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ORIGINAL ARTICLE

Economic Inquiry

Cooperation against all predictions

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Abstract

In Binary Threshold Public Good (BTPG) games, n players have binary choices: cooperation or non-cooperation. If at least k players cooperate, a public good is produced. The case $k = n$ is the Stag Hunt game with the two pure strategy equilibria E1 (all players cooperate) and E0 (no player cooperates). In four rather diverse examples of four-player Stag Hunt games, three prominent concepts of equilibrium selection favor E0. Experiments, however, result in cooperation frequencies between 70.3% and 99.7%. Also for $k < n$, the selected equilibria clearly differ from experimental behavior. We interpret our observations by suggesting the concept Behavioral Equilibrium Selection.

KEYWORDS

equilibrium selection, experiments, global games, payoff dominance, quantal response equilibria, risk dominance, Stag Hunt games

JEL CLASSIFICATION

D72; H42; D90

1 | INTRODUCTION

The success of human societies crucially depends on their ability to cooperate, that is, to coordinate costly individual activities. The Stag Hunt game was introduced by Rousseau (1997, original edition 1762) in order to explain obstacles to cooperation. In the story described, *n* hunters can together hunt down a stag, but if one hunter does not cooperate, the stag escapes. Instead of joining the other stag hunters, every hunter can catch a hare with certainty. A hare, however, is less valuable than a share of the stag. The two prominent equilibria of this game are E0 where no player cooperates and E1 where all players cooperate. E1 is the efficient (even *pay-off dominant*) equilibrium. However, it requires strong enough beliefs in the cooperation of all other hunters, in other words: *trust*. If trust is high enough, cooperation is a best reply; in coordination games, trust breeds *reliability*. Social scientists and even historians (Fukuyama, 1995) have often emphasized the important role of trust within groups and within a whole society. Robinson and Acemoglu (2012) investigate the role of good institutions for the success of a society; but even well designed institutions will not work without trust in these institutions. Formally, the emergence or nonemergence of trust corresponds to the selection of different

Abbreviations: ACPs, Average contribution probabilities; BES, Behavioral Equilibrium Selection; BTPG, Binary Threshold Public Good; QRE, quantal response equilibria; TU, Technische Universität.

equilibria of coordination games. These games often have a large number of equilibria, requiring extremely high, intermediate, or extremely low levels of trust.

In Binary Threshold Public Good (BTPG) games, n players simultaneously contribute to the production of a public good or not. The public good is produced if at least k players contribute. In our investigation, with an emphasis on the case $k = n$ (Stag Hunt games), our research questions are: (i) What are the characteristics of equilibria of BTPG games and which equilibria are selected by the most prominent equilibrium selection theories? (ii) Do the selected equilibria predict the behavior observed in our four-person BTPG experiments? (iii) Which regularities of behavior are observed in our experiments? (iv) If the answer in (ii) is negative, how should, considering (iii), an alternative positive theory be shaped?

1.1 | Equilibrium selection

Formal theories of equilibrium selection abstain from concepts as group specific trust and concentrate on the objective structures of games. With respect to coordination, they try to identify games where trust *emerges (or not)* from the incentive structure of these games. For Stag Hunt games, the question is when (under which parameter constellations) the most prominent theories of equilibrium selection predict the emergence of sufficient trust (E1) or not (E0). Equilibrium selection theories often rely on "tracing procedures." They follow a continuous path of best reply combinations starting from a state where players expect all others to act randomly or where their information about the parameters of the game is minimal. Continuously reducing the expectation of random behavior or of "noise" we reach, under certain conditions, one of the Nash equilibria of the game.

The Linear Tracing Procedure (selecting among all Nash equilibria) and the related concept of Risk Dominance (making pairwise comparisons) have been introduced by Harsanyi and Selten (1988) as their main principles of equilibrium selection for asymmetric games, that is, in the normal case. For symmetric games, they favor symmetric equilibria (same pay-off for all players) and Pay-Off Dominance (selecting the equilibrium with the highest pay-off). Pay-Off Dominance has often been criticized and even Harsanyi (1995) abandoned it later. In Stag Hunt games, the priority of Pay-Off Dominance may cause a switch from equilibrium E0 to E1 when moving from a slightly asymmetric to a symmetric game. Therefore, we will apply the criterion of Risk Dominance and the Tracing Procedure also for equilibrium selection in (almost) symmetric games.

Applications of the Linear Tracing Procedure/Risk Dominance are, for example, van Damme and Hurkens (2004) concerning price leadership in oligopolies and, recently, Mitzkewitz (2017), Boom (2018), and Bolle (2019a, 2019b) concerning multiple unit auctions, signaling games, and voting games. Van den Elzen and Talman (1999) and Herings and van den Elzen (2002) propose a numerical algorithm for the application of the Linear Tracing Procedure. Many applications (e.g., Schmidt et al., 2003, and literature cited in Section 1.2) concern 2×2 games in connection with experimental tests.

Carlsson and Van Damme (1993) transform common knowledge games into games of incomplete information with private and correlated signals (Global Games). While incomplete information (noise) vanishes, equilibrium play converges, under certain conditions, to one of the Nash equilibria of the original game. In an influential article, Frankel et al. (2003) show that the Global Games selection should be applied only to games with strategic complements because, otherwise, it may depend on the distribution of noise. For strategic complements, they suggest a method for the determination of the selected equilibrium (see Section 3.1).

A third prominent method of equilibrium selection was suggested by McKelvey and Palfrey (1995) as the limit of their quantal response equilibria (QRE) which assume all strategies (from a finite set) to be played with probabilities that are ordered according to the utilities these strategies gain against the strategies of the other players. QRE has been applied to several types of experiments (see Goeree et al., 2010; Palfrey et al., 2010), but usually with a finite "precision parameter" λ. $\lambda = 0$ describes completely random behavior, for $\lambda = \infty$ a Nash equilibrium is played. On the path from $\lambda = 0$ to $\lambda = \infty$, QRE (generically) converges to a Nash equilibrium. While QRE is certainly the most frequently applied stochastic extension of game theoretic models, Zhang and Hofbauer (2016) assert that there are only rather special attempts to theoretically characterize limits of QRE. They close this gap for 2×2 games.[1]

1.2 | Experimental studies

Stag Hunt games are mostly investigated as two-player games with the central question being whether Risk Dominance (mostly E0) or Pay-off Dominance (E1) is a successful prediction. In most cases, there is no clear evidence for the one

or the other. Rydval and Ortmann (2005), for example, find contribution rates mostly between 1/3 and 2/3 in their seven 2×2 Stag Hunt games. These results considerably deviate from the predictions E0 and E1. In all studies, the effect of parameter variations or different degrees of information or framing are investigated. Rydval and Ortmann (2005) find that Loss Aversion partly influences behavior while Feltovich (2011) and Feltovich et al. (2012) find a strong influence.[2] Battalio et al. (2001) find increasing cooperation if the optimization premium (value of successful cooperation minus contribution costs) increases. Whiteman and Scholz (2010) find a positive influence of social capital (e.g., common norms, reciprocity, and trust). Al-Ubaydli et al. (2013) find that cognitive ability and risk aversion have no impact on successful coordination while patience does. Büyükboyacı (2014) confirms this for a player's own risk attitude, but shows that information about the risk attitude of others changes behavior. Blume and Ortmann (2007) emphasize the positive influence of communication for coordinating on E1. Belloc et al. (2019) report the positive impact of time pressure on coordination. Feltovich and Grossman (2013) investigate the influence of group size (2–7 players). Without communication, contributions are independent of group size, between 37% and 45%.

For general games with Pareto-ranked equilibria, E0 indicates the least efficient and E1 the most efficient equilibrium. With two players, van Huyck et al. (1990) observe behavior in repeated games to converge to E1; for 14–16 players, convergence to E0 is observed (except if contributions are costless). The over-all evaluation of experimental results differ. For Cooper (2003, p. 1) "coordination failures are routinely observed in experimental games," while Devetag and Ortman (2007, p. 14) emphasize that experimental results suggest "myriad ways to engineer coordination successes in the lab." Engelmann and Norman (2010, p. 250) state "... previous minimum-effort experiments ... find Pareto-inferior average minimum-effort levels (and indeed rather often the lowest possible minimum-effort level) in groups with more than three participants." They find that coordination depends on "Scandinavian virtues": In an experiment in Copenhagen, cooperation increased with more Danish subjects in a session.

In an experimental investigation of financial attacks,[3] Heinemann et al. (2004, 2009) support the Global Games selection. In contrast, Cabrales et al.'s (2007) experiments show frequent deviations from this equilibrium and emphasize the importance of learning after which behavior can also converge to the payoff-dominant equilibrium. Also Duffy and Ochs (2012) find significant deviations from the Global Games equilibrium.

QRE has been applied to several types of experiments, often in connection with additional assumptions as social preferences and usually with a finite "precision parameter" λ. Because QRE(λ) is not necessarily unique, mostly the unique equilibrium on the path from $\lambda = 0$ to $\lambda = \infty$ is selected for the description of experimental behavior. An example of applying QRE to coordination games is Anderson et al. (2001). They show that, QRE is able to explain that effort levels decrease with increasing numbers of players or when effort costs increase (which does not affect the set of Nash equilibria). For further applications see Palfrey et al. (2010).

