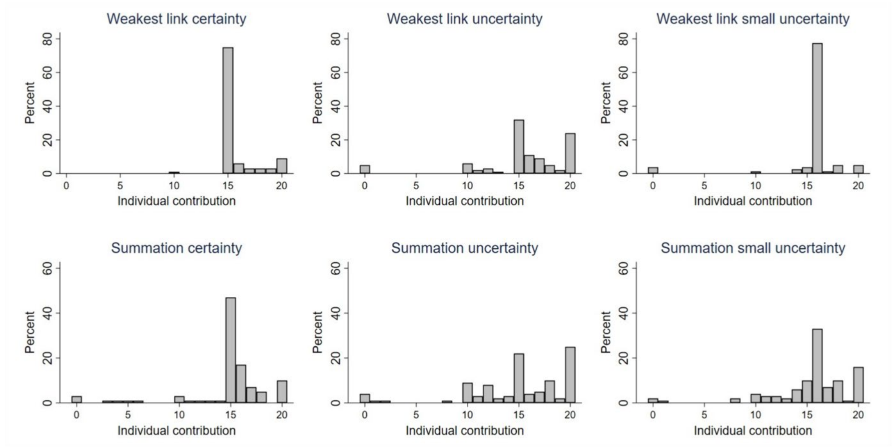

Fig. 2 Individual contributions in each treatment with pledges

summation, the modal contribution is 20 under uncertainty and 15 under certainty; under a small level of uncertainty, the modal contribution is 16. Thus, the modal contribution coincides with the upper bound of the support of $\overline{Q}$, divided by the number of players.

The lowest observed contribution in weakest link under certainty is 10, and 99 percent of subjects contribute 15 tokens or more. Under a weakest-link technology, the threshold thus works very well as a coordinating device. There is somewhat more free-riding under summation and certainty, with 3% of subjects contributing zero to the public good and 14% contributing fewer than 15 tokens. While other players can partly compensate for such low contributions, successful threshold attainment requires that other group members contribute an average of 16.7 tokens to the public good if one player contributes zero; and it becomes impossible to reach the threshold if more than two out of 10 people contribute zero.

Uncertainty changes the contribution patterns: For weakest link, 5% contribute zero under uncertainty (4% under small uncertainty) and 17% (8%) contribute fewer than 15 tokens. Low-contributing subjects are truly detrimental for the possibility of reaching the threshold, since under weakest link the other players cannot compensate for their behavior. The drastic drop in weakest-link threshold attainment under uncertainty is thus largely due to this small minority of low or zero contributors. Under summation, 25% of subjects contribute the full amount of 20 tokens (vs. 10% under certainty), yet there are also more subjects contributing fewer than 15 tokens (32% vs. 14%). Overall, as already noted, average contributions do not change.

4.3 The role of communication

While we have focused on contribution decisions so far, it is also crucial to understand whether and how contributions are affected by proposals for contributions within the group as well as individual non-binding contribution pledges. We begin

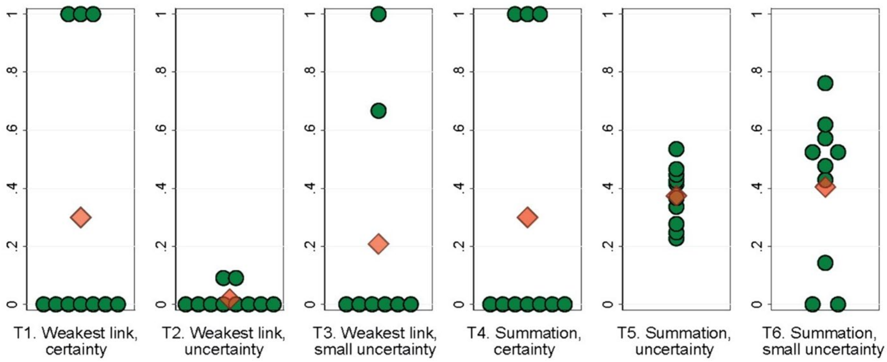

Fig. 3 Probability of reaching a threshold in treatments without pledges. Each green circle represents the outcome in one experimental group. The red diamonds give the average probability of success (reaching the threshold) across all groups in a given treatment

by investigating the effect of pledges and proposals and then discuss potential mechanisms. As pledges and proposals are to a large extent similar and highly correlated, our focus will therefore be on pledges of own contribution.[14]

