Peer Transparency in Teams: Does it Help or Hinder Incentives?

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Abstract

In a joint project involving two players who can contribute in one or both rounds of a two-round effort investment game, transparency, by allowing players to observe each other's efforts after the first round, achieves at least as much, and sometimes more, collective and individual efforts relative to a non-transparent environment in which efforts are not observable. Without transparency multiple equilibria can arise and transparency eliminates the inferior equilibria. When full cooperation arises only under transparency, it occurs *gradually*: no worker sinks in the maximum amount of effort in the first round, preferring instead to smooth out contributions over time. The benefit of transparency, demonstrated both for exogenous rewards and in terms of implementation costs (with rewards optimally chosen by a principal to induce full cooperation), obtains under a general *complementary* production technology. If the players' efforts are *substitutes*, transparency makes no difference to equilibrium efforts.
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1 Introduction

Joint projects in teams based on voluntary contributions of efforts are vulnerable to free-riding. In formulating incentives, an organization may try to influence its members' effort decisions by designing the *structure* of contributions. In particular, the organization may be able to determine how much the members know about each other's efforts. This type of knowledge can be facilitated by an appropriate work environment, such as an open space work-floor or regular reporting of team members' actual working hours. We aim to show how *transparency* in effort contributions within a team may (or may not) help to mitigate shirking and foster cooperation. Empirical evidence certainly point to the relevance of this kind of transparency as a key determinant of productive efficiency (Teasley et al., 2002; Heywood and Jirjahn, 2004; Falk and Ichino, 2006).

When efforts are observable during a project's live phase (i.e., in a transparent environment), team members play a *repeated contribution game*. On the other hand, when efforts cannot be observed (i.e., a non-transparent environment), the project is a *simultaneous move game*. The repeated contribution game expands the players' strategy sets relative to a simultaneous move game because later period actions can be conditioned on the history. The additional strategies can create new equilibria that are not available under the simultaneous move game, or remove existing equilibria of the simultaneous move game by introducing strategies that lead to profitable deviations. By enlarging or shrinking the equilibrium set or by simply altering it, does observability of interim efforts induce more overall efforts or less efforts? Which game form is better? We will show two main results. First, if the production technology exhibits *complementarity* in team members' efforts, transparency is beneficial. On the other hand, if the technology involves *substitutability* in efforts, transparency is mostly *neutral* in its impact on individual and collective team efforts.

In teams, repeated games and dynamic public good settings, the general issue of transparency (i.e., observability/disclosure of actions) and its incentive implications have been studied by several other authors. See Che and Yoo (2001), Lockwood and Thomas (2002), Andreoni and Samuelson (2006) etc. in the context of dynamic/repeated games, Winter (2006a), and Mohnen et al. (2008) in the context of sequential and repeated contribution team projects, and Admati and Perry (1991), Marx and Matthews (2000), etc. in dynamic voluntary contribution pure public good settings.[1]

[1] There is also a growing literature on tournaments with more recent contributions by Gershkov and Perry (2009), Aoyagi (2010), etc. where the focus is on interim performance evaluations (or feedbacks) as a way of incentivizing competing players to exert greater efforts. Transparency in teams, as an issue, is very different from the feedback idea for two reasons: (i) because of the public good nature of the players' rewards, in contrast to tournaments where the reward is of the winner-take-all variety; (ii) interim efforts do not directly

Our paper is closer to the peer transparency problems of Mohnen et al. (2008) and Winter (2006a). Mohnen et al. consider a team of two workers exerting efforts over any (or both) of two rounds, with the total output equaling the sum of efforts by the two workers (i.e., the technology is one of perfect substitutes). The workers are paid identical remunerations – a fixed wage plus bonus – with the latter being a positive fraction of the team output. When each worker is averse to inequality of efforts (relative to co-worker's effort), allowing the contribution game to be transparent by making each other's first-round efforts observable improves the overall contribution and output relative to when the workers cannot observe the first-round efforts. Further, if the workers' utility functions are modified by dropping the inequity aversion component, then transparency makes no difference to the equilibrium efforts (and output). Thus in their model the benefits of transparency are realized largely due to the workers' distaste for inequity.

In the context of a team project, Winter (2006a) asks when more information among peers about each other's efforts (*IIE* or 'internal information about effort' measuring transparency) makes it easier for the principal to provide incentives so that all agents exert "effort" (called the *INI* outcome).[2] The agents can either exert effort or shirk as a one-off effort investment decision, and each agent's effort choice is made at different points of time although an agent may or may not observe the past decisions by the earlier agents. With an acyclic binary order, k, on the agents reflecting an *IIE*,[3] if any two *IIE*s, say k_1 and k_2, can be compared in the manner k_1 is "richer" than k_2,[4] then k_1 is said to be more transparent than k_2. Then, defining a project to exhibit complementarity (substitution) if an agent's effort is marginally more (less) effective in improving the project's probability of success as the set of other agents who also exert effort expands, the paper makes several interesting observations: (i) if a project satisfies complementarity, then it is less costly to induce *INI* the more transparent the *IIE*; (ii) a sequential architecture in which each agent observes the effort decision of his immediate predecessor is the most transparent *IIE*; and (iii) if the project exhibits substitution, transparency is no longer important, i.e., neutral, in inducing *INI*; etc.

We complement and extend the analysis of Mohnen et al. (2008) and Winter (2006a), by

translate into rewards whereas in tournaments rewards are a function of interim performance.

[2]Winter (2006b) analyzes the problem of incentive provision in a team where its members exert efforts sequentially towards a joint project but does not analyze the transparency issue, whereas Winter (2004) studies another team efforts problem where the agents move simultaneously (rather than sequentially). On incentive design with complementarities across tasks but in a principal-agent setting (rather than team setting), see MacDonald and Marx (2001).

[3]An ordering of peers in the form of $i_1\ k\ i_2\ k ... k\ i_r$ indicates that peer i_1 knows peer i_2's effort, i_2 knows i_3's effort, and so on.

[4]I.e., $i\ k_2\ j$ would imply $i\ k_1\ j$ but not necessarily the other way around; see the previous footnote.

studying a team setting with some plausible and important model features not considered by these authors. There is a project consisting of two tasks. Two workers work over two rounds on one task each, and in each round a worker may choose to put in zero, one or two units of effort with total efforts over two rounds not exceeding two units. The success or failure of the project materializes only at the end of the second round. The project's success probability is increasing in the total efforts invested in each task. The project exhibits complementarity (substitutability) if the incremental success probability due to additional efforts in a task is increasing (decreasing) in the efforts invested in the other task. Following successful completion of the project each worker receives a (common) reward $v > 0$ and receives zero if the project fails; rewards cannot be conditioned on efforts as the latter might not be verifiable. Two alternative work environments are considered: in a *transparent* (or *open-floor*) environment first-round efforts are publicly observed by each worker before each chooses respective second-round efforts; in a *non-transparent* (or *closed-door*) environment efforts are not observed.

Among the modeling differences, ours consider more general technologies than the one analyzed by Mohnen et al. (general complementary/substitution technologies vs. perfect substitution technology) but the agents' preferences are standard utilitarian without any concern for equity. Different from Winter (2006a), we allow for *repeated efforts* by the players and thus transparency in our setting not only allows a player to influence another player's future play through his own action today but also by conveying how he himself might again play/respond in a future round.[5] This intertemporal coordination in players' actions through public observation of all players' past actions demands more complicated strategic considerations compared to the one-off effort investment decision model of Winter. So the relationships between transparency, technologies and incentive provision need further scrutiny.

We show the following results. Under complementary technology, with *exogenous* player rewards, the transparent environment is weakly better than the non-transparent environment (Propositions 2, 3 and Table 1) in the following sense: the best Nash equilibrium efforts pair in the non-transparent environment entailing partial or full cooperation by the players can be *uniquely* implemented in subgame-perfect equilibrium in the transparent environment, by eliminating any other inferior Nash equilibrium (or equilibria); in addition, we show that when shirking (i.e., $(0, 0)$) is the unique Nash equilibrium, under certain conditions the maximal efforts equilibrium or some form of cooperation (i.e., $(2, 2)$ or $(2, 1)$) can be achieved

[5] In Winter (2006a) the structure of *IIE* rules out mutual knowledge of efforts as there is a fixed timing structure according to which the agents make their investment decisions (formally, any binary order k reflecting *IIE* is *acyclic*).

with transparency.[6] Further, when full cooperation is induced only under observability of efforts, it involves each worker putting in one unit of effort in the first round followed by another unit of effort in the second round. Thus, full cooperation might be achieved at best *gradually* – transparency allows workers to make observable partial commitments in the first round and complete the project successfully by supplying the remaining efforts in the second round (Proposition 2).[7] These results we obtain assuming effort costs are linear. For increasing marginal costs, similar results (weak-dominance and gradualism) obtain except that now the uniqueness of equilibrium involving partial or full cooperation may not be guaranteed under transparency. Based on the weak-dominance result in Proposition 3 we further show that, when the principal determines the rewards *optimally*, compared to non-transparency the principal can achieve weak or unique implementation of full cooperation at no more and possibly lower overall costs in a transparent environment (Proposition 4). Finally we show that if the technology exhibits substitutability in efforts and effort costs are linear, transparency is *neutral* in terms of equilibrium efforts induced (Propositions 5 and 6).[8]

The weak-dominance property of transparency in our setup, while similar to the main theoretical result of Mohnen et al., is due to different underlying reasons. First, as our results show, the workers' inequity aversion is not necessary for explaining why organizations may favor transparency; in our setup the dominance (of transparency) obtains mainly due to the complementary nature of the production technology.[9] This enriches the possibilities under which organizations may favor a transparent work arrangement beyond the environment studied by Mohnen et al. The contrast between complementary and substitution technologies with their differing implications (for transparency) is similar to Winter's (2006a) result. But unlike in Winter's paper the players in our setting receive identical rewards, so there is no discrimination among team members (according to one's position in the sequential efforts chain).

Another related point may be noted here. In a pure public good setting, Varian (1994) made the observation that if agents contribute sequentially, rather than simultaneously, the free-riding problem gets worse – total contribution in a sequential move game is never more

[6] In the latter case $(2,2)$ obtains along with $(0,0)$, so transparency results in a weak improvement; when $(2,1)$ obtains, it is more likely that $(0,0)$ will be eliminated, which is a strict improvement.

[7] Besides a number of papers mentioned earlier, some of the other works on gradualism are Bagnoli and Lipman (1989), Fershtman and Nitzan (1991), and Gale (2001).

[8] Elsewhere Pepito (2010) has shown that for increasing marginal costs of effort, transparency is *harmful* (i.e., induces strictly lower efforts).

[9] Knez and Simester (2001) and Gould and Winter (2009) document the positive impact of peer efforts due to complementarity between team members' roles – the former is a case study on the performance of Continental Airlines in 1995, and the latter is a panel data analysis of the performance of baseball players. Gould and Winter also show negative peer effect when the players are substitutes.

and possibly less than in a simultaneous move game.[10] As Winter (2006a) has shown, if an external authority can give discriminatory rewards to the contributors of a joint project (unlike in voluntary contribution public good models), then even though such projects exhibit public good features, sequential game performs better than a simultaneous move game when player efforts are complementary. And we show that, in joint projects, the domination over the simultaneous move format can be extended to the repeated contributions format. So unlike in the sequential move game of Varian, observability of contributions is distinctly a positive aspect for complementary production technology.

The model is presented next. In sections 3 and 4, we derive our main results on transparency. Section 5 concludes. The proofs not contained in the text appear in the Appendix. A separate Supplementary materials file contains some additional results.

2 The Model

A team of two identical risk-neutral members, henceforth players, engage in a joint project involving two tasks, with one player each separately responsible for one of the tasks. The probability of the project's success depends on the players' aggregate effort profile over a horizon of two rounds.