There are several experimental investigations of BTPG games with $k < n$, aiming mostly at identifying factors that encourage or discourage contributions by the game participants. The case $k = 1$ refers to the Volunteer's Dilemma (Diekmann, 1985). Experimental results (Diekmann, 1993; Franzen, 1995) reject theoretical predictions from the unique mixed strategy equilibrium (see Section 2) about success probabilities (decreasing with group size) and about the order of contribution frequencies (higher for high cost players). Bolle (2017) finds limited abilities of backward induction in a sequential Volunteer's Dilemma experiment. Experiments with intermediate thresholds $1 < k < n$ require contributions from two of three players up to 6 of 10. Some examples from the vast literature are: Van de Kragt et al. (1983) emphasize the importance of communication for successful coordination. Dawes et al. (1986) investigate the (positive) influence of refunds of insufficient contributions and the punishment of successful free riding. Erev and Rapoport (1990) show that the sequential-moves game leads to more efficient outcomes than the simultaneous-moves game and that the information provided to the players in the sequential game matters. They and McEvoy (2010) find that, in sequential decisions, the pivotality (criticality) of players increases the contribution frequency. Bartling et al. (2015) find that pivotality increases responsibility *attribution*.

Linear Public Good games have a unique equilibrium and are, therefore, quite different from BTPG games. One interesting comparison, however, is the behavior in the positive frame (public good) vs. the negative frame (common pool). In spite of the theoretical equivalence, we often observe much more cooperation in the positive than in the negative frame (Andreoni, 1995; Dufwenberg et al., 2011; Park, 2000; Willinger & Ziegelmeyer, 1999). In the meta-study of Zelmer (2003) the difference is, however, only weakly significant. The negative frame of a BTPG game is, for example, an environment with positive external effects, which collapses if a threshold of individually profitable but environmentally harmful activity is surpassed. Sonnemans et al. (1998) is the only BTPG experiment with a positive and a negative frame. In their experiments with a partner design (the same group interacts over 20 periods) they again find more cooperation in the positive frame. In our experiments with a stranger design (changing coplayers in every period), there are no significant differences.

Our experimental four-person games cover a wide range of parameters: Symmetric, mildly asymmetric and strongly asymmetric games as well as games in the positive and the negative frame. For our four Stag Hunt games, all three equilibrium selection principles select E0; but with average contribution frequencies between 70.3% and 99.7% (for different games and different player types) behavior is much closer to E1. After the analysis of Stag Hunt games, we extend our investigation to BTPG games with $k < n$. These are not games with strategic complements; therefore, we do not apply the Global Games selection. Asymmetric BTPG games with $k < n$ have a plethora of equilibria, which makes the pairwise comparisons of Risk Dominance rather tedious. Therefore, in these cases only the Linear Tracing Procedure and limits of QRE are applied. Behavior is clearly different from the equilibrium selection predictions; but it is also significantly different from any prediction with homogeneous behavior of the whole population. In addition to this important result, further characteristics of experimental behavior are described and supported by nonparametric tests. Assuming a nonhomogeneous population, a behavioral theory is outlined (in particular for Stag Hunt games) which successfully describes behavior.

1.3 | Outlook

In Section 2, we define BTPG games and characterize their equilibria. Games in the negative frame are defined and social preferences are introduced. In Section 3, we investigate equilibrium selection theoretically. We apply the Global Games selection to Stag Hunt games and the Linear Tracing Procedure to all BTPG games, Risk Dominance is applied to Stag Hunt games and almost symmetric BTPG games. All the *general* theoretical results (Propositions 2, 3, 4, 5, 6 and Lemma 1) are novel. Selection by QRE is determined numerically only for the experimental cases. We develop the theory before we describe our experiments because it facilitates the understanding of our parameter choices. In Section 4.1, we describe our experiments. In Section 4.2, we justify our parameter choices, discuss the applicability of the theoretical results, and determine the minimum strength of social preferences for switching equilibrium selection (in Stag Hunt games) from E0 to E1. Section 5 reports averages and distributions of individual behavior and derives eight experimental results. These rely on a larger variance of experimental parameters than any other study from this field. Section 6 outlines a behavioral theory for BTPG games, in this paper mainly for Stag Hunt games. Section 7 concludes.

2 | BTPG GAMES

2.1 | General theory

Definition 1. In a BTPG game, n players simultaneously contribute to the production of a public good or not. The public good is produced if at least k players contribute. Contributing players bear costs $c_i > 0$; if the public good is produced, all players enjoy benefits $G_i > c_i$. There are no refunds if the public good is not produced.

The players' contribution probabilities are denoted as $p = (p_i)_{i = 1, \ldots, n}$. $Q = Q(p)$ denotes the probability of success, that is, that k or more players contribute to the production of the public good. Q_{-i} (Q_{+i}) denote the probability of success if i does not contribute (contributes). A player is *decisive* if exactly $k - 1$ other players contribute. The probability $q_i = Q_{+i} - Q_{-i}$ that exactly $k - 1$ other players contribute is called the *decisiveness* of player i.

Note that Q_{+i}, Q_{-i} and q_i depend only on $p_j, j \neq i$. Player i's expected revenue is

$$\begin{aligned} R_i(p) &= G_i{}^*Q(p) - p_i c_i \\ &= G_i{}^*Q_{-i} + p_i{}^*[G_i{}^*q_i - c_i]. \end{aligned} \tag{1}$$

A mixed strategy equilibrium with $0 < p_i < 1$ requires that R_i is independent of p_i, that is,

$$\partial R_i / \partial p_i = G_i{}^*q_i - c_i = 0. \tag{2}$$

If $G_i * q_i - c_i < (>)0$ then player i contributes with $p_i = 0$ (1). Inserting q_i from (2) into (1) provides us with the equilibrium profit which *i* expects if she plays a mixed strategy.

$$R_i = G_i{}^* Q_{-i} = G_i{}^* Q_{+i} - c_i. \tag{3}$$

Proposition 1. *The following statements apply in equilibrium*:

i. *If i plays a strictly mixed strategy, then* $q_i = r_i = c_i/G_i$.
ii. $q_i > r_i$ *implies* $p_i = 1$ *and* $q_i < r_i$ *implies* $p_i = 0$.
iii. $R_i = G_i Q_{-i}$ *applies for* $p_i < 1$ *and* $R_i = G_i Q_{+i} - c_i$ *for* $p_i > 0$.
iv. *If there are two equilibria p and* p' *with* $p_i \geq p_i'$ *for all i, then p Pareto-dominates* p'. *If, in addition,* $p_i > p_i'$ *for at least two i, then p strictly Pareto-dominates* p'.

Proof 1. Statements (i) and (ii) follow from (2). Statement (iii) follows from (3). Statement (iv) follows from $R_i = G_i Q_{-i}$ and the fact that Q_{-i} is (strictly if there is $p_j > p_j'$) larger for p than for p'.

Definition 2. We call players with equal $r_i = c_i/G_i$ *almost symmetric*. If all players are almost symmetric, the game is called almost symmetric.

Mixed strategy equilibria depend only on r_i. For Harsanyi and Selten (1988) all players in an almost symmetric game are symmetric and are required to play the same strategy. As we will see in Section 3, for QRE, the players are not symmetric and may play different strategies.

The case $k = n$ is called the Stag Hunt game and was first discussed by Rousseau (1997, first edition 1762). There are *two* (symmetric) *pure strategy equilibria*, namely all players contributing (E1) and all players not contributing (E0). Possibly, *one strictly mixed strategy equilibrium* exists where $q_i * G_i - c_i = 0$, that is, $\prod_{j \neq i} p_j = \frac{c_i}{G_i} = r_i$. Multiplying all these equations, taking the $(n-1)$th root and dividing the result by $\prod_{j \neq i} p_j = r_i$ yields

$$p_i = \frac{\left(\prod_j r_j\right)^{\frac{1}{n-1}}}{r_i}. \tag{4}$$

The condition for the existence of this equilibrium is $p_i \leq 1$ for all *i*. This condition is always fulfilled for $n = 2$ or if all r_i are identical. Smaller r_i are connected with larger p_i. In almost symmetric games, there are *no pure/mixed strategy equilibria*. If some players contribute with probability 1 and the others play the mixed strategy equilibrium of a reduced Stag Hunt game, the latter would earn zero revenues (Proposition 1 (iii)) and the former necessarily less because they incur costs with a higher probability. For players with different r_i the same argument applies for the highest r_i player; but there may be pure/mixed strategy equilibria where the lowest r_i players contribute with certainty. If, according to (4), the player with the lowest r_i shows $p_i > 1$, we set $p_i = 1$ and compute (3) without r_i and with $n-2$ instead of $n-1$.Thus all $p_j, j \neq i$ increase and i still has the incentive to contribute with certainty. If necessary, we repeat the procedure of setting $p_j = 1$ for j with the lowest r_j of the remaining players. This procedure necessarily stops, if only two players remain.