Figure 3 displays the distribution of observed probabilities of reaching the threshold in round 1; recall that the round without communication always preceded the round with communication.[15] Table C4 in Appendix C presents a summary of the corresponding observed probabilities. In round 1 (unlike round 2), the absence of communication means that individual contributions are completely independent of other group members. Thus, Table C4 also presents a set of simulated probabilities, each based on 1000 randomly selected groups with 10 individuals drawn from a given treatment. Unlike Fig. 3 (and Fig. 1 in Sect. 4.1), these simulated probabilities do not depend on the group composition actually observed, thus limiting the influence of chance due to the relatively small number of groups that we observe. However, simulated and observed probabilities are generally quite similar.

In all treatments, the average probability of reaching the threshold is lower without communication (round 1) than with communication (round 2). Threshold attainment for weakest link under certainty is 30 percent without communication and 90 percent with communication (see Sect. 4.1). For summation under certainty,

[14] The correlation between own pledge and proposed group contribution varies between 0.58 and 0.92. The correlation is stronger in the weakest-link treatments, where more than 80% of individuals pledge and propose the same contribution behavior. In the summation treatments, proposals and pledges fully coincide among 61–68 percent of subjects. However, in the summation treatments, proposed contributions are ambiguous in some cases. Although proposals could range between 0 and 200, some subjects proposed amounts that were similar in magnitude to their pledge, making us suspect that there was some misunderstanding.

[15] In order to eliminate the impact of randomization of subjects into groups as a confounder when comparing Fig. 3 with the analogous Fig. 1, we calculate success probabilities in round 1 based on the group composition in round 2. Note that the group composition in round 1 (or 2) should not affect behavior in round 2 as no feedback is given between rounds.

it is only 30 percent without communication and 60 percent with communication. In fact, in neither certainty treatment does any group move from threshold attainment without communication to non-attainment under communication. Similarly, we (weakly) reject the hypothesis of equal distributions of probabilities between the rounds with and without communication using conservative Wilcoxon signed-rank tests for the uncertainty treatments (15% vs. 2% in weakest link $p = 0.071$; 50% vs. 37% in summation $p = 0.047$). Across all treatments, there is no doubt that communication is associated with better threshold attainment ($p < 0.001$ for both weakest link and summation).

As discussed in Sect. 2, the absence of feedback or interaction in round 1 should rule out learning or experience effects, allowing us to interpret these significant differences in behavior and outcomes across rounds as the causal effect of communication. Even if there were indeed a learning effect, we note that such effects typically decrease contributions over time in public-good games, in which case our estimates would provide a lower bound for the true effect of communication.

The lower probability of reaching the threshold in the absence of communication is of course driven by lower contribution levels. Table C2 in Appendix C gives a full description of contributions. Most importantly, although contributions without communication are smaller on average and are distributed differently, all within-round comparisons across treatments yield similar results as with communication. Thus, we again find a lower average probability of reaching the threshold for weakest link under uncertainty compared with certainty, while there is no significant drop for the summation game.

For a closer look at contributions with and without communication, Fig. 4 plots each individual's contribution across the two experimental rounds. Observations on the 45-degree line contributed the same amount in rounds 1 and 2, while observations to the right of this line contributed more in round 2.