In each round, players simultaneously decide on how much effort to put in. Denote player i's sequence of effort choices by $\{e_{it}\}_{t=1}^{2}$, $i = 1, 2$ and his overall effort $\sum_{t=1}^{2} e_{it}$ by $e_i \in \mathbf{E_i} = \{0, 1, 2\}$. Let $p(e_i, e_j)$ be the project's success probability. The cost to player i of performing his task is c per unit of effort, $c > 0$. If the project succeeds, both players receive a common reward $v > 0$; otherwise, they receive nothing. The payoff to player i $(= 1, 2)$, given his overall effort e_i and player j's overall effort e_j $(j \neq i, j = 1, 2)$, is:

$$u_i(e_i, e_j) = p(e_i, e_j)v - ce_i. \tag{1}$$

The efforts are irreversible: shirking by player i $(e_i = 0)$ means $\{e_{it}\}_{t=1}^{2} = \{0, 0\}$, partial cooperation by player i $(e_i = 1)$ means either $\{e_{it}\}_{t=1}^{2} = \{1, 0\}$ or $\{e_{it}\}_{t=1}^{2} = \{0, 1\}$, and full cooperation by player i $(e_i = 2)$ implies any of the following: $\{e_{it}\}_{t=1}^{2} = \{2, 0\}$, $\{e_{it}\}_{t=1}^{2} = \{0, 2\}$, or $\{e_{it}\}_{t=1}^{2} = \{1, 1\}$. So a player can choose full cooperation either by making a single contribution of two units of effort early or late in the game or by contributing *gradually*, one unit of effort in each round.

[10] Bag and Roy (2008) show that if agents contribute repeatedly to a public good and have incomplete information about each other's valuations, expected total contribution may be higher relative to a simultaneous contribution game.

The success probability function $p(e_i, e_j)$ has the following properties:

A1. $p(2, 2) = 1$ and $p(0, 0) > 0$;

A2. *Symmetry*: $p(e_i, e_j) = p(e_j, e_i)$;

A3. *Monotonicity*: For given e_j, $p(e_i, e_j)$ is (strictly) increasing in e_i; and

A4. *General Complementarity*: For any $e_j \in \{0, 1\}$, $p(1, e'_j) - p(0, e'_j) > p(1, e_j) - p(0, e_j)$ and $p(2, e'_j) - p(1, e'_j) > p(2, e_j) - p(1, e_j)$, where $e'_j > e_j$.

In other words, while the project succeeds for certain if and only if both players exert the maximum amount of effort, there is, however, still some chance of success if players shirk or cooperate only partially. We have specified complementarity in a general form, requiring only that any additional effort by player i is more effective (in terms of incremental probability of success) the more cooperative player j is.[11] This formulation admits perfectly complementary technology, $p(e_i, e_j) = p(e_i)p(e_j)$, where $p(e_i)$ and $p(e_j)$ are the individual tasks' success probabilities. Also note that symmetry and monotonicity are very natural and weak assumptions; further, for complementary technology to be analyzed in section 3, we do not require any further curvature restriction on the success probability function: $p(.,.)$ can be concave or convex in each effort component (i.e., incremental probability of success is decreasing or increasing).[12]

Finally, v can be interpreted in two ways – as the players' valuation for the project, or their compensation as set by a principal, with v being common knowledge. The principal can condition the rewards only on the outcome and not directly on the efforts; in fact, the principal need not necessarily observe the efforts. Since players are identical, $v_1 = v_2 = v$. The paper's main insights do not depend on the identical players assumption. Most of the analysis will be carried out assuming v to be exogenous. Later on v will be solved to minimize the principal's costs of inducing full (or partial) cooperation.

We will consider two versions of the effort investment game. In one version, players are able to observe first-round effort choices in an interim stage before the second-round effort choices are made, while in the other version players are unable to observe actions taken in the first round. Observability of efforts (or the lack of it) may be due to the principal designing a suitable work environment or because of direct reporting. Following others studying similar

[11] The incremental gain (in terms of probability of success) from own effort is assumed to be *strictly* increasing in the other player's effort, in order to eliminate equilibrium involving asymmetric efforts under non-transparency. A similar assumption will be made for the substitution technology in section 4 for consistency in modeling.

[12] However, in section 4 with players' efforts acting as perfect substitutes, the success probability function will be strictly concave. See footnote 23.

environments, we term the observable effort case *transparent* and the one with non-observable actions *non-transparent.*

Most of our analysis in this paper will be carried out under the assumption of constant per-unit cost of effort, as specified above. Towards the end we discuss briefly how changing to increasing marginal costs (of effort) might alter the results.

3 Benefit of Transparency: Complementary Efforts

Unobservable contributions. When a player is unable to observe the amount of effort exerted by the other player before the end of the project's active phase, the overall efforts are determined by the Nash equilibrium (or *NE*) of the following simultaneous move game:

		Player 2: 0	Player 2: 1	Player 2: 2
Player 1	0	$p(0,0)v, p(0,0)v$	$p(0,1)v, p(0,1)v - c$	$p(0,2)v, p(0,2)v - 2c$
	1	$p(1,0)v - c, p(1,0)v$	$p(1,1)v - c, p(1,1)v - c$	$p(1,2)v - c, p(1,2)v - 2c$
	2	$p(2,0)v - 2c, p(2,0)v$	$p(2,1)v - 2c, p(2,1)v - c$	$v - 2c, v - 2c$

Figure 1: Simultaneous move game $\mathcal{G}$

Denote this one-shot game by $\mathcal{G}$, any strategy profile (e_1, e_2) of $\mathcal{G}$ by $\mathbf{e}_{\mathcal{G}}$, and a pure-strategy *NE*, (e_1^*, e_2^*) of $\mathcal{G}$, by $\mathbf{e}^*_{\mathcal{G}}$.

Lemma 1. *Suppose success probability $p(.,.)$ satisfies **A1-A4**. Then the game $\mathcal{G}$ has no asymmetric pure strategy Nash equilibrium.*

In view of Lemma 1, in the one-shot game we focus on the symmetric pure strategy Nash equilibrium (or equilibria):

Proposition 1 (One-shot Nash equilibrium). *In the one-shot game $\mathcal{G}$ (i.e., with unobservable contributions), the pure strategy Nash equilibrium (or equilibria) can be characterized as follows:*

Equilibrium $(e_1^*, e_2^*) = (0,0)$ obtains if and only if

$$c \geq \max\{(p(1,0) - p(0,0))v, [(p(2,0) - p(0,0))v]/2\};$$

Equilibrium $(e_1^*, e_2^*) = (1,1)$ *obtains if and only if*

$$(p(2,1) - p(1,1))v \le c \le (p(1,1) - p(0,1))v;$$

Equilibrium $(e_1^*, e_2^*) = (2,2)$ *obtains if and only if*

$$c \le \min\{(1 - p(1,2))v, [(1 - p(0,2))v]/2\}.$$

Note that the above is a characterization result. In the Appendix we show that *there always exists a pure strategy Nash equilibrium.*

Observable contributions. The effort investment game proceeds as follows:
Round 1: Players simultaneously choose their efforts $e_{i1} \in \{0,1,2\}$, $i = 1,2$.
Interim period: Players' first-round decisions are revealed. Denote the set of possible observed effort levels $\mathbf{e_1} = (e_{11}, e_{21})$ by $\hat{\mathbf{E}}_\mathbf{1}$. Clearly,

$$\hat{\mathbf{E}}_\mathbf{1} = \{(0,0),(0,1),(0,2),(1,0),(1,1),(1,2),(2,0),(2,1),(2,2)\}.$$

Round 2: Players make their effort decisions simultaneously, having observed each other's first-round effort choices. Denote player i's set of admissible second-round effort choices by $\hat{\mathbf{E}}_\mathbf{i2}$. Since overall effort e_i cannot exceed 2,

$$\hat{\mathbf{E}}_\mathbf{i2} = \begin{cases} \{0{,}1{,}2\} & \text{if } e_{i1} = 0; \\ \{0{,}1\} & \text{if } e_{i1} = 1; \\ \{0\} & \text{if } e_{i1} = 2. \end{cases} \tag{2}$$

At the end of Round 2, the project concludes. Both players receive reward v if the project is successful. If the project fails, they both receive 0. ||

With observability, the joint project induces a repeated contribution game in which players move simultaneously in each round. The extensive form appears in Fig. 2. The payoffs in each continuation game are in terms of the second-round *incremental* gains relative to those yielded by the pair of observed effort levels $\mathbf{e_1}$ that gives rise to the continuation game. For example, suppose that both players choose one unit of effort in the first round. This restricts the set of admissible actions for players 1 and 2 to $\hat{\mathbf{E}}_\mathbf{12} = \hat{\mathbf{E}}_\mathbf{22} = \{0,1\}$, resulting in a continuation game with the strategy space $\mathcal{S}_2 = \{0,1\} \times \{0,1\}$. (In general, the strategy space of any continuation game is $\mathcal{S}_2 = \hat{\mathbf{E}}_\mathbf{12} \times \hat{\mathbf{E}}_\mathbf{22}$.) Denote player i's *interim* payoff, i.e., payoff

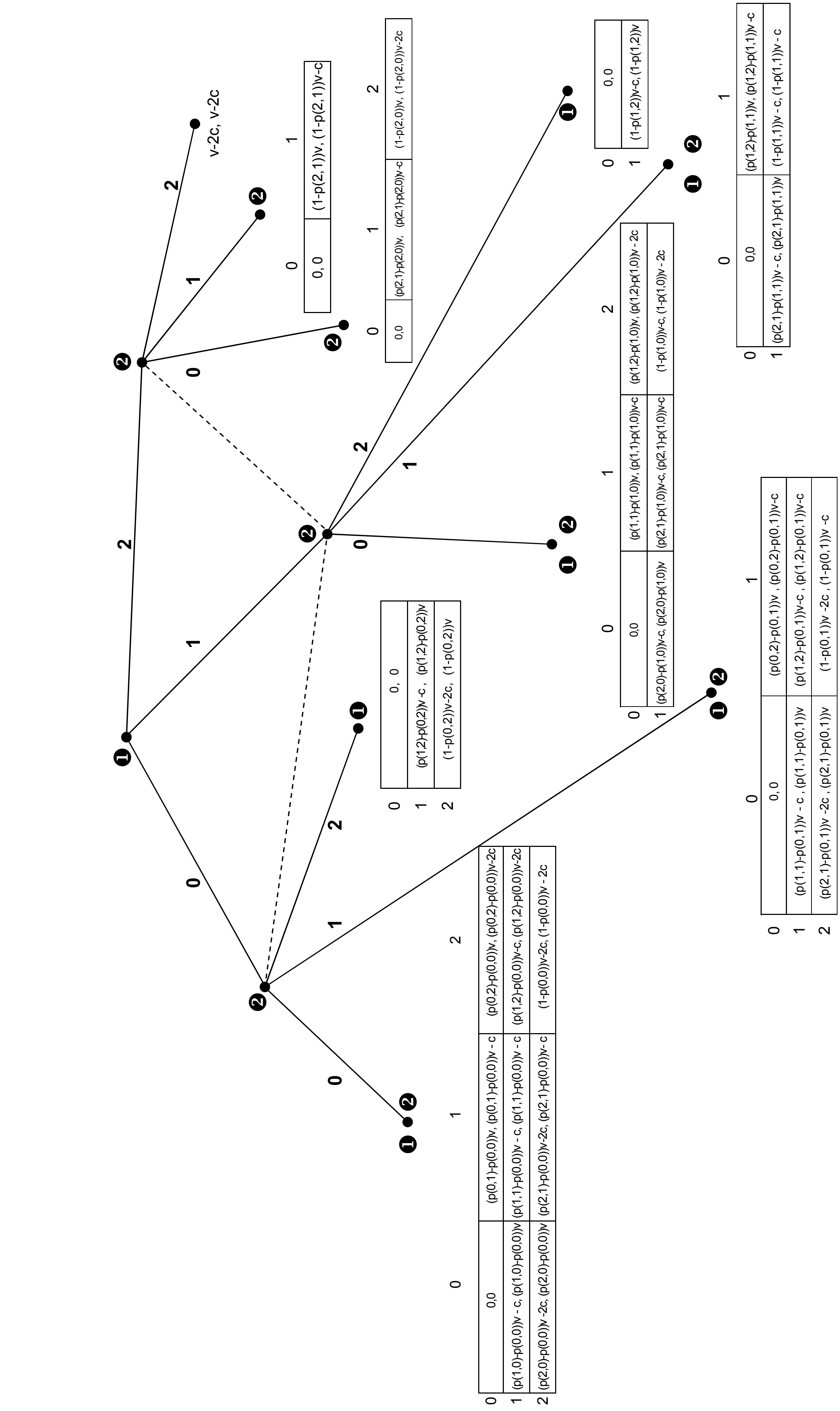

Figure 2: Extensive-form game $\widehat{\mathcal{G}}$

generated by observed effort levels $\mathbf{e_1} = (e_{11}, e_{21})$, by $\hat{u}_{i1}(e_{i1}, e_{j1})$,[13] and incremental gains following second-round actions (e_{i2}, e_{j2}) by $\hat{u}_{i2}(e_{i2}, e_{j2}|\mathbf{e_1}) = u_i(e_{i1}+e_{i2}, e_{j1}+e_{j2}) - \hat{u}_{i1}(e_{i1}, e_{j1})$.