Lemma 1. *Every Stag Hunt game has at least one strictly mixed or pure/mixed strategy equilibrium. In an almost symmetric Stag Hunt game, there is always a strictly mixed strategy equilibrium but no additional pure/mixed strategy equilibrium.*

(Without proof.)

The case $k = 1$ is the Volunteer's Dilemma, first investigated by Diekmann (1985, 1993). There are n pure strategy equilibria where exactly one player contributes. The only completely mixed strategy equilibrium is derived from Proposition 1 (i), $r_i = q_i = \prod_{j \neq i}(1 - p_j)$ and therefore

$$p_i = 1 - \frac{\left(\prod_j r_j\right)^{\frac{1}{n-1}}}{r_i}. \quad (5)$$

This equilibrium exists under the same conditions as that of the Stag Hunt game. Because of Proposition 1 (iii) and $Q_{+i} = 1$, in this equilibrium players earn $R_i = G_i - c_i$, that is, as much as players who contribute with certainty.

In cases $1 < k < n$, there are $\binom{n}{k}$ asymmetric pure strategy equilibria where exactly k players contribute, and there is the unique symmetric pure strategy equilibrium E0. For almost symmetric games with $r_i = \rho$, asymmetric mixed strategy equilibria may exist but are difficult to implement; symmetric mixed strategy equilibria (if existent) are more plausible. If all players contribute with probability π, player i's decisiveness is $q_i = f(\pi, k, n) = \binom{n-1}{k-1} * \pi^{k-1}(1-\pi)^{n-k}$. f is a unimodal function of π with a maximum at $\bar{\pi} = (k-1)/(n-1)$ and with $\rho^{max} = f(\bar{\pi})$.

Lemma 2. *For $1 < k < n$ with $r_i = \rho > \rho^{max}$, there is no solution of $q_i = \rho$, for $\rho = \rho^{max}$ there is one solution, and for $\rho < \rho^{max}$, there are two solutions $\pi^* < \bar{\pi} < \pi^{**}$.*

(Without proof.)

In cooperative pure strategy equilibria, the contributing players need a sufficient amount of trust in the willingness of some or all players to contribute. Trust completely characterizes the two pure strategy equilibria of the Stag Hunt game: Sufficiently high trust makes all players contribute and vice versa. Equilibrium selection predicts whether, under certain pay-off structures, enough mutual trust emerges. For $k < n$, behavior is motivated by the level of trust in others and own attempts to free ride.

2.2 | Positive versus negative frame

The negative frame of the Linear Public Good problem is the strategically equivalent Common Pool problem with the possible overexploitation of common resources. For the BTPG game, let us first give an example: In the basin of a river, n similar chemical plants are situated which can either purify their polluted water or discharge it nonpurified into the river (an action with negative opportunity costs c_i). If at least k of the plants discharge polluted water then a critical pollutant concentration is exceeded which, because of legal obligations, no longer allows the waterworks supplying the region with water from the river. They must use water from a distant source and all customers, including the n plants have to pay increased prices (negative benefit G_i). While, in this case, legal restrictions define a clear threshold, in other cases the threshold may be fuzzy but facilitate the exposition of a problem. For example, Russill and Nyssa (2009) observe a "tipping point trend in climate change communication."

We define a negative frame as $G_i < c_i < 0$. After exchanging the labels of strategies "contributing" and "not contributing," the game is equivalent to a game with opportunity costs and benefits $0 < -c_i < -G_i$ in the positive frame with a threshold $n - k + 1$. Therefore, we apply equilibrium selection only for the positive frame.

2.3 | Social preferences

Pure strategy equilibria as E0 and E1 are not affected by social preferences, except in the cases of, for example, extreme altruism or spite. Their selection, however, may change with altruism, inequality aversion or other deviations from income maximization. Let us investigate, as an example, the consequences of introducing *altruism and/or warm glow* in the spirit of Andreoni's (1989, 1990) suggestion. This changes the game only insofar as the cost/benefit ratios r_i are multiplied by a factor. Following Andreoni (1989, 1990) we add an "altruistic" term by substituting G_i by $G_i + a_i * G_{-i}$ with $G_{-i} = \sum_{j \neq i} G_j$ and we introduce an additional "warm glow" utility $w_i = b_i * c_i$ of contributing to the public good.

(Expressing warm glow as fraction of costs simplifies the following formulas.) With such a utility function, players who play mixed strategies with probabilities p_i have revenues

$$R_i = Q^*(G_i + a_i^*G_{-i}) - (1-b_i)^*p_i^*c_i. \tag{6}$$

Contributing is now a best reply if

$$(G_i + a_i^*G_{-i})^*q_i - (1-b_i)^*c_i \geq 0 \quad \text{or} \tag{7}$$

$$q_i \geq r_i^*s_i \text{ with } s_i = \frac{1-b_i}{1+a_i^*G_{-i}/G_i}. \tag{8}$$

As an example, take $n = 4$, $a_i = 0.5$, and $b_i = 0$. If all G_i are equal, we get $s_i = 0.4$. Mixed strategy equilibria and the selection of equilibria now depend on $r_i * s_i$ instead of r_i. As it will become apparent in Section 3, the smaller s_i, the more probable it is that the three selection theories do not select E0.

3 | EQUILIBRIUM SELECTION

3.1 | The global games selection for Stag Hunt games

The Stag Hunt game as defined in Section 2 assumes common knowledge. We can add "noise" to this game by assuming that revenues depend on an unknown state for which players receive private and correlated signals and thus transform it into a *Global Game*. For the technical definition of these games, see Frankel et al. (2003). While noise vanishes, equilibrium play converges, under certain conditions, to one of the Nash equilibria of the original game. Frankel et al.'s (2003) determination of a unique limiting equilibrium relies on revenue functions (1) having bounded derivatives (obviously true in our setting) and strategies being strategic complements. For Stag Hunt games, $Q_{-i} = 0$ and $q_i = \prod_{j \neq i} p_j$ applies. According to (1), if a player j increases p_j, then q_i, $R_i(p_i, p_{-i}) = p_i(G_iq_i - c_i)$, as well as $R_i(p_i + \varepsilon, p_{-i}) - R_i(p_i, p_{-i}) = \varepsilon(G_iq_i - c_i)$ increase. The latter is Frankel et al.'s (2003) definition of complementarities. It implies that i's best reply does not decrease when p_j increases.

Proposition 2. *If* $\sum_i r_i > 1$, *then* $a^* = (0, ..., 0)$ *is the unique Global Games equilibrium of a Stag Hunt game.*

Proof. See Appendix.

Corollary 1. *In the two almost symmetric experimental treatments with cost/benefit ratios* $r_i = 0.4$ *for all* i and *in the asymmetric treatment with* $r = (0.225, 0.25, 0.275, 0.3)$, *the unique Global games equilibrium in the positive frame is* $a^* = (0, 0, 0, 0)$ *and* $a^* = (1, 1, 1, 1)$ *in the negative frame. In the case* $r = (0.1, 0.2, 0.3, 0.4)$ *with* $\sum_i r_i = 1$, *the condition of Proposition* 2 *fails.*

Proof. Proposition 2.

For $k < n$, q_i is no longer a monotone function of p_j, that is, strategies are no longer strategic complements. Frankel et al. (2003) show that, then, the selected equilibrium can depend on the distribution of noise.

3.2 | The linear tracing procedure and risk dominance for BTPG games

Harsanyi and Selten (1988) select equilibria mainly by the application of the *Linear Tracing* Procedure. The procedure starts from the *centroid* of a game Γ which consists of the strategy profile where every pure strategy is played with the

same probability. In games with binary pure strategies, both strategies are played with probability ½. In the *Tracing Procedure*, for every $0 \le s \le 1$, equilibria are determined in a game $\Gamma(s)$ where player i assumes that, with probability s, the original game Γ is played, and with $1 - s$ the other players decide according to the probabilities of the centroid. If there is a unique continuous path of equilibria from $s = 0$ to $s = 1$, then the equilibrium at $s = 1$ is selected. If there are different paths with different equilibria at $s = 1$, then Harsanyi and Selten (1988) suggest additional criteria for the selection of a unique equilibrium.

Proposition 3. (almost symmetric BTPG games). *Let us define* $q(0) = f\left(\frac{1}{2}, k, n\right)$, *If* $r_i = \rho$ *for all i, the Linear Tracing Procedure selects the following equilibria*.

i. *If* $k = 1$, *the unique mixed strategy equilibrium* (5) *is selected*.
ii. *If* $1 < k \le n$ *and* $\rho > q(0)$, *then E*0 *is selected*.
iii. *If* $1 < k < n$ *and* $\rho < q(0)$, *then the equilibrium with* π^{**} *from Lemma* 2 *is selected*.
iv. *If* $k = n$ *and* $\rho < q(0)$, *then E*1 *is selected*.

Proof. See Appendix.