Many subjects do not change their contribution behavior, and this holds particularly true for subjects making what are arguably focal contributions, such as 15 and 20. Still, there is a shift toward higher levels of contributions with communication. For weakest link and certainty (uncertainty), 72% (44%) contributed the same amount in the two rounds, while 22% (36%) increased their contribution with communication. Under summation and certainty (uncertainty), 49% (31%) of subjects made the same contribution in both rounds, while 35% (50%) increased their contribution with communication. Thus, communication appears especially useful in uncertainty treatments.

Beyond potentially increasing average contributions, pledges may boost threshold attainment by facilitating better coordination of individual contributions, which is particularly important in weakest-link settings where threshold attainment, and thus welfare, is driven by the smallest contribution level within a group. It is thus crucial to understand the mechanisms through which communication affects contributions. For this, we consider two steps: First, how do chosen pledges in round 2 compare against individual contributions in round 1? Second, how do own pledges impact own contribution choices in round 2?

We first examine the connection between round 1 contributions and pledges. Figure 5 plots this relationship. Pledges are generally higher than contributions in the

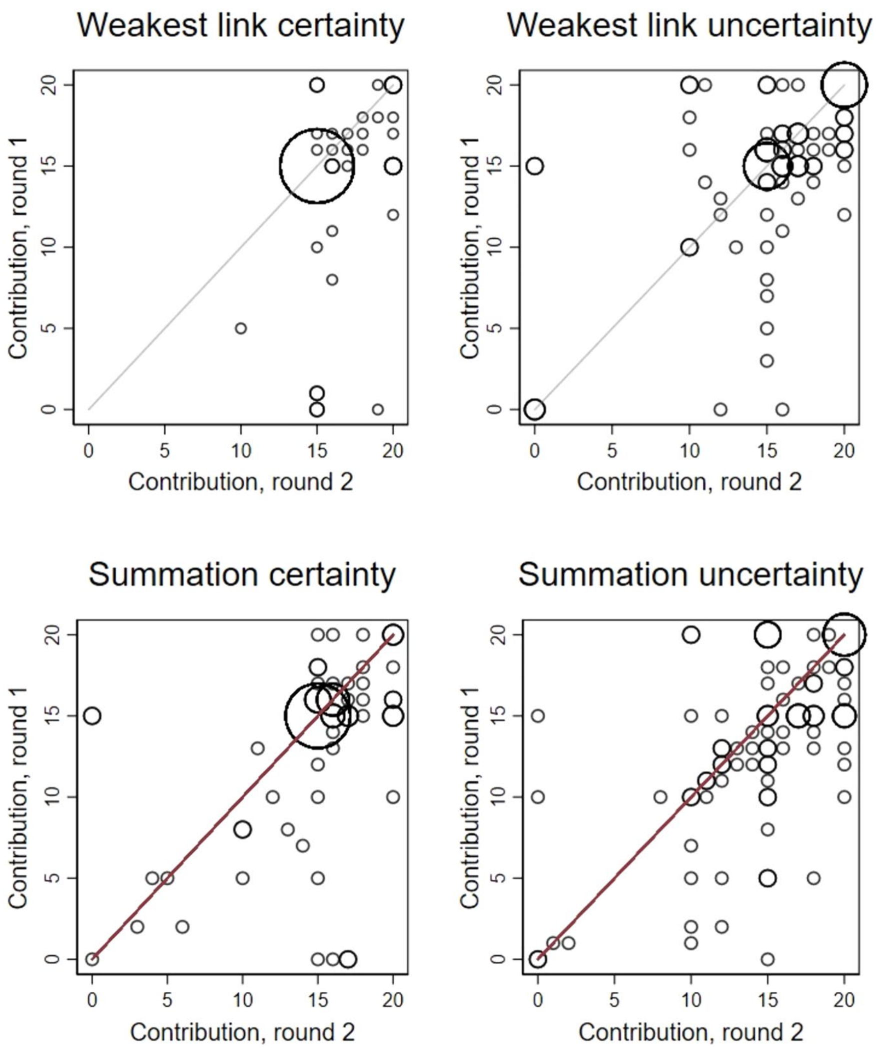

Fig. 4 Contributions in experiments with and without pledges

round without pledges: For weakest link under certainty (uncertainty), 24% (37%) pledged more than they contributed in round 1. For summation under certainty (uncertainty), the corresponding figure is 30% (51%). The pattern is confirmed in Wilcoxon signed-rank tests at the individual level (see Table C5 in Appendix C: weakest link certainty, $p = 0.002$; weakest link uncertainty, $p = 0.01\ 5$; summation certainty, $p = 0.064$; summation uncertainty, $p < 0.001$). Thus, subjects make relatively large pledges, possibly to induce higher contributions in round 2.

Focusing on the weakest-link treatments, two additional observations are particularly noteworthy because they suggest that subjects are indeed using pledges