Therefore, player i's payoffs in the continuation game following $\mathbf{e_1} = (1,1)$ are

$$\hat{u}_{i2}(e_{i2}, e_{j2}|(1,1)) = \begin{cases} 0 & \text{if } e_{i2} = 0, e_{j2} = 0; \\ (p(1,2) - p(1,1))v & \text{if } e_{i2} = 0, e_{j2} = 1; \\ (p(2,1) - p(1,1))v - c & \text{if } e_{i2} = 1, e_{j2} = 0; \\ (1 - p(1,1))v - c & \text{if } e_{i2} = 1, e_{j2} = 1. \end{cases}$$

Payoffs for the other continuation games are computed in the same way.

One specific continuation game is worth noting here: the game following $(0,0)$ efforts in the first round. This continuation game is same as the one-shot game $\mathcal{G}$ except that all the payoffs are subtracted by $p(0,0)v$. For later use, we will describe these two games as *identical*, given that the players' strategic decisions will be the same.

Denote the extensive-form game by $\widehat{\mathcal{G}}$, and any subgame-perfect equilibrium (or *SPE*) strategy $(e^*_{11}, e^*_{21}; e^*_{12}(e^*_{11}, e^*_{21}), e^*_{22}(e^*_{11}, e^*_{21}))$ of this game by $\mathbf{e}^*_{\widehat{\mathcal{G}}}$.[14]

Given the extensive-form representation in Fig. 2, we can evaluate how the overall equilibrium efforts change when efforts are made transparent. In particular, take an equilibrium (or equilibria) that arises in the one-shot game; from Proposition 1 we see that this equilibrium (or equilibria) results if and only if certain conditions hold. Taking these conditions as given, we then examine the setting with repeated, observable contributions, and determine which overall efforts result (or do not result) in an *SPE* under these conditions.

Below we start with some preliminary results hoping to demonstrate, at the end, how transparency can sometimes be critical to achieving full cooperation and ensure the project's success.

Lemma 2. *Assume* ***A1-A4****.*

(i) *If, without observability, full cooperation is not an equilibrium, then the only way full cooperation can arise with observability is through gradual cooperation, i.e.,* $(1,1;1,1)$.

(ii) *If, without observability, partial cooperation is an equilibrium while full cooperation is not, then full cooperation cannot arise with observability.*

[13] Interim payoffs are calculated assuming as if the players will exert no further effort in Round 2.

[14] To be precise, equilibrium second-round strategies should be more general functions of any first-round effort decisions and not just of (e^*_{11}, e^*_{21}). Our equilibrium analysis uses the formal definition of *SPE*.

Lemma 3. *Assume **A1-A4**. Suppose, without observability, shirking is the unique equilibrium. Then full cooperation may arise with observability and can only be through gradual cooperation. A set of sufficient conditions that guarantee full cooperation, and which can be consistent with shirking as the unique equilibrium without observability, is as follows*:

$$\left.\begin{array}{rr} p(0,2)v > v-2c \geq p(1,2)v-c & \\ p(0,1)v-c & > p(0,2)v-2c \\ \textit{and} \qquad v-2c & \geq p(0,1)v. \end{array}\right\} \tag{3}$$

Moreover, if shirking is the unique equilibrium without observability and (3) *hold, shirking remains an equilibrium with observability.*

Fig. 3 illustrates Lemma 3 for the perfectly complementary technology, $p(e_1, e_2) = p(e_1)p(e_2)$, where for $i = 1, 2$,

$$p(e_i) = \begin{cases} \alpha & \text{if } e_i = 0; \\ \beta & \text{if } e_i = 1; \\ 1 & \text{if } e_i = 2. \end{cases} \tag{4}$$

Given this specification, $p(0,2) = \alpha$, $p(1,2) = \beta$, $p(0,1) = \alpha\beta$, and $p(1,1) = \beta^2$. The figure plots the payoffs against β and identifies the values of β such that the payoffs satisfy conditions (3) for a profile of the remaining parameters, $(\alpha = \frac{1}{5}, v = 2.4, c = 1)$.[15] Further, $\mathbf{e}^*_{\mathcal{G}} = (0,0)$ since for all $\beta \in (0,1)$, $\alpha^2 v > 0$, $\alpha\beta v - c < 0$, and $\alpha v - 2c < 0$ (i.e., $p(0,0)v > 0$, $p(1,0)v - c < 0$, and $p(2,0)v - 2c < 0$). To verify uniqueness of $\mathbf{e}^*_{\mathcal{G}} = (0,0)$, first note that $(1,1)$ is not an *NE* since $p(0,1)v > p(1,1)v - c$ (because $\alpha v > \beta^2 v - c$), and $(2,2)$ is not an *NE* because $p(0,2)v > v - 2c$ (follows from (3)), and there is no other pure strategy equilibrium (by Lemma 1).

Let us now denote the value of β at which $v - 2c = \beta v - c$ by β_1. In this example, $\beta_1 = \frac{7}{12}$, and we see that, for the given parameter values of (α, v, c), all the conditions (i.e., (3) as well as uniqueness of $\mathbf{e}^*_{\mathcal{G}} = (0,0)$) are simultaneously satisfied for $\beta \in \left(\frac{1}{5}, \frac{7}{12}\right]$.

It is clear from the first and the third conditions in (3) above that $p(0,2)v > v - 2c > p(0,0)v$. In other words, full cooperation Pareto-dominates shirking, though the latter prevails when there is no way to observe the ongoing contributions. There is mutual interest in cooperating, but it is not in any player's *individual* interest to cooperate. In this setting, making efforts observable encourages full cooperation. However, since efforts are irreversible, sinking two units of effort in the first round is risky, as the other player can exert zero effort

[15]The figure has been generated in Mathematica.

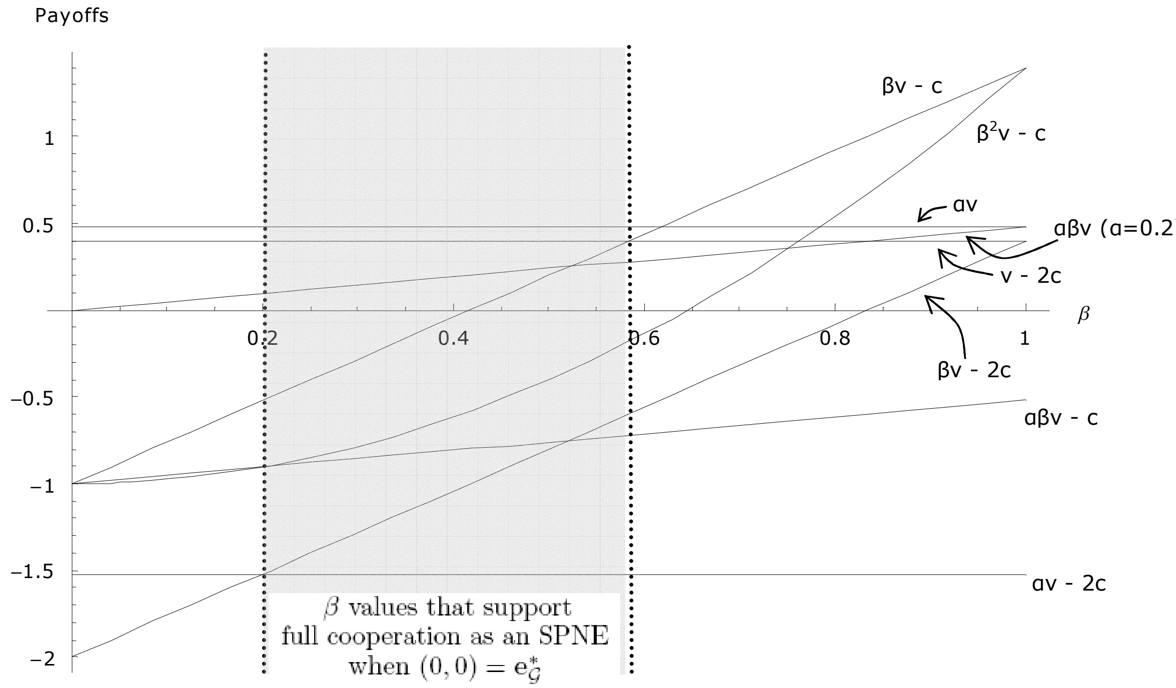

Figure 3: $(0,0)$ is the unique $\mathbf{e}^*_{\mathcal{G}}$ and $(2,2)$ is supported in subgame-perfect equilibrium, for $p(e_1, e_2) = p(e_1)p(e_2)$ with $p(0) = \alpha,\ p(1) = \beta$, and $p(2) = 1$.

in both rounds, get $p(0,0)v > v-2c$, and go unpunished. (The only way to punish him would be for the cooperating player to move back to shirking, which is not possible.) Therefore, while transparency induces cooperation, it can only do so using partial commitments, i.e., gradually. The result is similar to the gradualism result of Lockwood and Thomas (2002).

Lemma 2 and Lemma 3, together, yield the following behavioral prediction for one type of full cooperation equilibrium under observability:

Proposition 2 (Gradualism). *Suppose a joint project involves two tasks satisfying a general form of complementarity as defined in* ***A1-A4*** *in section 2.*

If full cooperation does not arise when transparency is lacking, then transparency can achieve full cooperation only through ***gradual*** *reciprocity. Moreover, in this case full cooperation obtains under transparency only if under non-transparency partial cooperation fails to realize* (*along with full cooperation not being an* NE), *and if conditions* (3) *hold.*

Thus gradualism is one way to make transparency make a difference when, without it, only the worst (i.e., shirking) would have realized. This may lead to a distinct cost advantage for a principal who wants to design reward incentives to uniquely implement full cooperation, as we will see in Proposition 4. Proposition 2 also prompts the question whether a similar domination could be achieved but without realizing full cooperation. Later in Table 1 we will verify that indeed this is possible, sometimes by achieving overall equilibrium efforts of $(2,1)$ in the transparent environment while $(0,0)$ is the only equilibrium under non-transparency.

In Proposition 2 we assumed full cooperation not being an equilibrium under non-transparency. It is possible that sometimes shirking or partial cooperation is not an equilibrium under non-transparency. Then, a similar outcome also fails to realize under transparency:

Lemma 4. *(i) If $(0,0) \neq \mathbf{e}^*_{\mathcal{G}}$, then overall efforts of $(0,0)$ cannot arise in an* SPE *of the extensive-form game $\widehat{\mathcal{G}}$.*

(ii) If $(1,1) \neq \mathbf{e}^*_{\mathcal{G}}$, then overall efforts of $(1,1)$ cannot arise in an SPE *of the extensive-form game $\widehat{\mathcal{G}}$.*

Finally, full cooperation being an equilibrium under non-transparency has the following implications for the transparency regime:

Lemma 5. *Suppose full cooperation is an* NE *in the one-shot game. Then:*

(i) Full cooperation obtains in an SPE *in the transparent environment. Specifically, all strategy profiles in the extensive-form game $\widehat{\mathcal{G}}$ that correspond to full cooperation are* SPE.