Proposition 4. (asymmetric BTPG games). *Let us assume* $r_1 < r_2 < .... < r_n$ *and define m as* $m = 0$ *if* $r_1 > q(0) = f\left(\frac{1}{2}, k, n\right)$ *and* $m = n$ *if* $r_n \le q(0)$. *Otherwise m is defined by* $r_m \le q(0)$ *and* $r_{m+1} > q(0)$. *The Linear Tracing Procedure selects the following equilibria*.

i. *If* $1 < k \le n$ *and* $m < k - 1$, *then E*0 *is selected*.
ii. *If* $1 < k \le n$ *and* $m \ge k$, *then the equilibrium is selected where players* 1, ..., k *contribute and the others not*.
iii. *If* $1 < k \le n$ *and* $m = k - 1$ *then* (*i*) *applies if* $s_{k-1} < s^k$ *and* (*ii*) *applies if* $s_{k-1} > s^k$ *where* s_{k-1} *and* s^k *are defined by* $(1 - s_{k-1})q(0) = r_{k-1}$ *and* $(1 - s_k)q(0) + s_k * 1 = r_k$.
iv. *If* $k = 1$, *then player* 1 *contributes and the others do not*.

Proof. See Appendix.

Note that Propositions 3 and 4 leave a gap for r_i which are neither equal nor strictly ordered. This gap can easily be closed but needs discussing additional subcases.

Corollary 2. *For* $r = (0.4, 0.4, 0.4, 0.4)$ *and* $r' = (0.225, 0.25, 0.275, 0.3)$ *and* $r'' = (0.1, 0.2, 0.3, 0.4)$, *the Linear Tracing Procedure predicts*:

i. *In Stag Hunt games* ($k = 4$), *with cost/benefit ratios r, r′ and r″, E*0 *is selected*.
ii. *In Volunteer's Dilemma games* ($k = 1$), *equilibrium* (5) *is selected for r and the equilibrium, where only player* 1 *contributes, for r′ and r″*.
iii. *In games with intermediate thresholds* ($k = 2, 3$), *E*0 *is selected for r. The equilibrium, where only the first k players contribute, is selected for r′ and r″*.

Proof. Corollary 2 follows directly from Propositions 3 and 4, for statement (iii) with $q(0) = f\left(\frac{1}{2}, 2, 4\right) = f\left(\frac{1}{2}, 3, 4\right) = 3/8$ for $k = 2$ and $k = 3$ and $q(0) = f\left(\frac{1}{2}, 4, 4\right) = 1/8$ for $k = 4$.

Risk Dominance is concerned with the pairwise comparison of equilibria. The risk dominance relation can be intransitive (Harsanyi & Selten, 1988, p. 217). For the question of whether a mixed or pure strategy equilibrium p risk dominates another equilibrium p', first the *bicentric prior* of p and p' is derived. For our games with two pure strategies, we have to determine, for every $0 \le t \le 1$, whether $a_i = 1$ (contribute) or $a_i = 0$ (do not contribute) is a best response of player i to the other players contributing according to the t-mixture of $p_{-i} = (p_1, ..., p_{i-1}, p_{i+1}, ... p_n)$ and p'_{-i}, that is, with probabilities $t * p_{-i} + (1 - t) * p'_{-i}$. The shares of t with $a_i = 1$ constitute a vector of prior probabilities. For the two equilibria and these priors (instead of those of the centroid), the Linear Tracing Procedure is carried out. If one of the two equilibria is selected it is said to risk dominate the other.

Proposition 5. *In Stag Hunt Games, if* $r_i > \prod_{j\neq i}\left(1-(r_j)^{\frac{1}{n-1}}\right)$ *for all i, then E*0 *risk dominates all other equilibria.*

Proof. See Appendix.

In almost symmetric games, we have with $r_i = \rho$ for all i. Harsanyi and Selten (1988) require equilibrium selection to be independent of positive linear utility transformations of all players. Therefore, for them, our almost symmetric games are symmetric. They also require that symmetric players play the same strategy.

Proposition 6. *Let us assume an almost symmetric BTPG game in the positive frame.*

i. *For* $k = 1$, *there is a unique symmetric equilibrium, described by* (5).
ii. *For* $1 < k < n$ *and* $\rho > \rho^{max}$, *E*0 *is the only symmetric equilibrium.*
iii. *For* $1 < k < n$ *and* $\rho \leq \rho^{max}$ *let* $\pi^* \leq \pi^{**}$ *be the* (*one or*) *two solutions of* $f(\pi, k, n) = \rho$. *If* $1-\frac{\pi^*}{\pi^{**}} < \pi^*$ *or* $1-\frac{\pi^*}{\pi^{**}} > \pi^{**}$, *then E*0 *risk dominates the only two other symmetric equilibria* $p^* = (\pi^*)$ *and* $p^{**} = (\pi^{**})$.

Proof. See Appendix.

Corollary 3. *In the experimental cases* (*positive frame*), *in Stag Hunt games and, for almost symmetric games, for thresholds* $k > 1$, *E*0 *risk dominates all other equilibria.*

Proof. Corollary 3 follows directly from Propositions 5 and 6, statement (iii) with $\pi^* = 0.22$ and $\pi^{**} = 0.46$ for $k = 2$ (implying $1-\frac{\pi^*}{\pi^{**}} > \pi^{**}$) and $\pi^* = 0.54$ and $\pi^{**} = 0.78$ for $k = 3$ (implying $1-\frac{\pi^*}{\pi^{**}} < \pi^*$).

3.3 | Equilibrium selection by logistic QRE for the experimental cases

McKelvey and Palfrey (1995) define QRE and use a variant of the *Tracing Procedure* from Harsanyi and Selten's (1988) theory to select a generically unique equilibrium. QRE assume all strategies (from a finite set) to be played with probabilities that are ordered according to the utility a strategy gains against the strategies of other players. Let us assume the positive frame and that player i contributes with probability $\boldsymbol{p_i}$. In the case of *logistic* QRE and Stag Hunt games with the two strategies *contributing* and *not contributing* the probability of player i of contributing is

$$p_i = \frac{\exp(\lambda(q_i{*}G_i - c_i))}{\exp(\lambda(q_i{*}G_i - c_i)) + \exp(\lambda{*}0)} = \frac{1}{1+\exp(-\lambda(q_i{*}G_i - c_i))}. \tag{9}$$

$q_i * G_i - c_i$ and 0 are the expected utilities after choosing contributing and not contributing. In the negative frame, utilities are different but we reach the same formula, only with $q_i = \prod_{j\neq i}(1-p_j)$. λ is the "precision parameter" characterizing the magnitude of deviations from best responses. The solution of the system (9) is the QRE with λ, denoted as $QRE(\lambda)$. For $\lambda = 0$, $p_i = 0.5$ for all i. For $\lambda \to \infty$, $QRE(\lambda)$ converges to a Nash equilibrium. Generically, there is a unique continuous path from $QRE(0)$ to $QRE(\infty)$, and $QRE(\infty)$ is suggested by McKelvey and Palfrey (1995) for equilibrium selection. For 2x2 coordination games, Zhang and Hofbauer (2016) completely characterize the selection by $QRE(\infty)$.

We determine $QRE(\infty)$ numerically. We use $\lambda(i) = 0.05 * 1.001^i$, $i = 0, ..., 10{,}000$ which results in λ values from 0.05 to 1096. The equilibrium with $\lambda(i)$ is used as the starting value for the numerical computation of the equilibrium with $\lambda(i+1)$. Figure 1 shows that always the equilibrium without cooperation is selected: (0,0,0,0) in the positive and (1,1,1,1) in the negative frame. For $k < n$, respective computations are carried out. The paths of QRE equilibria are shown in the Appendix (Figures A1, A2, and A3). The results in the positive frame are presented in Table 1. The contribution frequencies in the negative frame with a threshold k, $ACF_i^-(k)$, are equal to $1-ACF_i^+(n-k+1)$, where $ACF_i^+(n-k+1)$ is the contribution frequency in the positive frame with a threshold

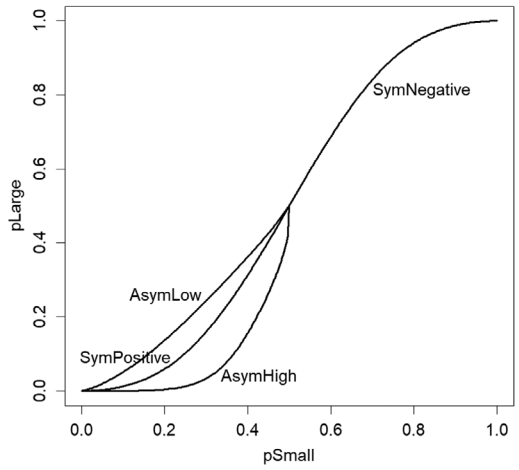

FIGURE 1 QRE selection in the experimental Stag Hunt games. pSmall (pLarge) = probability of contributing by small (large) player in the almost symmetric games SymPositive with $\left(\frac{c_i}{G_i}\right) = \left(\frac{4}{10}, \frac{4}{10}, \frac{8}{20}, \frac{8}{20}\right)$ and $k = 4$ and SymNegative with $\left(\frac{c_i}{G_i}\right) = \left(\frac{-4}{-10}, \frac{-4}{-10}, \frac{-8}{-20}, \frac{-8}{-20}\right)$ and $k = 1$. pSmall (pLarge) = probability of lowest (highest) cost player in the asymmetric games AsymLow with $\left(\frac{c_i}{G_i}\right) = \left(\frac{4.5}{20}, \frac{5}{20}, \frac{5.5}{20}, \frac{6}{20}\right)$ and AsymHigh with $\left(\frac{c_i}{G_i}\right) = \left(\frac{2}{20}, \frac{4}{20}, \frac{6}{20}, \frac{8}{20}\right)$ and $k = 4$ in both cases. *Remarks*: All paths of QRE start at QRE(0) = (0.5,0.5,0.5,0.5) and end at the Nash equilibrium QRE(1,096) = (0, 0, 0, 0) in the positive frame and QRE(1,096) = (1, 1, 1, 1)in the negative frame. In the almost symmetric games, the strategies of the two small and the two large players are equal. For the asymmetric games the strategies of the middle cost players are not indicated