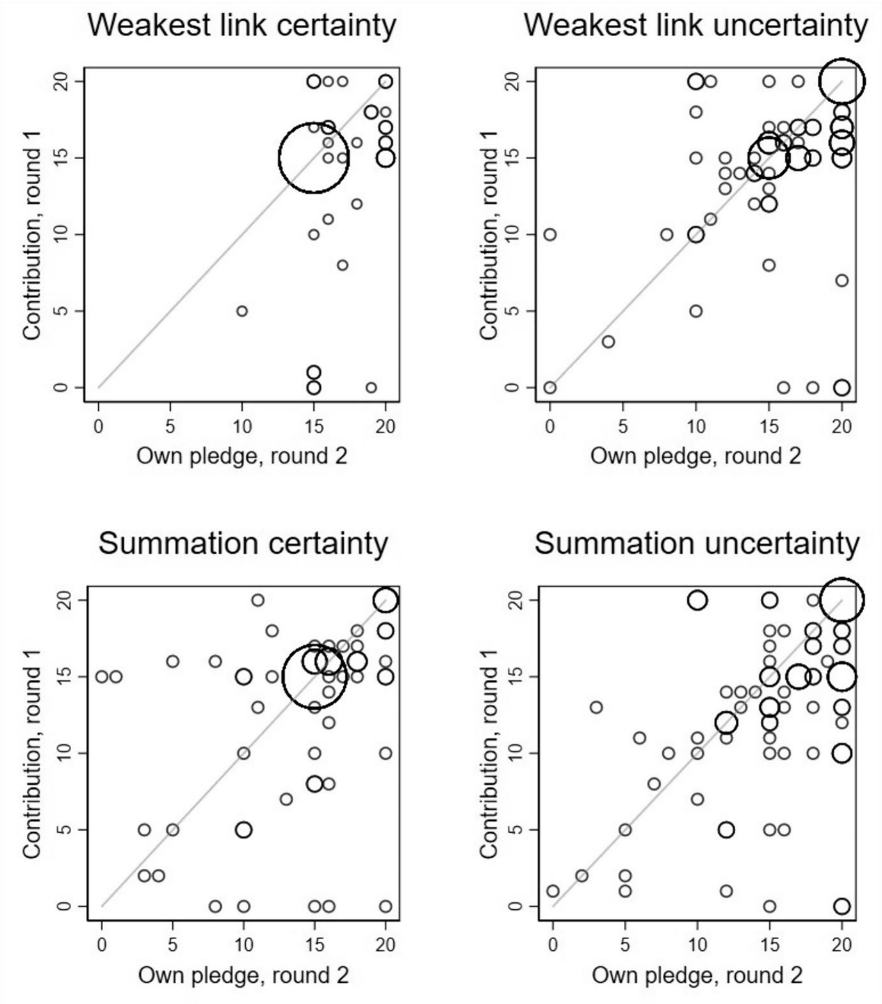

Fig. 5 (Own) pledge in round 2 vs. contributions in round 1

purposefully as a coordination device. First, under certainty, *all* subjects who contributed fewer than 15 tokens in round 1 pledged more than they contributed. Under uncertainty, there is a similar but slightly weaker pattern that centers on 10 tokens (the lower bound of $\overline{Q}$) rather than 15: all subjects who contributed strictly less than 10 in round 1 pledge at least as high in round 2. Second, under uncertainty, the modal pledge is 20. While 23% contributed this amount in round 1, 35% of subjects pledged to do so in round 2, thereby attempting to fully eliminate threshold risk. The corresponding