(ii) Partial cooperation, i.e. $(1,1)$, cannot arise in an SPE *of the extensive-form game $\widehat{\mathcal{G}}$.*

While Lemmas 4 and 5 (and other lemmas to be reported) may not offer a very clean picture of their standalone economic implications/motivations, these should be seen as necessary steps to develop our main results on the performance of transparency vis-à-vis non-transparency for implementation of better effort profiles and the related optimal incentive costs.

We begin with the claim that by allowing players to observe each other's efforts during the project's active phase, the principal would do no worse and possibly do better. For example, if full cooperation is an equilibrium in the one-shot game but not necessarily unique, then full cooperation must be the only equilibrium in the extensive-form game.

Define the set of outcomes ***inferior*** to $\mathbf{e}_{\mathcal{G}} = (e_1, e_2)$ by

$$\mathcal{I}_{\mathbf{e}_{\mathcal{G}}} = \{(\tilde{e}_1, \tilde{e}_2) \mid \tilde{e}_1 < e_1 \text{ or } \tilde{e}_2 < e_2\}\,.$$

Note that by this definition, $(2, 0)$ and $(0, 2)$ are inferior to the effort pair $(1, 1)$.

We now look at two cases: when partial cooperation is a one-shot equilibrium, and when full cooperation is a one-shot equilibrium.

Lemma 6. *Suppose that* $\mathbf{e}^*_{\mathcal{G}} = (1, 1)$ (*not necessarily unique*). *Then under transparency overall efforts that entail shirking by any player cannot arise in an* SPE.

Lemma 7. *Suppose that* $\mathbf{e}^*_{\mathcal{G}} = (2, 2)$ (*not necessarily unique*). *Then under transparency overall efforts where any player exerts less than two units of effort cannot arise in an* SPE.

Thus, making efforts observable eliminates all outcomes inferior to the 'best' one-shot equilibrium possible where 'best' is interpreted in terms of total team efforts. But still elimination does not establish superiority of transparency. We must show that the best one-shot equilibrium, or perhaps a better effort profile, can be supported as a pure-strategy *SPE* of the extensive-form game under transparency. The following proposition achieves this objective.

Proposition 3 (Beneficial Transparency). *Suppose a joint project involves two complementary tasks as defined in* ***A1-A4****. Then transparency dominates over non-transparency in the following sense:*

Equilibrium (*or equilibria*) *in the non-transparent environment entailing partial or full cooperation by both players is weakly improved upon in a* ***unique equilibrium*** *in the transparent environment by retaining the* ***best*** *equilibrium and at the same time by eliminating all* ***inferior*** *effort profiles* (*i.e., ones in which at least one player exerts lower effort*).

Moreover, under appropriate conditions, when shirking (*i.e.,* $(0, 0)$) *is a unique equilibrium under non-transparency, with transparency it is possible to achieve full cooperation by both players.*

Thus, *when there are multiple one-shot equilibria*, the weak dominance of transparency is achieved through (i) preservation of the best one-shot equilibrium and (ii) the elimination of all potential inferior outcomes (including inferior one-shot equilibria). When the one-shot equilibrium is *unique* and *involves cooperation* (partial or full), overall equilibrium efforts under transparency coincide with the efforts under non-transparency. Finally, *when shirking is the unique one-shot equilibrium*, transparency improves upon non-transparency by making full cooperation possible (under certain conditions) through partial commitments.

As already mentioned in the Introduction, relative to non-transparency the expanded strategies under transparency has the potential to result in additional equilibria and equally it could eliminate some one-shot equilibrium. Proposition 3 confirms both these predictions to be true but what is interesting is the uniform impact of the two effects to make transparency superior in terms of effort incentives (not only inferior outcomes are eliminated, strictly superior outcome may emerge). For an intuition note that with *complementary* efforts whenever there are multiple equilibria in the one-shot game, the equilibria can be strictly Pareto-ranked from the players' point of view with the equilibrium involving highest symmetric efforts dominating the lower symmetric efforts equilibrium (or equilibria). This allows a player to be unilaterally aggressive to play his "best" one-shot equilibrium effort in the first round under observability. The unique best response of the other player, then, is to choose aggregate efforts over two rounds to correspond to his best one-shot *NE*. Thus, any player, through an aggressive play, can eliminate all inferior effort pairs (not just inferior *NE*) from being supported in *SPE*. By a similar logic, due to complementarity observability (of efforts) can generate strictly higher efforts than is possible under non-observability. Later on we will see that if, instead, the efforts are substitutes, transparency is either neutral or sometimes may even be harmful.

Another aspect worth emphasizing is that, while equilibrium selection using the criterion of Pareto domination may seem a valid reason not to worry about the inferior equilibria (in the case of multiple equilibria under non-transparency), the problem of miscoordination in team settings is a very reasonable concern which gets worse as the team size becomes large. And with the introduction of slight risk aversion on the part of the players (in our treatment players are risk neutral in monetary rewards), non-transparency is likely to tilt the balance towards lower efforts equilibria. Transparency fully resolves this coordination problem by eliminating the inferior equilibria.[16]

In Table 1 we provide (see detailed formal derivations in the Appendix), for a complete breakdown of the cost parameter c in an ascending order (for any given value of v and the project technology $p(e_1, e_2)$), the list of various equilibria under the two arrangements, non-transparency and transparency.[17] It demonstrates cleanly the value of mutual observability of team members' interim efforts.

The case of increasing marginal costs. So far our analysis has been based on

[16]For example, in the case where $\mathbf{e}^*_{\mathcal{G}} = (0, 0)$, $\mathbf{e}^*_{\mathcal{G}} = (1, 1)$, and $\mathbf{e}^*_{\mathcal{G}} \neq (2, 2)$, transparency allows any player to confidently sink in one unit of effort early on regardless of whether the other player chooses zero effort or one, because when the other player observes his move it will be in his best interest to match it (if he has not already done so). Since this decision by any player will always be matched by the other player, a situation where one player partially cooperates and the other player shirks cannot arise with observability.

[17]In Table 1 and later on in Table 2 and for the supporting derivations for Table 1 in the Appendix, we will slightly abuse the notation $\mathbf{e}^*_{\hat{\mathcal{G}}}$ to refer to overall efforts pair in the two-round game that can be supported in *SPE*.

Table 1: **Improved outcome possibilities with transparency**

	Parameter Configuration		$\mathbf{e}^*_{\mathcal{G}}$	$\mathbf{e}^*_{\hat{\mathcal{G}}}$
	Main condition	**Additional conditions**		
(a)	$c < (p(2,0) - p(1,0))v$	$c \leq (p(1,0) - p(0,0))v$	$(2,2)$	$(2,2)$
(b)		$(p(1,0) - p(0,0))v < c$ and $c < \frac{(p(2,0)-p(0,0))v}{2}$	$(2,2)$	$(2,2)$
(c)		$(p(1,0) - p(0,0))v < c$ and $\frac{(p(2,0)-p(0,0))v}{2} \leq c \leq \frac{(1-p(0,2))v}{2}$	$(2,2)$ and $(0,0)$	$(2,2)$
(d)		$(p(1,0) - p(0,0))v < c$ and $\frac{(1-p(0,2))v}{2} < c$	$(0,0)$	$(0,0)$
(e)	$(p(2,0) - p(1,0))v \leq c < (p(2,1) - p(1,1))v$	$c < (p(1,0) - p(0,0))v$	$(2,2)$	$(2,2)$
(f)		$c = (p(1,0) - p(0,0))v$	$(2,2)$ and $(0,0)$	$(2,2)$
(g)		$(p(1,0) - p(0,0))v < c \leq \frac{(1-p(0,2))v}{2}$	$(2,2)$ and $(0,0)$	$(2,2)$
(h)		$(p(1,0) - p(0,0))v < c$ and $\frac{(1-p(0,2))v}{2} < c \leq \frac{(1-p(0,1))v}{2}$	$(0,0)$	$(2,2)$ and $(0,0)$
(i)		$(p(1,0) - p(0,0))v < c$ and $\frac{(1-p(0,1))v}{2} < c$	$(0,0)$	$(0,0)$

Table 1: **Improved outcome possibilities with transparency, contd.**

Parameter Configuration			$\mathbf{e}^*_{\mathcal{G}}$	$\mathbf{e}^*_{\hat{\mathcal{G}}}$
	Main condition	**Additional conditions**		
(j)	$(p(2,1)-p(1,1))v \leq c \leq (1-p(1,2))v$	$c \leq \frac{1-p(0,2)}{2}v$ and $c < (p(1,0)-p(0,0))v$	$(2,2)$ and $(1,1)$	$(2,2)$
(k)		$c \leq \frac{1-p(0,2)}{2}v$ and $(p(1,0)-p(0,0))v \leq c \leq (p(1,1)-p(0,1))v$	$(2,2)$, $(1,1)$ and $(0,0)$	$(2,2)$
(l)		$c \leq \frac{(1-p(0,2))v}{2}$ and $(p(1,1)-p(0,1))v < c$	$(2,2)$ and $(0,0)$	$(2,2)$
(m)	main cond. $\Rightarrow\Leftarrow$ add. conds	$\frac{(1-p(0,2))v}{2} < c \leq \frac{(1-p(0,1))v}{2}$ and $c \leq (p(1,0)-p(0,0))v$	–	–
(n)		$\frac{(1-p(0,2))v}{2} < c \leq \frac{(1-p(0,1))v}{2}$ and $(p(1,0)-p(0,0))v < c \leq (p(1,1)-p(0,1))v$	$(1,1)$ and $(0,0)$	$(1,1)$
(o)		$\frac{(1-p(0,2))v}{2} < c \leq \frac{(1-p(0,1))v}{2}$ and $(p(1,1)-p(0,1))v < c$	$(0,0)$	$(2,2)$ and $(0,0)$
(p)		$\frac{(1-p(0,1))v}{2} < c$ and $c \leq (p(1,1)-p(0,1))v$	$(1,1)$ and $(0,0)$	$(1,1)$
(q)		$\frac{(1-p(0,1))v}{2} < c$ and $(p(1,1)-p(0,1))v < c$	$(0,0)$	$(0,0)$

Table 1: **Improved outcome possibilities with transparency, contd.**

Parameter Configuration			$\mathbf{e}^*_{\mathcal{G}}$	$\mathbf{e}^*_{\widehat{\mathcal{G}}}$
	Main condition	**Additional conditions**		
(r)	$(1-p(1,2))v < c$	$c < (p(1,0)-p(0,0))v$	(1,1)	(1,1)
(s)		$(p(1,0)-p(0,0))v \leq c \leq (p(1,1)-p(0,1))v$	$(1,1)$ and $(0,0)$	$(1,1)$
(t)		$(p(1,1)-p(0,1))v < c \leq (p(1,2)-p(0,2))v$ and $\frac{p(1,2)-p(0,0)}{2}v < c$	$(0,0)$	$(0,0)$
(u)		$(p(1,1)-p(0,1))v < c \leq (p(1,2)-p(0,2))v$ and $\frac{p(1,2)-p(0,0)}{2}v = c$	$(0,0)$	$(0,0)$ and $(2,1)$
(v)		$(p(1,1)-p(0,1))v < c \leq (p(1,2)-p(0,2))v$ and $c < \frac{p(1,2)-p(0,0)}{2}v$	$(0,0)$	$(2,1)$
(w)		$(p(1,2)-p(0,2))v < c$	$(0,0)$	(0,0)

Table 2: **Improved outcome possibilities with transparency: the case of rewards**