TABLE 1 Selections of equilibria by QRE(∞) in the positive frame

	Sym Pos		**AsymLow**				**AsymHigh**			
c_i/G_i	**4/10**	**8/20**	**4.5/20**	**5/20**	**5.5/20**	**6/20**	**2/20**	**4/20**	**6/20**	**8/20**
k										
1	0.60	0	1	0	0	0	1	0	0	0
2	0.46	0.46	1	0.73	0.75	0	1	1	0	0
3	0	0	1	1	0.7	0.73	1	1	1	0
4	0	0	0	0	0	0	0	0	0	0

$n - k + 1$. Note that the selection by QRE(∞) may differentiate between almost symmetric players with different $\boldsymbol{c_i}$ and $\boldsymbol{G_i}$ values.

4 | EXPERIMENTS

4.1 | Treatments and logistics

All our experimental games are with four players who can invest c_i in the production of a public good. If at least k players invest, the public good is produced and they receive benefits G_i. In Treatment SymPos (almost symmetric, positive frame), players 1 and 2 with $(c_i, G_i) = (4, 10)$ Lab-Dollars are called small players; players 3 and 4 with $(c_i, G_i) = (8, 20)$ are called large players. The players in this treatment are almost symmetric.

A session of our experiments consisted of 32 games (periods) with the same eight subjects who, in SymPos, always kept their role as a small or a large player. In every session of SymPos, there were four players of each type. In every period (game), they were allocated randomly to two experimental groups under the restriction that every group consisted of two small and two large players. There are $\binom{4}{2} * \binom{4}{2} = 36$ different combinations of four-player groups.

TABLE 2 Game parameters (in lab dollars) in the four treatments for players $i = 1,2,3,4$ and number of sessions with eight subjects either at TU (Technische Universität Berlin) or V (Europa-Universität Viadrina Frankfurt (Oder))

Treatment	Endowment	Costs c_i	Benefits G_i	c_i/G_i	#sess. At (V, TU)
SymPos	8	(4,4,8,8)	(10,10,20,20)	0.4	(10, −)
SymNeg	20	(−4,−4,−8,−8)	(−10,−10,−20,−20)	0.4	(10, −)
AsymLow	8	(4.5, 5, 5.5, 6)	20	(0.225, 0.25, 0.275, 0.3)	(6, 12)
AsymHigh	8	(2, 4, 6, 8)	20	(0.1, 0.2, 0.3, 0.4)	(10, 6)

During the 32 periods, all thresholds $k = 1, 2, 3, 4$ were adopted in a random order in blocks of eight repetitions. Example: In periods 1, ..., 8 (position 1) the threshold was $k = 3$, In periods 9, ..., 16 (position 2) the threshold was $k = 1$, in periods 17, ..., 24 (position 3) the threshold was $k = 4$, and in periods 25, ..., 32 (position 4) the threshold was $k = 2$. In the 10 sessions with treatment SymPos, each k was used either 2 or 3 times at each of the four positions. Interaction was anonymous; players did not know whether and when they might have met a coplayer from a previous round. Subjects were not informed about the order of the thresholds in the beginning, but only when the threshold changed. They were informed about how many players contributed to the public good, but not who contributed.

In Treatment SymNeg (almost symmetric, negative frame) G_i and c_i have the same absolute values as in SymPos, but both are negative, that is, players earn a profit by contributing and suffer a loss if the threshold is reached or surpassed. Again, players 1 and 2 are called small players and 3 and 4 large players. All players in SymPos and SymNeg have cost/benefit ratios $c_i/G_i = 0.4$. In the asymmetric treatments AsymLow and AsymHigh, benefits were $G_i = 20$ and only costs varied. In treatment AsymLow, contribution costs (c_i) and cost/benefit ratios (r_i) had a small spread; in treatment AsymHigh they showed a large spread. (See Table 2.) The costs and benefits of a player define his *type*. A player kept his type during the whole experiment. Every subject participated in only one treatment. The course of a session was the same as for treatment SymPos.

The experiments were conducted as computerized laboratory experiments (implemented in a z-tree program design, Fischbacher, 2007) at two locations, the Vialab (V) of the Europa-Universität Viadrina in Frankfurt (Oder) and in the experimental laboratory of the Technische Universität (TU) Berlin. Table 2 describes the experimental parameters and how many sessions of a treatment were conducted at TU and Viadrina.

Before subjects played the games, they got printed instructions and had the possibility to ask questions. Instructions contained general information, the description of the Binary Threshold Public Good game and an example calculation (see Appendix). Furthermore, they had to answer five comprehension questions to make sure that everyone understood the game. The experiment did not start until all subjects had answered the questions correctly. In cases of problems, personal advice was given. In every period the subjects were reminded of the actual threshold and, every eighth period, the changing of the threshold was announced. In each period, subjects were informed on the *decision screen* that the group composition had changed and they were required to decide whether to contribute. On the *profit display screen*, they were informed about the number of contributing players and whether the threshold was reached. They further received information about their payoff in the current period.

In all of the 32 periods, players were endowed with 8 Lab-Dollars in the positive frame and 20 Lab-dollars in treatment SymNeg.[4] If the threshold of k contributions was reached or surpassed, all players received the benefit G_i (suffered losses in treatment SymNeg); otherwise, they received nothing. Their total income in a period consisted of their endowment minus their costs of contributing (if they contributed) plus possible (positive or negative) benefits. One Lab Dollar was worth 4 Eurocents. The total income of a subject consisted of the sum of incomes in all periods.[5] Participants earned between 17 and 36 Euros with an average of 28.11 Euros. Sessions lasted roughly 45 min.

The design of our experiment is comparable with many other investigations of Stag Hunt games and other "simple" games, for example, with Feltovich (2011) and Feltovich et al. (2012), who also investigate equilibrium selection. In every session, their subjects played five different two-player games (three of them Stag Hunt games), each with 20 or 40 repetitions.

4.2 | The applicability of theory and the choice of parameters

Let us assume (i) that a player's goal is utility maximization with a utility function which is linear in incomes of all players. Let us further assume that (ii) in one shot games, a certain principle of equilibrium selection applies. Then,

equilibrium selection does not change when we regard finitely repeated instead of one-shot games. In period 32, all subjects know that this is the last game played. Therefore, equilibrium selection (ii) of the one shot game applies and, because of (i), the selection of E is independent of the play in previous periods. Now, backward induction applies as usual. Note that the incorporation of equilibrium selection is essential; otherwise, in repeated games, the equilibrium may switch from period to period.[6]

If subjects believe that noncontribution has to be expected in one-shot games and, disregarding backward induction, try to conserve cooperation in future periods by cooperating in the present period, then we should observe "end effects" as in finitely repeated Prisoner's Dilemma games. We will look for evidence of dynamic behavior in our data, but we will find almost constant behavior in the asymmetric games (all periods) and in the symmetric games (periods 17–32).

In this paper, we want to test the predictive power of the three most often used equilibrium selection theories. As these are static theories they should be applied only to one-shot games or if behavior is stationary. If, for our investigation, we use only the data from period 1 or only from period 32, we arrive at exactly the same conclusions as when using averages over stationary behavior. Almost all experiments with public goods production and with other "simple" games have a repeated games design. One-shot games suffer from the problem that, even after some previous test games, we may doubt that subjects "understand" the game and have rational expectations about the behavior of their coplayers. In linear Public Good games, for example, we regularly observe decreasing contributions, ultimately with "steady state behavior" close to the unique equilibrium of the game which requires zero contributions. An additional argument for our design is that, in "real life," people play sequences of similar games with different people.

With strong enough altruism or warm glow as described at the end of Section 2, E0 needs no longer be selected in Stag Hunt games. Let us investigate the effect (for Stag Hunt games) if all r_i are changed to $s * r_i$ as the introduction of altruism/warm glow in Section 2 suggests.[7] The Global Games selection of E0 needs $s \geq 0.63$ for the symmetric games and $s \geq 0.95$ (1) for AsymHigh (AsymLow). The Linear Tracing Procedure needs $s \geq 0.31$ for the symmetric games and $s \geq 0.50$ (0.69) for AsymHigh (AsymLow). Risk Dominance needs $s \geq 0.31$ for the symmetric games and $s \geq 0.75$ (0.45) for AsymHigh (AsymLow). The QRE selection of E0 requires $s \geq 0.29$ for the symmetric games and $s \geq 0.38$ (0.39) for AsymHigh (AsymLow). Therefore, except for the Global Games selection for the asymmetric games, we need considerable amounts of altruism in order to prevent equilibrium E0 to be selected.