numbers for the summation treatment are almost identical (23% and 36%, respectively), and a pledge of 20 is modal here as well.

We now move to the second question: to what extent do subjects follow through with their pledges? Clearly, subjects seem to have used the pledges to increase or

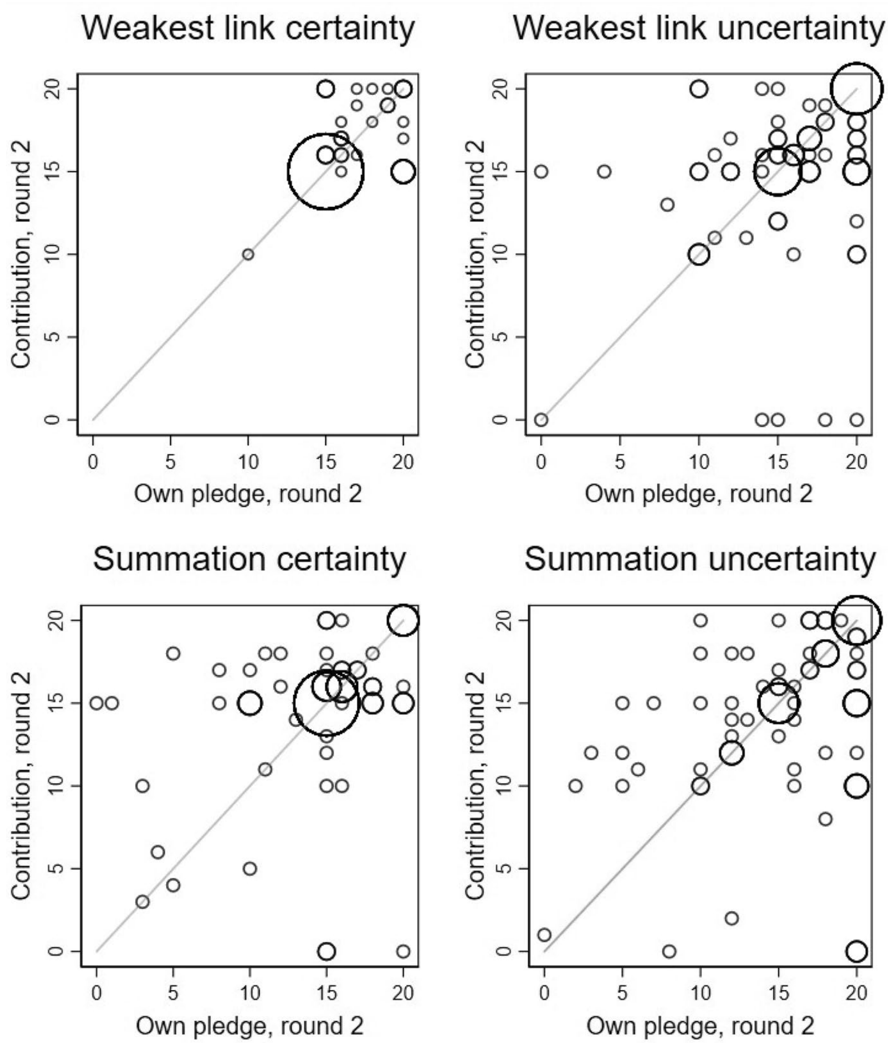

Fig. 6 (Own) pledge in round 2 vs. contributions in round 2

coordinate the contributions of other group members. However, pledges are non-binding. Whether coordination based on pledges is successful or not might differ between summation and weakest-link settings, given that summation allows for (some) free riding, thus potentially providing incentives to renege on the pledge.