	Parameter Configuration		$\mathbf{e}^*_{\mathcal{G}}$	$\mathbf{e}^*_{\widehat{\mathcal{G}}}$
	Main condition	**Additional conditions**		
(a)	$\frac{c}{p(2,0)-p(1,0)} < v$	$\frac{c}{p(1,0)-p(0,0)} \leq v$	$(2,2)$	$(2,2)$
(b)		$\frac{2c}{p(2,0)-p(0,0)} < v < \frac{c}{p(1,0)-p(0,0)}$	$(2,2)$	$(2,2)$
(c)		$v < \frac{c}{p(1,0)-p(0,0)}$ and $\frac{2c}{1-p(0,2)} \leq v \leq \frac{2c}{p(2,0)-p(0,0)}$	$(2,2)$ and $(0,0)$	$(2,2)$
(d)		$v < \frac{c}{p(1,0)-p(0,0)}$ and $v < \frac{2c}{1-p(0,2)}$	$(0,0)$	$(0,0)$
(e)	$\frac{c}{p(2,1)-p(1,1)} < v \leq \frac{c}{p(2,0)-p(1,0)}$	$\frac{c}{p(1,0)-p(0,0)} < v$	$(2,2)$	$(2,2)$
(f)		$v = \frac{c}{p(1,0)-p(0,0)}$	$(2,2)$ and $(0,0)$	$(2,2)$
(g)		$\frac{2c}{1-p(0,2)} \leq v < \frac{c}{p(1,0)-p(0,0)}$	$(2,2)$ and $(0,0)$	$(2,2)$
(h)		$v < \frac{c}{p(1,0)-p(0,0)}$ and $\frac{2c}{1-p(0,1)} \leq v < \frac{2c}{1-p(0,2)}$	$(0,0)$	$(2,2)$ and $(0,0)$
(i)		$v < \frac{c}{p(1,0)-p(0,0)}$ and $v < \frac{2c}{1-p(0,1)}$	$(0,0)$	$(0,0)$

Table 2: **Improved outcome possibilities with transparency: the case of rewards, contd.**

Parameter Configuration			$\mathbf{e}^*_{\mathcal{G}}$	$\mathbf{e}^*_{\widehat{\mathcal{G}}}$
	Main condition	**Additional conditions**		
(j)	$\frac{c}{1-p(1,2)} \leq v \leq \frac{c}{p(2,1)-p(1,1)}$	$\frac{2c}{1-p(0,2)} \leq v$ and $\frac{c}{p(1,0)-p(0,0)} < v$	$(2,2)$ and $(1,1)$	$(2,2)$
(k)		$\frac{2c}{1-p(0,2)} \leq v$ and $\frac{c}{p(1,1)-p(0,1)} \leq v \leq \frac{c}{p(1,0)-p(0,0)}$	$(2,2)$, $(1,1)$ and $(0,0)$	$(2,2)$
(l)		$\frac{2c}{1-p(0,2)} \leq v$ and $v < \frac{c}{p(1,1)-p(0,1)}$	$(2,2)$ and $(0,0)$	$(2,2)$
(m)		$\frac{2c}{1-p(0,1)} \leq v < \frac{2c}{1-p(0,2)}$ and $\frac{c}{p(1,0)-p(0,0)} \leq v$	–	–
(n)		$\frac{2c}{1-p(0,1)} \leq v < \frac{2c}{1-p(0,2)}$ and $\frac{c}{p(1,1)-p(0,1)} \leq v < \frac{c}{p(1,0)-p(0,0)}$	$(1,1)$ and $(0,0)$	$(1,1)$
(o)		$\frac{2c}{1-p(0,1)} \leq v < \frac{2c}{1-p(0,2)}$ and $v < \frac{c}{p(1,1)-p(0,1)}$	$(0,0)$	$(2,2)$ and $(0,0)$
(p)		$v < \frac{2c}{1-p(0,1)}$ and $\frac{c}{p(1,1)-p(0,1)} \leq v$	$(1,1)$ and $(0,0)$	$(1,1)$
(q)		$v < \frac{2c}{1-p(0,1)}$ and $v < \frac{c}{p(1,1)-p(0,1)}$	$(0,0)$	$(0,0)$

Table 2: **Improved outcome possibilities with transparency: the case of rewards, contd.**

(r)	$v < \frac{c}{1-p(1,2)}$	$\frac{c}{p(1,0)-p(0,0)} < v$	$(1,1)$	$(1,1)$
(s)		$\frac{c}{p(1,1)-p(0,1)} \leq v \leq \frac{c}{p(1,0)-p(0,0)}$	$(1,1)$ and $(0,0)$	$(1,1)$
(t)		$\frac{c}{p(1,2)-p(0,2)} \leq v < \frac{c}{p(1,1)-p(0,1)}$ and $v < \frac{2c}{p(1,2)-p(0,0)}$	$(0,0)$	$(0,0)$
(u)		$\frac{c}{p(1,2)-p(0,2)} \leq v < \frac{c}{p(1,1)-p(0,1)}$ and $v = \frac{2c}{p(1,2)-p(0,0)}$	$(0,0)$	$(0,0)$ and $(2,1)$
(v)		$\frac{c}{p(1,2)-p(0,2)} \leq v < \frac{c}{p(1,1)-p(0,1)}$ and $\frac{2c}{p(1,2)-p(0,0)} < v$	$(0,0)$	$(2,1)$
(w)		$v < \frac{c}{p(1,2)-p(0,2)}$	$(0,0)$	$(0,0)$

the assumption of linear effort costs. We now briefly discuss possible modification to the main result if effort costs are convex: the cost of exerting the second unit of effort within the same round is $c + \delta$, $\delta > 0$, i.e., the marginal cost of effort is increasing within a round.

With the change in effort costs, our previous intuition in favor of transparency gets somewhat weakened. After all, due to increasing marginal costs players are strongly discouraged against sinking in two units of effort within a single round. This gives fewer options to contribute two units of effort in both the transparent and the non-transparent environments, as the players should like to space out their effort contributions over the two rounds. In the non-transparent environment this lack of options is of no real consequence, because the players can shift their contributions across the two rounds privately. But in the transparent environment, this creates a perverse incentive among the players to withhold individual contributions in the first round, thereby credibly conveying to the other player that pushing up contribution in a later round would be unlikely (this effect is the principal reason why transparency is potentially harmful in the substitution technology case). So players may well end up in a bad coordination under transparency with reduced first-round efforts and lower aggregate efforts. We show that, in our three efforts setup, such harmful effect never arises and transparency continues to be (weakly) better than non-transparency. The main difference, compared to the linear effort costs case, is that we can no longer guarantee the uniqueness of the overall equilibrium efforts in the extensive-form game. The formal analysis is developed in a separate Supplementary materials file.

Optimal rewards. So far we did not consider the question of optimal incentives: what should be the minimal rewards to induce a particular pair of aggregate efforts, with and without transparency? Table 1 provides an exhaustive summary of the various equilibria possible as the effort cost parameter, c, is varied. We then construct Table 2 by rearranging the same information given in Table 1 but now in terms of the ranges of v, in decreasing order of v. It should be clear from Table 2 how to determine the optimal v: for any given effort implementation target, identification of the required minimal v would minimize the implementation costs. Below we demonstrate the procedures for unique implementation of full cooperation; similar methods apply for weak implementation of full cooperation.

Suppose the objective is to uniquely implement full cooperation under non-transparency. From Table 2, we know that the 'optimal' reward, call it v^u_{NT}, is either in (a), (b), or (e) (by 'optimal' reward we mean the lower bound (i.e., the *infimum*) of the reward, v, inducing any target efforts pair).

Let $\mathfrak{c}$ be a typical condition enumerated in the first column in Table 2, and denote the lower bound of any set of v values defined by $\mathfrak{c}$, when non-empty, by $m_{\mathfrak{c}}$. Clearly, $m_{\mathfrak{c}}$ is equal to either the lower bound of v satisfying the main condition or the lower bound of v

satisfying the additional condition(s) (under $\mathfrak{c}$), whichever is greater.

Suppose that the set of v-values defined by (b) and (e) are empty, i.e., respectively **(i)** $\frac{c}{p(1,0)-p(0,0)} \leq \frac{c}{p(2,0)-p(1,0)}$ and $\frac{c}{p(2,0)-p(1,0)} \leq \frac{c}{p(1,0)-p(0,0)}$, or **(ii)** $\frac{c}{p(1,0)-p(0,0)} \leq \frac{2c}{p(2,0)-p(0,0)}$ and $\frac{c}{p(2,0)-p(1,0)} \leq \frac{c}{p(1,0)-p(0,0)}$.

Suppose **(i)** holds. Then it must be that $\frac{c}{p(2,0)-p(1,0)} = \frac{c}{p(1,0)-p(0,0)}$, and $v^u_{NT} = m_{(a)} = \frac{c}{p(2,0)-p(1,0)}$. Now under transparency, aside from $v^u_{NT} = \frac{c}{p(2,0)-p(1,0)}$, any v that satisfies any of the conditions in $\Lambda_1 = \{(f),(g),(k),(l)\}$ (i.e., the union of v-values defined by each of these configurations) would uniquely implement full cooperation.[18]

If the set defined by (f) is non-empty (in which case it is single-valued), then the set defined by (g) is also non-empty; moreover, any v satisfying (g) will be strictly less than the v satisfying (f). Therefore, for unique implementation under transparency, we can restrict to the set of v-values defined by $\Lambda_1 \setminus \{(f)\}$.

Now note that $m_\mathfrak{c}$, when it is well-defined for any $\mathfrak{c} \in \Lambda_1 \setminus \{(f)\}$, will be strictly less than $\frac{c}{p(2,0)-p(1,0)}$.[19] Then it must be that the least-cost reward that uniquely implements full cooperation under transparency, call it v^u_T, is equal to the $\min\{m_\mathfrak{c}\}$ with $\mathfrak{c}$ being the elements from $\Lambda_1 \setminus \{(f)\}$ for which $m_\mathfrak{c}$'s are well-defined. By construction $v^u_T = \min\{m_\mathfrak{c}\} < v^u_{NT}$, whenever $m_\mathfrak{c}$ is well-defined for at least one $\mathfrak{c} \in \Lambda_1 \setminus \{(f)\}$; otherwise, $v^u_T = v^u_{NT}$.

However, suppose **(ii)** holds. Then it must be that $\frac{c}{p(2,0)-p(1,0)} < \frac{c}{p(1,0)-p(0,0)}$ (the equality case was considered in **(i)**), and $v^u_{NT} = m_{(a)} = \frac{c}{p(1,0)-p(0,0)}$. Under transparency, aside from $v^u_{NT} = \frac{c}{p(1,0)-p(0,0)}$, any v that satisfies any of the conditions in $\Lambda_2 = \{(c),(g),(k),(l)\}$ would uniquely implement full cooperation.[20] Therefore, by construction $v^u_T = \min\{m_\mathfrak{c}\} < v^u_{NT}$, whenever $m_\mathfrak{c}$ is well-defined for at least one $\mathfrak{c} \in \Lambda_2$; otherwise, $v^u_T = v^u_{NT}$.

Next, suppose that $\max\{\frac{c}{p(2,0)-p(1,0)}, \frac{2c}{p(2,0)-p(0,0)}\} < \frac{c}{p(1,0)-p(0,0)}$ so that the set of v's defined by (b) is non-empty, and $\frac{c}{p(2,0)-p(1,0)} \leq \frac{c}{p(1,0)-p(0,0)}$ so that the set of v's defined by (e) is empty. Then $v^u_{NT} = m_{(b)} = \max\{\frac{c}{p(2,0)-p(1,0)}, \frac{2c}{p(2,0)-p(0,0)}\}$. By construction $v^u_T = \min\{m_\mathfrak{c}\} < m_{(b)} = v^u_{NT}$, whenever $m_\mathfrak{c}$ is well-defined for at least one $\mathfrak{c} \in \{(c),(g),(k),(l)\}$;[21] otherwise, $v^u_T = v^u_{NT}$.

[18] Configurations (b) and (e) were already excluded under non-transparency. If $\frac{c}{p(2,0)-p(1,0)} = \frac{c}{p(1,0)-p(0,0)}$, then (c) is empty-valued; further, $v \leq \frac{c}{p(2,1)-p(1,1)} < \frac{c}{p(1,0)-p(0,0)}$ (by applying **A4** on the right-hand side of the main condition of (j)), thus configuration (j) is also empty-valued.

[19] It should be clear that the permissible v's are decreasing as we move down the list of configurations.

[20] Earlier, configurations (b) and (e) were excluded (see footnote 18). Configuration (f) is empty-valued since $\frac{c}{p(2,0)-p(1,0)} < \frac{c}{p(1,0)-p(0,0)}$. Configuration (j) is also empty-valued: the right-hand side of the main condition implies $v < \frac{c}{p(2,0)-p(1,0)}$, so to be non-empty it must be that $\frac{c}{p(1,0)-p(0,0)} < \frac{c}{p(2,0)-p(1,0)}$, which is impossible by hypothesis.