Our choice of the cost/benefit ratio $\rho = r_i = 0.4$ in the almost symmetric games has been guided by the goal to make cooperation neither "too easy" nor "too risky." Prima facie, the risk of investing and losing 32 cents seems to be high against the chance of winning additional 48 cents if the other three players also invest. The magnitude of ρ was also limited by the fact that, for thresholds $k = 2$ and 3, and $\rho > 4/9$, symmetric strictly mixed strategy equilibria (which we wanted to use as benchmarks for the empirical frequencies) do not exist.

For the choice of cost/benefit ratios of the asymmetric games, the question which ratios are comparable with those of the symmetric games is difficult. The first idea might be that the average should be the same; on second thought, in Stag Hunt games the same maximum seems plausible. If one player refrains from cooperation this is plausibly the player with the maximum ratio—and all others may expect this. Of course, such simplified rationale ignores higher levels of reasoning. Our treatment "AsymHigh" with the large spread of cost benefit/ratios has the same maximum as the symmetric games but a smaller average, namely 0.25. Our treatment "AsymLow" has almost the same average as "AsymHigh," namely 0.26, but a lower maximum, namely 0.3. Therefore, we have the possibility to test whether, for cooperation rates, the maximum of cost/benefit ratios is important, but not the average or vice versa. These two hypotheses are not alternatives and they have a weak fundament. A more formal aspect is our derivation of limits of s to altruism/warm glow for which E0 is selected. For all our selection theories, we found the same qualitative result: In the symmetric treatments, E0 is selected for lower s than in the asymmetric treatments.

5 | RESULTS

5.1 | Stag Hunt games

The average contribution frequencies are presented in Table 3. In one of eight tests, the results in the TU and V laboratories differed (5% level). Nonetheless, we aggregate our data.

Result 1: In the four Stag Hunt games, the selection of E0 (E1) in the positive (negative) frame by the Linear Tracing Procedure, Risk Dominance, by Global Games, and by $QRE(\infty)$ is clearly rejected. The results are closer to Pay-off Dominance with the contrary prediction.

Result 2: Large and small players do not behave significantly differently.
Result 3: Players in the negative and in the positive frame do not behave significantly differently.
Result 4: There is a partly significant tendency that, in asymmetric games, players with low cost/benefit ratios contribute more frequently than players with high cost/benefit ratios.

For a further illustration of the results and further tests, we investigate the distribution of individual contribution frequencies ICF = number of contributing decisions of a player in the eight repetitions of a game (Figures 2 and 3). Comparing the distributions by chi-square tests, we confirm Results 2 and 3. With ICFs, we can also test the hypothesis that subjects behave according to a unique mixed strategy or a pure strategy plus "trembling hands" deviations. Then, ICFs should be distributed binomially—but they are not.

Result 5: The hypothesis of a binomial distribution of ICFs is rejected for the almost symmetric games and for asymmetric games (except for the player type with the lowest cost/benefit relation) with extreme levels of significance ($p < 10^{-10}$ in Figures 2 and 3).

TABLE 3 Average contribution probabilities (ACPs) in almost symmetric games with $r = 0.4$ and in two games with different r

SymPositive, $k = 4$	Two small pl. with $c/G = 4/10$		Two large pl. with $c/G = 8/20$	
ACP	0.744		0.809	
SymNegative, $k = 1$	Two small pl. with $c/G = 4/10$		Two large pl. with $c/G = 8/20$	
1-ACP	0.703		0.744	
AsymLow, $k = 4$	$c/G = 4.5/20$	$c/G = 5/20$	$c/G = 5.5/20$	$c/G = 6/20$
ACP	0.997	0.948	0.931	0.944[a]
AsymHigh, $k = 4$	$c/G = 2/20$	$c/G = 4/20$	$c/G = 6/20$	$c/G = 8/20$
ACP	0.984	0.945	0.918	0.883[a,b]

Notes: k = necessary number of contributions for the production of the public good. For the asymmetric games, aggregated data from TU and V. *Tests*: No significant differences between small and large players in two-sided Wilcoxon matched pairs-test. No significant differences between positive and negative frame in two-sided Mann–Whitney tests between $ACP(pos.\ frame)$ and $1 - ACP(neg.\ frame)$. All tests are based on averages from 10 sessions and $p < .05$.
[a]Significant differences between player types compared with type $c_i/G_i = 6/20$ (8/20) and $c_i/G_i = 4.5/20$ (2/20) in two-sided Wilcoxon tests on the 5% level. Tests are based on averages from 18 sessions (low asymmetry) and 16 sessions (high asymmetry) and $p < .05$.
[b]Significant difference (5% level) between the six sessions at TU and the 10 sessions at V in two-sided Mann–Whitney tests.

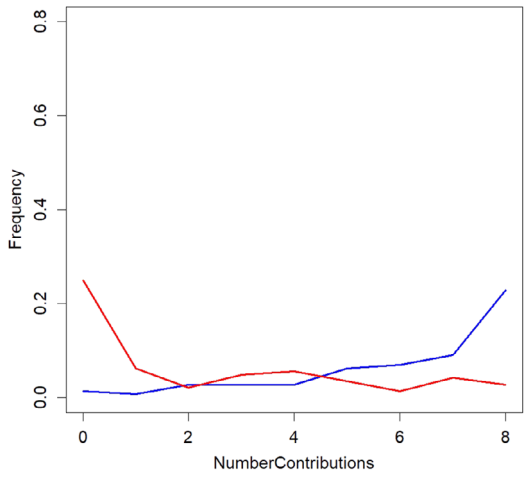

FIGURE 2 Distributions of individual contribution frequencies ICF in eight repetitions of almost symmetric Stag Hunt games with $r = 0.4$ in the positive frame (blue, 80 subjects) and in the negative frame (red, 80 subjects). *Tests*: In chi-square tests, the distributions of ICF in the positive frame ($\chi^2 = 8{,}272$, df = 7, $p < 10^{-10}$) and 8-ICP in the negative frame ($\chi^2 = 6{,}098$, df = 7, $p < 10^{-10}$) are significantly different from binomial distributions but not significantly different from one another ($\chi^2 = 11.2$, df = 8, $p = 0.189$)

Table 2 as well as Figures 2 and 3 suggest (and chi-square and Wilcoxon tests confirm) that, in the asymmetric games, average contribution frequencies are higher than in the almost symmetric games. We have derived this in the last section from the "stability" of the E0 selection against altruism/warm glow preferences.

Finally, we briefly consider the dynamics of the games (Figures 4 and 5). Games are played in eight rounds, but have different positions in the order of games with thresholds $k = 1,2,3,4$. When, for example, a game is played as the third game, it is played in periods 17–24. While contributions in the asymmetric games are on a continuously high level, contributions in the symmetric games show a surprising dynamic. If the Stag Hunt game was played first (periods 1–8) or second (periods 9–16), then contributions are strongly decreasing. If players had previous experience with two games

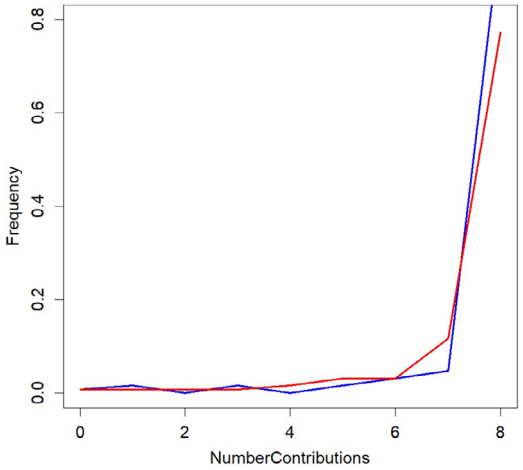

FIGURE 3 Distributions of individual contribution frequencies ICF in eight repetitions of the Stag Hunt game in the low asymmetry treatment (blue, 144 subjects) and in the high asymmetry treatment (red, 128 subjects). *Tests*: In chi-square tests with classes {0,1,2,3}, {4,5}, {6},{7},{8}, the distributions of ICFs in the treatment with small asymmetry ($\chi^2 = 18{,}586$, df = 3, $p < 10^{-10}$) and in the treatment with large asymmetry ($\chi^2 = 3{,}050$, df = 3, $p < 10^{-10}$) are significantly different from binomial distributions but not significantly different from one another ($\chi^2 = 6.0$, df = 4, $p = 0.201$). Also the distributions for the three player types with the highest cost/benefit ratios are significantly different from a binomial distribution

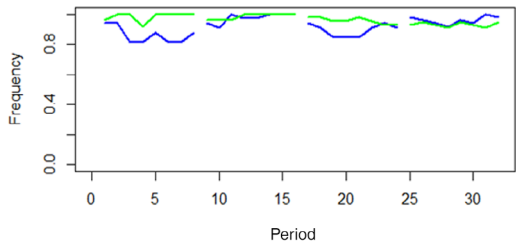

FIGURE 4 Frequency of contributions in the Stag Hunt game over periods in different positions. Blue = AsymHigh, green = AsymLow

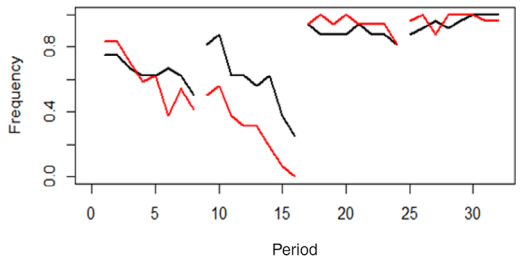

FIGURE 5 Contributions (noncontributions in the case of SymNeg) in the Stag Hunt game over periods. Black = SymPos, red = SymNeg

with other thresholds, they keep cooperating on the same level as in asymmetric games. Therefore, we have no hints concerning the question whether average costs or maximum costs are more important for cooperation in Stag Hunt games.