To check whether this was the case, Fig. 6 scatter plots individual pledges and own contributions in round 2. We see that sizeable fractions of subjects do contribute what they pledged, and they do so in all treatments. For weakest link under certainty, 77 percent contribute exactly what they pledged, while the corresponding figure for summation is 52 percent; under uncertainty, the corresponding numbers are 51 and 44 percent. Indeed, average contributions do not significantly differ from pledges, and this holds in all treatments (Wilcoxon signed-rank tests, see Table C6 in Appendix C). Furthermore, the within-group variance of contributions does not differ from the within-group variance of pledges, and the group-minimum contributions do not differ significantly from group-minimum pledges (see Table C6 in Appendix C). We thus conclude that pledges are generally trustworthy.

This latter finding is in stark contrast to Barrett and Dannenberg (2014). While, as we have already seen, contributions under threshold uncertainty are substantially lower in their experiment than in ours, the pledges in Barrett and Dannenberg (2014) almost coincide with the levels we observe in our experiment. Thus, they find that final contributions on average are only about 50% of the pledged amounts. One explanation for this could be that their experiment included five practice rounds (with reshuffling) that may have revealed relevant information about how subjects behaved relative to what they pledged. In any case, our results taken together suggest that threshold uncertainty under summation leads to smaller contributions only when subjects fail to adhere to their previously made pledges.

5 Conclusions

In this paper, we compare the voluntary provision of public goods under different technologies when their provision is subject to a threshold. We explicitly compare two prominent technologies that translate individual contributions into public-good provision: summation and weakest link. While the extant (experimental) literature has so far concentrated on summation, we argue that many important examples of public goods (e.g., terrorism, pandemics, and team production) have weakest-link characteristics.

Our experiment investigates the effects of threshold uncertainty on individual contributions and threshold attainment under both technologies. While our design largely follows Barrett and Dannenberg (2012, 2014) for the summation technology, we do not corroborate their finding that (large) uncertainty in the level of a threshold is detrimental to its function as a coordination device. This difference seems to be driven by the fact that, unlike in Barrett and Dannenberg (2012, 2014), pledges are trustworthy within our subject pool.

In contrast, uncertainty has a much more severe effect in the weakest-link setting. While a certain threshold proves to be a highly effective coordination device, threshold uncertainty reduces the chance of threshold attainment to almost zero. This is even though each individual subject is more pivotal to the outcome under weakest link, thus potentially making cooperation more likely. Instead, the outcome is dominated by an opposing structural element of weakest link, namely that low contributions by some subjects cannot be compensated by others. Our experiment thus reveals an important interaction between threshold effects and the technology that aggregates individual contributions into the provision of a public good.

We additionally show that, in all treatments, successfully reaching the threshold strongly hinges on subjects' ability to engage in pre-play communication through non-binding pledges and proposals regarding the contribution of others. The benefits of such communication are particularly large under weakest link. Pledges seem to have created a degree of trust, allowing individuals to make (non-binding) pledges beyond what they would otherwise have contributed. Observing similarly large pledges from other group members, subjects then mostly follow through with their pledges.

Our results do underline the difficulty of cooperating to produce a threshold weakest-link public good in the presence of uncertainty. Importantly, we limit our investigation to settings with homogenous players. For summation, heterogeneity regarding endowment or benefits from the public good is known to provide another obstacle to successful cooperation. For weakest link, such heterogeneities might necessitate the implementation of some transfer mechanism even in the absence of uncertainty (e.g., Vicary & Sandler, 2002). While we note the importance of player heterogeneity in real-world threshold weakest-link settings, we leave the investigation of behavior in such situations to future research.

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Declarations

Conflict of interest None.

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