[21] Configuration (e) is already excluded under non-transparency. If $\frac{c}{p(2,0)-p(1,0)} \leq \frac{c}{p(1,0)-p(0,0)}$ holds, then (f) is empty-valued. Configuration (j) is also empty-valued, by the same argument as in footnote 20.

Finally, suppose the set of v's defined by (e) is non-empty, i.e., $\frac{c}{p(1,0)-p(0,0)} < \frac{c}{p(2,0)-p(1,0)}$. Then $v^u_{NT} = m_{(e)} = \max\{\frac{c}{p(2,1)-p(1,1)}, \frac{c}{p(1,0)-p(0,0)}\}$. By construction $v^u_T = \min\{m_{\mathfrak{c}}\} < m_{(e)} = v^u_{NT}$, whenever $m_{\mathfrak{c}}$ is well-defined for at least one $\mathfrak{c} \in \{(g), (j), (k), (l)\}$;[22] otherwise, $v^u_T = v^u_{NT}$.

More generally, we can make the following observation:

Proposition 4 (Implementation costs). *Suppose a joint project involves two complementary tasks as defined in **A1-A4**. Then full cooperation by both players, i.e. overall efforts* $(2,2)$*, can be uniquely (or weakly) implemented under transparency for a reward that is no more and possibly less than the minimal reward needed for unique (respectively, weak) implementation under non-transparency.*

4 Substitution Technology: A Neutrality Result

In this section, we consider team projects with player efforts primarily as substitutes. The main objective is to see whether the change from complementary to substitution technology alters how transparency impacts on team members' efforts. We hope to convince that much of the benefits of transparency will be lost as a result, and transparency may even prove rather unhelpful.

To formalize, let the project's success probability, denoted by $\rho(e_1, e_2)$, inherit properties **A1-A3** from the previous section and satisfy the following property:

A4′. *General Substitutability*: For any $e_j \in \{0,1\}$, $\rho(1, e'_j) - \rho(0, e'_j) < \rho(1, e_j) - \rho(0, e_j)$ and $\rho(2, e'_j) - \rho(1, e'_j) < \rho(2, e_j) - \rho(1, e_j)$, where $e'_j > e_j$.

That is, the incremental probability of project success due to an extra unit of effort by a player is decreasing in the other player's effort.[23] We continue to assume linear effort costs. At the end we discuss the likely changes in results if one assumes increasing marginal costs.

Unobservable contributions. When efforts are unobservable, the induced effort contribution game is essentially a simultaneous move game although the efforts are exerted over two rounds. The normal form, denoted by $\mathcal{G_S}$, is as follows:

[22]By hypothesis, $\frac{c}{p(1,0)-p(0,0)} < \frac{c}{p(2,0)-p(1,0)}$, so (f) is empty-valued.

[23]It is easy to check that in the perfect substitution case, $\rho(e_1, e_2) = \rho(e_1 + e_2)$, the general substitutability property implies $\rho(1) - \rho(0) > \rho(2) - \rho(1) > \rho(3) - \rho(2) > \rho(4) - \rho(3) > 0$, i.e., $\rho(e_1, e_2)$ is strictly concave separately in each player's effort.

		Player 2		
		0	1	2
	0	$\rho(0,0)v, \rho(0,0)v$	$\rho(0,1)v, \rho(0,1)v - c$	$\rho(0,2)v, \rho(0,2)v - 2c$
Player 1	1	$\rho(1,0)v - c, \rho(1,0)v$	$\rho(1,1)v - c, \rho(1,1)v - c$	$\rho(1,2)v - c, \rho(1,2)v - 2c$
	2	$\rho(2,0)v - 2c, \rho(2,0)v$	$\rho(2,1)v - 2c, \rho(2,1)v - c$	$v - 2c, v - 2c$

Figure 4: Simultaneous move game $\mathcal{G}_{\mathcal{S}}$

Denote the *NE* of this game by $\mathbf{e}^*_{\mathcal{G}_{\mathcal{S}}}$. In the Appendix we show that there always exists a pure-strategy *NE* in $\mathcal{G}_{\mathcal{S}}$. We also establish the following result:

Lemma 8. *In the normal-form game $\mathcal{G}_{\mathcal{S}}$, multiple symmetric pure strategy Nash equilibria cannot arise. That is, any $\mathbf{e}^*_{\mathcal{G}_{\mathcal{S}}} = (e, e)$ must be a unique equilibrium.*

While for complementary technology one-shot equilibrium is necessarily symmetric, for substitution technology one-shot equilibrium can be asymmetric. Moreover, an asymmetric equilibrium can arise along with a symmetric one-shot equilibrium.[24]

Observable contributions. When first-round efforts are observable, the extensive form is as in Fig. 5. Denote the extensive-form game by $\widehat{\mathcal{G}_{\mathcal{S}}}$, any *SPE* of this game by $\mathbf{e}^*_{\widehat{\mathcal{G}_{\mathcal{S}}}}$, and the continuation game following $\mathbf{e_1} = (e_{11}, e_{21})$ in the extensive-form game $\widehat{\mathcal{G}_{\mathcal{S}}}$ by $\mathcal{G}_{\mathcal{S}(e_{11},e_{21})}$.

With player efforts as substitutes (as opposed to complementary efforts), free-riding becomes a more serious problem under either contribution format, with and without transparency, because one player's slack can be more easily picked up by another player. But then a player cannot easily free ride by simply putting in low effort in the first round because this effort reduction can be made up for by the same player by putting in more effort in the second round, given linear costs of effort. So how substitutability in efforts affects the players' overall effort incentives under the two formats, transparency and non-transparency, is not a priori clear.

Our next result shows that unlike in the complementary technology case, when efforts are substitutes, transparency cannot eliminate inferior efforts equilibrium if there are multiple equilibria under non-transparency.

[24]For example, suppose that $v - 2c > p(1,2)v - c$ and $v - 2c = p(0,2)v$, such that $\mathbf{e}^*_{\mathcal{G}_{\mathcal{S}}} = (2,2)$. By Lemma 8, we know that $\mathbf{e}^*_{\mathcal{G}_{\mathcal{S}}} \neq (1,1)$ and $\mathbf{e}^*_{\mathcal{G}_{\mathcal{S}}} \neq (0,0)$. However, $v - 2c > p(1,2)v - c$ and $v - 2c = p(0,2)v$ imply that, using **A4′** and **A2**, $p(0,2)v - 2c > p(2,1)v - c$ and $p(0,2)v - 2c > p(0,0)v$. Together with the fact that $v - 2c = p(0,2)v$, these conditions imply that $\mathbf{e}^*_{\mathcal{G}_{\mathcal{S}}} = (0,2)$.

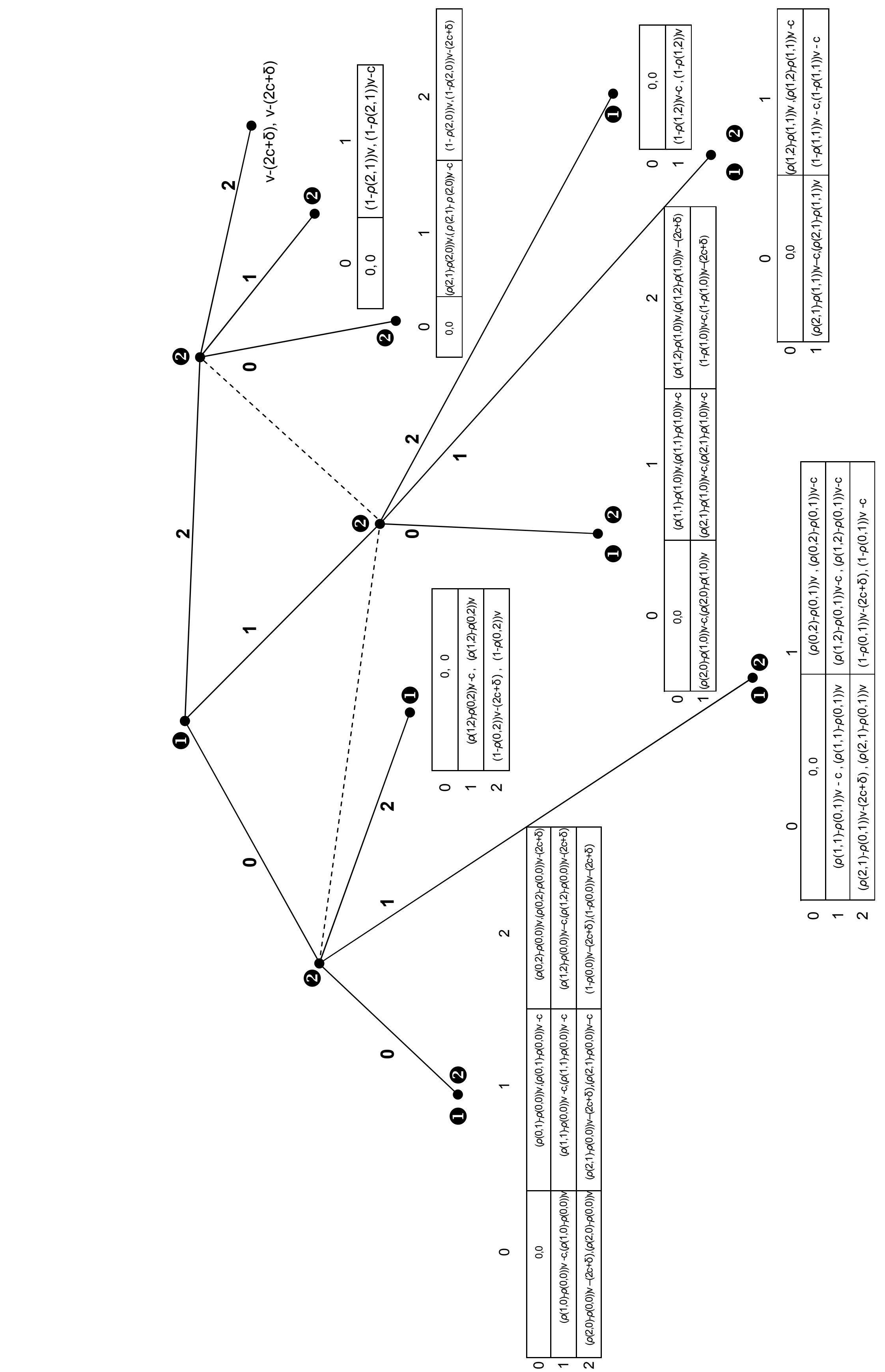

Figure 5: Extensive-form game $\widehat{\mathcal{G}_{\mathcal{S}}}$

Proposition 5. *Suppose a joint project involves effort substitution as defined by* ***A1-A3*** *and* ***A4'****. Any* NE *efforts pair* (η_1^*, η_2^*) *under non-transparency can be supported as an* SPE *of the effort contribution game under transparency with the strategy profile* $\mathbf{e}_{\widehat{\mathcal{G}_S}} = (\eta_1^*, \eta_2^*; 0, 0)$.

The next result shows that any overall effort profile achievable under transparency can also be replicated in the one-shot game under non-transparency:

Proposition 6. *Suppose a joint project involves effort substitution as defined by* ***A1-A3*** *and* ***A4'****. If under transparency* $\mathbf{e}_{\widehat{\mathcal{G}_S}} = (e_{11}^*, e_{21}^*; e_{12}^*(e_{11}^*, e_{21}^*), e_{22}^*(e_{11}^*, e_{21}^*))$ *is an* SPE, *then the aggregate efforts pair* $\mathbf{e}_{\mathcal{G}_S} = (\eta_1^*, \eta_2^*)$, *where* $\eta_1^* = e_{11}^* + e_{12}^*$ *and* $\eta_2^* = e_{21}^* + e_{22}^*$, *is an* NE *of the effort contribution game under non-transparency.*

Substitutability in efforts thus takes away from transparency the distinctive advantage of 'gradualism' noted previously: under complementary technology sometimes full cooperation could be supported mainly by gradualism that might fail to materialize otherwise.