Result 6: When played as the third or fourth block in the sequence of the experimental games with thresholds 1,2,3,4, the Stag Hunt game ($k = 4$ in SymPos, $k = 1$ in SymNeg) is played constantly with cooperation rates about 90% or above.

Finally, let us emphasize:

Result 7: Result 1 is maintained if we evaluate behavior only in period 1 or in period 32.

5.2 | Non-Stag Hunt BTPG games

Table 4 reports results for symmetric and Tables 5 and 6 for asymmetric games. In the following, all results with an apostrophe attached (e.g., Result 1′) are concerned with symmetric non-Stag Hunt games, all those attached with a double apostrophe (e.g., Result 4″) are concerned with asymmetric non-Stag Hunt games. This notation allows a better comparison of results with those for Stag Hunt games.

Result 1′: With two exceptions where the predictions by Pay-off Dominance (PO Dom) and Risk Dominance/Linear Tracing Procedure or QRE(∞) coincide, PO Dom is always superior.
Result 2′: With one exception, large and small players do not behave significantly different.
Result 3′: Players in the negative and in the positive frame do not behave significantly different.

TABLE 4 Average contribution frequencies $ACF_i^+(k)$ in treatment SymPos and $1-ACF_i^-(5-k)$ in treatment SymNeg

	$ACF_i^+(k)$		$1-ACF_i^-(5-k)$		Predictions		
k	SmPl	LaPl	SmPl	LaPl	PO Dom	R Dom/LTP	QRE(∞)
1	0.35$^{\#}$	0.37$^{\#}$	0.25§	0.41	0.26	0.26	(0.60,0)
2	0.49$^{\#}$	0.56	0.43$^{\#}$	0.51$^{\#}$	0.46	0	0.46
3	0.61	0.63$^{\#}$	0.57$^{\#}$	0.61$^{\#}$	0.78	0	0

Notes: PO Dom = pay-off dominance. R Dom/LTP = risk dominance as well as linear tracing procedure. Small player type i = SmPl with $(G_i, c_i) = (10, 4)$ and large player type i = LaPl with $(G_i, c_i) = (20, 8)$; k = threshold. Predictions are the same for small and large players except for QRE(∞) and $k = 1$ with the prediction $p_i = 0.6$ for small and $p_i = 0$ for large players. All tests are two-sided, at the 5% level, and based on averages in 10 sessions. Small versus large players: §Significant in Wilcoxon matched pairs-tests. k (position of *) versus $k + 1$: $^{\#}$Significant in Wilcoxon matched-pairs test. For $k = 3$, the comparison is with the contribution frequencies in Table 3. SymPos versus SymNeg: No significant differences in Wilcoxon tests of $ACF_i^+(k)$ versus $1-ACF_i^-(n-k+1)$.

TABLE 5 Average contribution frequencies of the four player types in treatment AysmLow (aggregated over V and TU) and predictions

	Experiment				Linear tracing procedure				QRE(∞)			
r_i	0.225	0.25	0.275	0.3	0.225	0.25	0.275	0.3	0.225	0.25	0.275	0.3
k												
1	0.39	**0.50**	0.33*	0.25*	1	0	0	0	0.75	0.77	0	0
2	0.62	0.63	**0.48***	0.48	1	1	0	0	1	0.73	0.75	0
3	0.73	0.79	0.73§	**0.56*§**	1	1	1	0	1	1	0.7	0.73

Notes: All tests are two-sided, at the 5% level, and based on averages in six sessions at V and 12 sessions at TU. V versus TU: Three differences are significant (bold types) in Wilcoxon tests, three higher probabilities in TU, one in V. k versus $k + 1$: 9 of the 12 differences are significant in Wilcoxon matched-pairs tests with 18 independent sessions. (Exceptions $k = 2$, $r_i = 0.2$, $k = 2$, $r_i = 0.3$). All differences between k and $k + 2$ are significant. Player types: * (§) Significant differences between player types compared with the type $r_i = 0.225$ (0.25) in Wilcoxon matched pairs tests.

TABLE 6 Average contribution frequencies of the four player types in treatment AsymHigh (aggregated over V and TU) and predictions

	Experiment				Linear tracing procedure				QRE(∞)			
r_i	0.1	0.2	0.3	0.4	0.1	0.2	0.3	0.4	0.1	0.2	0.3	0.4
k												
1	0.68	0.34*	0.23*	0.28*	1	0	0	0	1	0	0	0
2	0.78	0.61	0.40*	0.42*	1	1	0	0	1	1	0	0
3	0.93	0.84	0.69*§	0.64*,§	1	1	1	0	1	1	1	0

Notes: Tests are two-sided, at the 5% level, and based on averages in 10 sessions at V and 6 sessions at TU. V versus TU: No significant differences in Wilcoxon tests. k versus $k + 1$: All differences are significant in Wilcoxon matched-pairs tests (except $k = 1$, $r_i = 0.1$,). Player types: * (§) Significant differences compared to the type with $r_i = 0.1$ (0.2) in Wilcoxon matched pairs tests.

Result 8′: Confirming the prediction by PO Dom, the contribution probability is always higher for threshold $k + 1$ than for k (significantly in 8 of 12 cases).

The asymmetric games do not have Pareto-ordered equilibria, but again we find large differences when comparing predictions by the Linear Tracing Procedure and QRE(∞) with experimental behavior. The following results refer to both tables.

Result 1″: Average contribution probabilities are clearly different from those of the equilibria selected by the Linear Tracing Procedure and QRE(∞).
Result 4″: There is a partly significant tendency that, in asymmetric games, players with low cost/benefit ratios contribute more frequently than players with high cost/benefit ratios. This tendency is much stronger in the games with high asymmetry.
Result 8″: The contribution probability is always higher for threshold $k + 1$ than for k (significantly in 20 of 24 cases).

For (almost) symmetric as well as for asymmetric games we again find:

Result 7′/7″: Result 1 does not change if we take into account only the behavior in period 1 or in period 32.

Testing the distributions of ICFs for non-Stag Hunt games, we again find:

Result 5′/5″: The hypothesis of a binomial distribution of ICFs is rejected for the almost symmetric games and for asymmetric games with extreme levels of significance ($p < 10^{-10}$).

6 | A POSITIVE THEORY FOR STAG HUNT GAMES

Results 5/5′/5″ show that all theories assuming a homogenous population with stationary behavior are rejected with extreme levels of significance. According to Pay-off Dominance and, with a sufficiently altruistic population, according to the other three selection theories, contribution rates should be 1 in the Stag Hunt game—but this does not explain the distribution of ICFs, even if we assume a constant error rate. A successful explanation of the results requires the assumption of subpopulations with different behavior. Assuming that such subpopulations exist, Bolle (2019b) explains the data of this investigation in the framework of his Behavioral Equilibrium Selection (BES) theory.

According to estimations of BES, for our Stag Hunt games, an (aggregate) subpopulation plays "always cooperate" (as if selecting E1) with a joint share between 67% and 80% of the population. There may be different motives for contributing (which refer to different subpopulations in the games with $k < n$): E1 is fair; E1 is the most efficient equilibrium; according to the Categorical Imperative, contributing is simply the right thing to do.[8] 3–7% of the population play "never cooperate" (as if selecting E0), and 17–26% play a mixed strategy (from an equilibrium with a certain warm glow parameter). There are deviations from strategies of about 0.03, that is, the pure strategy populations contribute with probabilities 0.97 and 0.03; because of the relatively low magnitude of these deviations, one might think of them as trembling hand behavior. For details, see Bolle (2019b).