To summarize, Propositions 5 and 6 together establish, in contrast to our findings in section 3, a form of '*neutrality of transparency*' when player efforts are broad substitutes in team output and effort costs are linear: observability of efforts is neither gainful nor harmful for inducing efforts. The result further implies that *if one were to explicitly design incentives to implement full cooperation (or partial cooperation), the optimal reward v will be identical with and without transparency.*

Our *neutrality* result contrasts with Varian (1994), who showed that total contribution in a two-player voluntary contribution public good game under observability of contributions is often less than (and never exceeds) the total contribution under non-observability. Note that in Varian's setup, due to sequential structure of contributions, an early mover has the opportunity to free ride on the late mover by committing to low contribution; in our setup, the fact that in the last round both players get to move simultaneously, combined with the fact that marginal cost of effort is constant, completely nullify the extra free-riding opportunity associated with an early move and observability makes no difference. But if marginal cost of effort is increasing, low contribution in the early round will have a commitment value similar to Varian's setup because to make it up in the second round will push up the player's effort costs at an increasing rate, making observability of efforts *harmful* (from the organization's point of view).[25] This result is demonstrated elsewhere in a

[25] A similar contrast can be found between the dynamic contribution game of Admati and Perry (1991), which assumes sequential contributions, and the repeated contribution game of Marx and Matthews (2000), which assumes simultaneous contributions within each round.

related paper by Pepito (2010) in a continuous efforts formulation of a two-player, two-round repeated efforts joint project game, assuming the players' efforts are substitutes.[26]

Also as we discussed in the Introduction, our neutrality property of transparency is similar to Winter (2006a)'s result. The important difference between Winter's setup and ours is that a player in our model may choose non-zero efforts over multiple rounds giving rise to *repeated* efforts contribution game, whereas in Winter's analysis a player gets to exert effort (or shirk) only once so that the effort investment game is mostly *sequential* in nature (late movers observe the early movers' efforts and not the other way around).[27]

5 Conclusion

Transparency is an important subject of debate in public economics and its applications in team settings. Samuelsonian formulation of public goods, in a majority of models, takes substitutability of contributions in public good's production as a starting point, with the free-rider problem as the main challenge. Team productions in organizations, on the other hand, may exhibit a large degree of complementarity, while the benefits of team performance are similar to a public good.

To see how the paper adds to the literature on transparency, in Table 3 we present a summary of the main features and results of our model and three related papers. Our model has the following attributes: joint (or team) project, repeated contribution of efforts, self-interested utilitarian contributors (whose preferences we describe as "standard preferences"), complete information, and the two types of production technologies – complementary and substitutes.

Of the papers listed in Table 3, Varian (1994) is in pure public good setting. Winter's (2006a) is in a team setting (similar to ours) analyzing the architecture of information (i.e., how different peers are positioned in the observability-of-efforts chain) and its implications for what should be the right kind of team (function-based or process-based) from the optimal design viewpoint. Except Mohnen et al. (2008), all the papers listed assume standard utilitarian agents; Mohnen et al. consider the implications when agents view an inequitable

[26]The continuous efforts formulation in Pepito (2010) allows comparison with the result of Mohnen et al. (2009) who also considered continuous efforts and have shown that transparency is *neutral* if the players are selfish utilitarian and the players' marginal cost of effort is increasing. The difference between Pepito (2010) and Mohnen et al. (2009) lies in the way efforts translate into output: in Mohnen et al. output is linear in efforts (output equalling sum of efforts) whereas in Pepito each player's effort translates into team project's success at a decreasing rate.

[27]In Winter's setup, in some of the stages more than one worker may move (simultaneously) in which case they do not observe each other's efforts, but the late movers do observe the early movers' efforts.

Table 3: **Alternative related models of transparency**

This paper	**Mohnen et al.**	**Winter[2006a]**	**Varian**
complete info.	complete	complete/ incomplete	complete
effort contr.	effort contr.	effort contr.	public good
repeat contr.	repeat contr.	mainly sequential; simult. in some stages	sequential
standard preferences	inequity aversion#	standard preferences	standard preferences
complementary tech.; transparency adv.	substitution; transparency adv.	complementary; transparency adv.	substitution; transparency disadv.
substitution tech.; transparency neutral[a]	#change to std. pref. ⇒ transparency neutral	substitution; transparency neutral	–

[a] This holds for linear effort costs; for strictly convex effort costs, transparency is harmful (Pepito, 2010).

distribution of the burden of contribution with extra aversion beyond the direct utility-of-rewards calculations.

Appendix

Proof of Lemma 1. For various comparisons in this proof, refer to Fig. 1. Suppose $(e_1^*, e_2^*) = (1, 0)$. This implies that

$$\begin{aligned} p(1,0)v - c &\geq p(0,0)v, \\ \text{and} \qquad p(1,0)v &\geq p(1,1)v - c. \end{aligned}$$

These imply, respectively, that $(p(1,0)-p(0,0))v-c \geq 0$ and that $(p(1,1)-p(1,0))v-c \leq 0$, leading to inconsistencies given that $p(1,1) - p(1,0) = p(1,1) - p(0,1) > p(1,0) - p(0,0)$, by **A2** and **A4**. Therefore, $(1, 0)$ cannot be an *NE*, and by symmetry, nor can $(0, 1)$.

Suppose that $(e_1^*, e_2^*) = (2, 0)$. Therefore,

$$\begin{aligned} p(2,0)v &\geq v - 2c, \\ \text{and} \qquad p(2,0)v - 2c &\geq p(0,0)v, \end{aligned}$$

yielding, respectively, $(1 - p(2,0))v - 2c \leq 0$ and $(p(2,0) - p(0,0))v - 2c \geq 0$, which are inconsistent given that $(1-p(2,0))v-2c = (p(2,2)-p(2,0))v-2c = (p(2,2)-p(0,2))v-2c > (p(2,0) - p(0,0))v - 2c$, by **A2** and **A4**. Therefore, $(2, 0)$ and $(0, 2)$ cannot be *NE*.

Finally, suppose that $(e_1^*, e_2^*) = (2, 1)$. This implies that

$$\begin{aligned} p(2,1)v - c &\geq v - 2c, \\ \text{and} \qquad p(2,1)v - 2c &\geq p(1,1)v - c, \end{aligned}$$

yielding, respectively, $(1 - p(2,1))v - c \leq 0$ and $(p(2,1) - p(1,1))v - c \geq 0$, which are inconsistent given that $(1 - p(2,1))v - c = (p(2,2) - p(2,1))v - c = (p(2,2) - p(1,2))v - c > (p(2,1) - p(1,1))v - c$, by **A2** and **A4**. Therefore, $(2, 1)$ and $(1, 2)$ cannot be *NE*. ■

Proof of Proposition 1. Equilibrium $(e_1^*, e_2^*) = (0, 0)$ occurs if and only if

$$\begin{aligned} p(0,0)v &\geq p(1,0)v - c, \\ \text{and} \qquad p(0,0)v &\geq p(2,0)v - 2c, \end{aligned}$$

i.e., $c \geq \max\{(p(1,0) - p(0,0))v, [(p(2,0) - p(0,0))v]/2\}$, which is satisfied for high c values.

Equilibrium $(e_1^*, e_2^*) = (1, 1)$ occurs if and only if

$$\begin{aligned} p(1,1)v - c &\geq p(0,1)v, \\ \text{and} \qquad p(1,1)v - c &\geq p(2,1)v - 2c, \end{aligned}$$

i.e., $(p(2,1) - p(1,1))v \leq c \leq (p(1,1) - p(0,1))v$.

Finally, equilibrium $(e_1^*, e_2^*) = (2, 2)$ occurs if and only if

$$\begin{aligned} v - 2c &\geq p(1,2)v - c, \\ \text{and} \qquad v - 2c &\geq p(0,2)v, \end{aligned}$$

i.e., $c \leq \min\{(1 - p(1,2))v, [(1 - p(0,2))v]/2\}$, which is clearly satisfied for low values of c. ■

Existence of pure strategy NE in $\mathcal{G}$. *The one-shot game, $\mathcal{G}$, has at least one pure-strategy Nash equilibrium.*

Proof. Suppose that $\mathbf{e}^*_{\mathcal{G}} \neq (0,0)$. Then (refer to Fig. 1) $p(0,0)v < \max\{p(1,0)v - c, p(2,0)v - 2c\}$. If $\max\{p(1,0)v - c, p(2,0)v - 2c\} = p(1,0)v - c$, then

$$\begin{array}{llll} & p(1,0)v - c \geq p(2,0)v - 2c, & \text{i.e.,} & c \geq (p(2,0) - p(1,0))v, \\ \text{and} & p(1,0)v - c > p(0,0)v, & \text{i.e.,} & (p(1,0) - p(0,0))v > c, \end{array}$$

from which we can infer, using **A4**, that

$$(p(1,2) - p(0,2))v > (p(1,1) - p(0,1))v > (p(1,0) - p(0,0))v > c \geq (p(2,0) - p(1,0))v. \quad (5)$$

Now if $c \geq (p(2,1) - p(1,1))v$, then using (5) write

$$(p(1,1) - p(0,1))v > c \geq (p(2,1) - p(1,1))v,$$

and we conclude that $\mathbf{e}^*_{\mathcal{G}} = (1,1)$, by Proposition 1. On the other hand, if $(p(2,1) - p(1,1))v > c$, then by **A4**,

$$(1 - p(1,2))v > c. \quad (6)$$

From (5), we know that $p(1,2) - p(0,2))v > c$, hence

$$(1 - p(1,2))v + (p(1,2) - p(0,2))v > 2c, \quad \text{i.e.,} \quad [(1 - p(0,2))v]/2 > c,$$

which, together with (6), implies that $\mathbf{e}^*_{\mathcal{G}} = (2,2)$, by Proposition 1.

If $\max\{p(1,0)v - c, p(2,0)v - 2c\} = p(2,0)v - 2c$, then

$$\begin{array}{llllll} & p(2,0)v - 2c \geq p(1,0)v - c, & \text{i.e.,} & (p(2,0) - p(1,0))v \geq c, & \text{i.e.,} & (1 - p(1,2))v > c \text{ (by } \mathbf{A4}); \\ \text{and} & p(2,0)v - 2c > p(0,0)v, & \text{i.e.,} & \dfrac{(p(2,0) - p(0,0))v}{2} > c, & \text{i.e.,} & \dfrac{(1 - p(0,2))v}{2} > c \text{ (by } \mathbf{A4}). \end{array}$$

Therefore, $c < \min\{(1 - p(1,2))v, [(1 - p(0,2))v]/2\}$, and $\mathbf{e}^*_{\mathcal{G}} = (2,2)$, by Proposition 1.

Otherwise, $\mathbf{e}^*_{\mathcal{G}} = (0,0)$. Therefore, $\mathcal{G}$ has at least one pure-strategy Nash equilibrium. ■

Proof of Lemma 2. **(i)** First we claim that full cooperation cannot be achieved in the extensive-form game through $(0,0;2,2)$ or $(2,2;0,0)$. The first case implies that $(2,2)$ is an *NE* in the continuation game following $\mathbf{e_1} = (0,0)$, contradicting our hypothesis that

$(2,2) \neq \mathbf{e}^*_{\mathcal{G}}$ (recall, the continuation game following $\mathbf{e_1} = (0,0)$ is simply $\mathcal{G}$). The second case cannot be supported in equilibrium as any player i would have an incentive to deviate from $e_{i1} = 2$ to either $e_{i1} = 1$ or $e_{i1} = 0$, because full cooperation is not an equilibrium in the one-shot game: in the extensive form i can deviate the same way as he would have done in the one-shot game, first by deviating in the first round (as in the one-shot game) and then putting in zero effort in the second round.

Next consider full cooperation of the form $(2,1;0,1)$ or $(1,2;1,0)$ and each player collecting a payoff of $v-2c$ overall. Since $(2,2) \neq \mathbf{e}^*_{\mathcal{G}}$, at least one of the following must hold (see Fig. 1):

$$p(0,2)v > v - 2c, \tag{7}$$

$$p(1,2)v - c > v - 2c. \tag{8}$$

But then the player who is considering to cooperate gradually in the extensive-form game (say, player 1) can either shirk in both rounds and obtain an overall payoff $p(0,2)v$ that exceeds $v-2c$, or partially cooperate in the first round and shirk in the second round to receive $p(1,2)v-c$ that exceeds $v-2c$; one of these profitable deviations must be possible, by (7) and (8). Thus, neither $(2,1;0,1)$ nor $(1,2;1,0)$ can be sustained as *SPE*.