In order to show that the assumption of three (aggregated) subpopulations in Stag Hunt games is not only successful for our data, we apply it to data of Feltovich (2011). His experimental procedure is comparable with ours. Subjects play three 2 × 2 Stag Hunt and two Hawk Dove games in blocks with 20 repetitions, that is, his subjects play 100 periods. The order of the blocks is randomized. We investigate only the Stag Hunt games and only the experiments in a stranger design (changing partners in every period). We test the hypothesis that depending on the parameters of the game, his subjects can be separated into three subpopulations: P1, P0, and Pm playing "always cooperate," "never cooperate," and a mixed strategy (possibly from the unique mixed strategy equilibrium Em with a certain warm glow parameter). The payoff matrix of the game stag hunt high payoffs (SHH) is presented in Table 7. The payoff matrices of the two other Stag Hunt games are derived from SHH by subtracting 140 in the game stag hunt medium payoffs (SHM) or 240 in the game stag hunt low payoffs (SHL) from all payoffs of SHH. All Stag Hunt games have the same unique mixed strategy equilibrium Em*, with $\pi^* = 0.69$ (without social preferences). Feltovich (2011) shows that, although the set of equilibria does not change, lower payoffs make subjects in Stag Hunt games more cooperative. Our three-populations analysis does not provide new insights regarding the origin of this behavioral shift but describes its nature in greater detail.

TABLE 7 Stag Hunt game (SHH)

	Coop	***Non-coop***
Coop	360, 360	40, 260
Non-coop	260, 40	260, 260

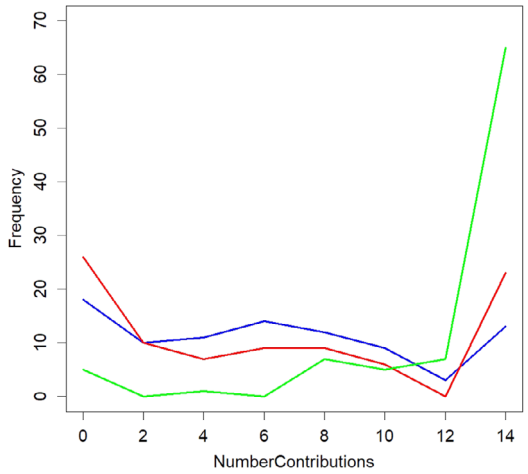

FIGURE 6 Individual frequencies (ICFs) of cooperative or peaceful behavior in the Stag Hunt games. "0" indicates the category of subjects who never or only once cooperated, "2" the catagory who, two or threee times contributed, and so forth. Blue: SHH, Red: SHM, Green: SHL

TABLE 8 Parameters (standard errors in brackets) and evaluation of the three-population model for the 2 × 2 Stag Hunt game in a stranger design

	α_1	α_0	α_m	π	ε	χ^2	p (df = 4)
SHH	0.182	0.299	0.519	0.486	0.076	6.06	.195
	(0.030)	(0.036)		(0.013)	(0.012)		
SHM	0.276	0.379	0.345	0.488	0.057	9.52	.049
	(0.033)	(0.036)		(0.016)	(0.008)		
SHL	0.767	0.057	0.176	0.601	0.031	3.93	.415
	(0.033)	(0.017)		(0.027)	(0.006)		

Because our hypothesis is about static behavior, we omit the initial five of the 20 rounds for every game (see Feltovich, 2011, Figure 3, for evidence that, in the first five rounds, an adaptation process may have occurred). For the remaining 15 decisions, we count, for every subject, the number ICF of cooperative decisions. After merging adjacent classes, the distribution of the ICFs is presented in Figure 6. Table 8 provides the minimum chi-square estimations based on the distributions in Figure 6. It shows that the distribution of ICFs can be successfully interpreted as a superposition of three binomial distributions according to the strategies of the subpopulations P1, P0, and Pm plus a "trembling hand" error ε which is the same for all decisions. All estimations of π are close to ½, which may alternatively be interpreted as a simple heuristic. The main effect of subtracting a constant amount from the payoff matrices is the increase of the P1 subpopulation but not a systematic increase of π. SHL shows shares of populations which are comparable with the shares reported for our four-person Stag Hunt games. SHM and SHH show less cooperation.

7 | CONCLUSION

Investigating BTPG games, we have illustrated the difference between experimental behavior and equilibria selected by Risk Dominance, the Linear Tracing Procedure, limits of Global Games, and limits of QRE. Our results are obtained for a broader range of parameters than those in earlier investigations and can therefore claim more generality. In our experimental *Stag Hunt* games, we find high average contribution rates (between 70.3% and 99.7% for different games and player types). These results completely contradict all the applied equilibrium selection theories, which predict zero contributions. For almost symmetric games with $k = 2$ or 3, again E0 is selected by Risk Dominance and the Tracing Procedure, for $k = 3$ also by QRE(∞). For asymmetric games with thresholds $k < n$, the Tracing Procedure selects the pure strategy equilibria where exactly the k players with the lowest cost/benefit ratios contribute, and QRE(∞) select either these or alternative pure/mixed strategy equilibria. All these predictions are completely different from experimental results.

In addition to testing equilibrium selection theories, we report a number of behavioral regularities (Results 2–8). Any positive theory of behavior in BTPG games has to imply these regularities. We find that theoretic invariances concerning small and large players and a positive vs. a negative frame are supported by nonsignificant differences (Results 2 and 3). Players with lower cost/benefit ratios contribute more often (Result 4). With increasing thresholds, players contribute more frequently (Result 8). We also find that, on average, cooperation rates are higher in our asymmetric than in our symmetric games, but this is not true if we compare behavior only in periods 17–32. Players in the symmetric treatments seem to learn from similar games they played in periods 1–16. Such type of learning is characteristic for "real life." It has been observed also in previous studies and is discussed as "hysteresis effect" by Romero (2015). Most important, however, for any positive theory is Result 5: A homogeneous population playing a single deterministic or stochastic strategy cannot explain behavior in BTPG games. In Stag Hunt games, E1 is a far better description of behavior than E0, but E1 plus a constant trembling hand error is still significantly rejected.

Based on this fundamental result, we outline a "semirational" theory of BES in Section 6. For Stag Hunt games, BES predicts three subpopulations, playing the strategies from E0 and E1, and a mixed strategy. All strategies are perturbed by a constant trembling hand error. Successful estimations (nonrejection by a chi-square test for individual contribution frequencies) are reported for our data as well as data from Feltovich (2011).

We contradict extant equilibrium selection theories, but do not state that earlier experimental results are less reliable than ours. Some of them are based on different games (e.g., Minimum Effort instead of Stag Hunt games), most of the Stag Hunt games are 2×2 instead of our $2 \times 2 \times 2 \times 2$ games, and all games have different incentives. Compared with all the investigations from the literature, our experiments have larger variations. This shows the stability of our results for a large region of parameters, but not necessarily for all parameters. The connection between the parameters of, for example, a Stag Hunt game and the amount of cooperation we observe is still an open question. BES states that there are six subpopulations (four of them playing according to E1 in Stag Hunt games) with different principles of behavior. The shares of the populations are to be estimated, however. In Bolle (2019a 2019b), it is shown that these shares are constant over thresholds $k = 1,2,3,4$; they are *similar* but significantly different for our games with different cost/benefit ratios. The parameter changes of Feltovich (2011), however, cause *considerable changes* of population shares (Section 6). A theory which predicts the frequencies of behavioral modes (equilibrium strategies or not) from the parameters of a game may be based on a meta-study with the application of BES (or a similar theory); but our opinion is that we still need much more experience with different parameters before we can predict those shares.

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ENDNOTES

[1] In addition to these concepts, there are the theory of Güth and Kalkofen (1989), approaches with learning to play equilibria (e.g., Berninghaus & Ehrhart, 1998) and other dynamic approaches (Binmore & Samuelson, 1999; Young, 1993). Kim (1996) investigates further proposals for equilibrium selection in symmetric normal form games with Pareto-ranked equilibria.

[2] Data of Feltovich (2011) will be further investigated in Section 6.

[3] Successful financial attacks require a sufficient number of attackers. If all players are required to attack, we have a Stag Hunt game, otherwise a game where a club good is provided (only the attackers earn a profit). Therefore, attacks are strategic complements.

[4] Thus, incomes in SymPos and SymNeg are equal if the distribution of contributing decisions in SymPos is the same as the distribution of noncontributing in SymNeg.

[5] There is a long tradition of propagating stochastic payment according to a single period, for example, Azrieli et al. (2018). Paying all periods may cause wealth effects with consequences for risk attitudes and hedging of choices. We are aware of this danger, but not paying every period may have disadvantages, too. With many periods, the subjects may lack the direct experience of profitable and unprofitable decisions. Our subjects have to adapt to the special environment of the experiment. There may be a learning process until they are sure about their decisions. We discuss this issue in connection with Figure 5 and with the estimation of a behavioral model with data from Feltovich (2011) in Section 6. Learning may be much easier with "real pay-off" in separately paid periods.

[6] We could try to apply equilibrium selection to the repeated game instead of the stage game. Every selection with arbitrary switches between equilibria, however, has to solve the coordination problem involved in such a sequence of equilibria. This problem is similar to selecting asymmetric equilibria in symmetric games.

[7] This is an analysis under complete information. If there is incomplete information about other's social preferences, dynamic behavior caused by Bayesian updating of beliefs about the distribution of preferences in one's session is implied. Bolle (2017) applies such a model in order to explain behavior in sequential Volunteer's Dilemma games.

[8] Also Faillo et al. (2013, p. 1) find that efficiency (Pareto dominance) and fairness are "good predictors for coordination choices."

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