Then consider $(0,1;2,1)$ (or similarly $(1,0;1,2)$) as an equilibrium possibility. It is easy to see that there is a profitable deviation for player 1 in the second round, given that one of (7) and (8) must be true.

The above eliminations leave us with gradual cooperation, i.e. $(1,1;1,1)$, as the only equilibrium possibility.

(ii) Since $\mathbf{e}^*_{\mathcal{G}} = (1,1)$, by Proposition 1,

$$(p(2,1) - p(1,1))v \leq c \leq (p(1,1) - p(0,1))v. \tag{9}$$

Independently, since by hypothesis $(2,2) \neq \mathbf{e}^*_{\mathcal{G}}$, applying part **(i)** of this lemma we conclude that the only way full cooperation can arise with observability is through $(1,1;1,1)$. But to generate $(e^*_{12}(1,1), e^*_{22}(1,1)) = (1,1)$, it must be that $(1-p(1,1))v - c \geq (p(1,2)-p(1,1))v$ (see Fig. 2), i.e.,

$$v - 2c \geq p(1,2)v - c.$$

Further, since $(2,2) \neq \mathbf{e}^*_{\mathcal{G}}$, either (7) or (8) must apply. Condition (7) and $v-2c \geq p(1,2)v-c$ (an implication of gradualism) imply that

$$(p(1,2) - p(0,2))v < c,$$

which contradicts the right-hand side (weak) inequality in condition (9) (since $(p(1,1) - p(0,1)) < (p(1,2) - p(0,2))$, by **A4**). On the other hand, condition (8) directly contradicts $v - 2c \geq p(1,2)v - c$ (established above). Thus, gradualism is also ruled out as an equilibrium possibility. So full cooperation cannot arise with observability. ■

Proof of Lemma 3. Given that shirking is the unique equilibrium without observability, by Lemma 2 the only way full cooperation can arise with observability is via *gradualism*, i.e., through the sequence of efforts $(1,1;1,1)$. Below we verify compatibility of gradual cooperation with shirking being the unique equilibrium, under the stated sufficient conditions. The sufficient conditions will be verified to be non-empty.

Recalling the first of the triple conditions in (3),

$$p(0,2)v > v - 2c \geq p(1,2)v - c, \tag{10}$$

we can further write

$$(1 - p(1,2))v \geq c > (p(1,2) - p(0,2))v. \tag{11}$$

Also write the left-hand side inequality of (10) separately as

$$(1 - p(0,2))v - 2c < 0. \tag{12}$$

We now claim that condition (10) (equivalently, conditions (10) and (11) together) implies that $\mathbf{e}^*_{\mathcal{G}} = (0,0)$ and it is a unique equilibrium.

By Proposition 1, $\mathbf{e}^*_{\mathcal{G}} = (0,0)$ if and only if $c \geq \max\{(p(1,0) - p(0,0))v, [(p(2,0) - p(0,0))v]/2\}$. The right-hand side inequality of (11) and **A4** imply that $c > (p(1,0) - p(0,0))v$, and (12) and **A4** imply that

$$[(p(2,0) - p(0,0))v]/2 < c, \tag{13}$$

so $\mathbf{e}^*_{\mathcal{G}} = (0,0)$.

Next, recall that $(1,1)$ is an *NE* in the one-shot game if and only if

$$(p(2,1) - p(1,1))v \leq c \leq (p(1,1) - p(0,1))v$$

(by Proposition 1). The right-hand side (weak) inequality above implies that $c < (p(1,2) - p(0,2))v$ (by **A4**). But from (11) (which derives from (10)), we know that $c > (p(1,2) - p(0,2))v$. Therefore $\mathbf{e}^*_{\mathcal{G}} \neq (1,1)$.

Finally, (12) implies that $\mathbf{e}^*_{\mathcal{G}} \neq (2,2)$ (by Proposition 1). Thus, $\mathbf{e}^*_{\mathcal{G}} = (0,0)$ is unique.

Let us next consider how gradual cooperation can be supported as an equilibrium under observability.

In the continuation game following $\mathbf{e_1} = (1,1)$, $(e^*_{12}(1,1), e^*_{22}(1,1)) = (1,1)$ if and only if $v - 2c \geq p(1,2)v - c$ (see Fig. 2), which is guaranteed by the right-hand (weak) inequality in condition (10). Now going back to the start of the extensive-form game and considering the strategy profile $(1,1;1,1)$, the overall payoff to each player is

$$u_i(1,1;1,1) = v - 2c.$$

Suppose now player 1 contemplates deviation in Round 1 to $e_{11} = 2$ while player 2 continues to choose $e_{21} = 1$. Since $v - 2c \geq p(2,1)v - c$ (using right-hand inequality in (10) and **A2**), in Round 2 player 2 can choose either $e_{22} = 0$ or $e_{22} = 1$ (see Fig. 2), neither of which results in a profitable deviation for player 1, since

$$\begin{aligned} u_1(2,1;0,0) &= p(2,1)v - 2c, \\ \text{and} \quad u_1(2,1;0,1) &= v - 2c. \end{aligned}$$

Next we rule out a possible deviation by player 1 in Round 1 to $e_{11} = 0$ (refer to Fig. 2) by identifying <u>sufficient</u> conditions. In the continuation game following $\mathbf{e_1} = (0,1)$, we show that $(e_{12}, e_{22}) = (0,0)$ is an *NE* if the following condition holds (along with (10), i.e., (11) and (12)):

$$p(0,1)v - c > p(0,2)v - 2c. \tag{14}$$

(Recall, this is the second of the triple conditions in (3) specified in the lemma statement.) This condition implies that $c > (p(0,2) - p(0,1))v$, which is not inconsistent with (11) <u>and</u> (12). Therefore, condition (14) is not inconsistent with the fact that the unique one-shot equilibrium is $\mathbf{e}^*_{\mathcal{G}} = (0,0)$.

In addition to (14), suppose that the following condition applies (the last of the triple conditions under (3)):

$$v - 2c \geq p(0,1)v. \tag{15}$$

Note that this condition is also not inconsistent with the fact that $\mathbf{e}^*_{\mathcal{G}} = (0,0)$ is unique, since it merely implies that $(1 - p(0,1))v - 2c \geq 0$ and $c \leq \frac{1-p(0,1)}{2}v$, which do not necessarily contradict (11) <u>and</u> (12) holding together.

We can now show that if (10), (14), and(15) (i.e., (11), (12), (14) and (15)) hold, then player 1 does not gain by unilaterally deviating to $e_{11} = 0$. From condition (11), we see that

$(p(1,2)-p(0,2))v-c<0$, which in turn implies that

$$(p(1,1)-p(0,1))v-c<0,$$

using **A4**. Also, from condition (12) and using **A4**, we conclude that

$$(p(2,1)-p(0,1))v-2c<0.$$

Given these last two derived inequalities and using conditions (11) and (12) directly, it can be checked using Fig. 2 that in the continuation game following $\mathbf{e_1}=(0,1)$, $e_{12}=0$ is the (strict) dominant strategy for player 1. Given that player 1 chooses $e_{12}=0$, then from condition (14), player 2's (unique) best response is $e_{22}=0$, generating an overall payoff to player 1 of

$$u_1(0,1;0,0)=p(0,1)v,$$

which, by condition (15), is not a gainful deviation. Therefore, there is no incentive for player 1 to engage in a unilateral first-round deviation from $e_{11}=1$.

By symmetric arguments as above, for the specified conditions, in Round 1 player 2 will not deviate from $e_{21}=1$ either. Therefore, when shirking is the unique equilibrium in the one-shot game, full cooperation (only in the form of gradual cooperation) can be supported as an *SPE* if conditions (10), (14) and (15) hold. Fig. 3 shows an example of parameter constellations satisfying these sufficient conditions.

However, under these conditions, shirking remains an *SPE*. To see this, first note that shirking in the extensive form implies $\mathbf{e}^*_{\widehat{\mathcal{G}}}=(0,0;0,0)$, from which any player i, say player 1, receives

$$u_1(0,0;0,0)=p(0,0)v.$$

Suppose he deviates by choosing $e_{11}=1$. From (11) and (12) (which follow from (10)) and **A4**, and from (14), we see that $(e_{12},e_{22})=(0,0)$ is an *NE* following $(1,0)$; moreover, from (10), it is clear that player 2 chooses $e_{22}=0$ following player 1's first-round deviation to $e_{11}=2$. These deviations yield to player 1, respectively, the payoffs $u_1(1,0;0,0)=p(1,0)v-c$ and $u_1(2,0;0,0)=p(2,0)v-2c$, both of which are no better than $u_1(0,0;0,0)=p(0,0)v$, by condition (14). ■

Proof of Lemma 4. (i) Shirking in the extensive form implies $\mathbf{e}^*_{\widehat{\mathcal{G}}}=(0,0;0,0)$. But if $(0,0)\neq\mathbf{e}^*_{\mathcal{G}}$, then $(e^*_{12}(0,0),e^*_{22}(0,0))\neq(0,0)$, since the continuation game following $\mathbf{e_1}=(0,0)$ is simply $\mathcal{G}$; a contradiction.

(ii) When effort is observable, four strategy profiles entail partial cooperation: $(0,0;1,1)$,

$(1,0;0,1)$, $(0,1;1,0)$ or $(1,1;0,0)$. We immediately rule out $\mathbf{e}^*_{\widehat{\mathcal{G}}} = (0,0;1,1)$: the continuation game following $\mathbf{e_1} = (0,0)$ is simply $\mathcal{G}$, and since $(1,1) \neq \mathbf{e}^*_{\mathcal{G}}$, therefore $(e^*_{12}(0,0), e^*_{22}(0,0)) \neq (1,1)$.

We next rule out $\mathbf{e}^*_{\widehat{\mathcal{G}}} = (1,0;0,1)$. The fact that $(1,1) \neq \mathbf{e}^*_{\mathcal{G}}$ implies that at least one of the following two conditions must hold:

$$\begin{aligned} p(1,1)v - c &< p(1,0)v, &(16)\\ p(1,1)v - c &< p(1,2)v - 2c. &(17)\end{aligned}$$

The first inequality implies that $(p(1,1) - p(1,0))v - c < 0$. If, following $\mathbf{e_1} = (1,0)$, player 1 chooses $e_{12} = 0$, player 2 would benefit by deviating to $e_{22} = 0$ from $e_{22} = 1$ (see Fig. 2); hence $(1,0;0,1)$ cannot be an equilibrium. The second inequality implies that $p(1,1)v - c - p(1,0)v < p(1,2)v - 2c - p(1,0)v$, i.e., $(p(1,1) - p(1,0))v - c < (p(1,2) - p(1,0))v - 2c$, which means in the second round player 2 does better by deviating to $e_{22} = 2$; so once again $(1,0;0,1)$ cannot be an *SPE*. By symmetry, $(0,1;1,0)$ is also ruled out to be an *SPE*.

Finally, consider $(1,1;0,0)$. Since $(1,1) \neq \mathbf{e}^*_{\mathcal{G}}$, either (16) or (17) must hold. If (17) holds, then following $\mathbf{e_1} = (1,1)$ player 2 would deviate in Round 2 by choosing $e_{22} = 1$ as player 1 continues to choose $e_{12} = 0$ (see Fig. 2). This implies that $(1,1;0,0)$ is not an *SPE*. Suppose now that (17) fails so that

$$p(1,1)v - c \geq p(1,2)v - 2c. \tag{18}$$

Then it must be that (16) holds, hence,

$$p(1,0)v > p(1,1)v - c \geq p(1,2)v - 2c. \tag{19}$$

We claim that player 1 would deviate in Round 1 to $e_{11} = 0$, given that player 2 continues to choose $e_{21} = 1$, followed by $(e^*_{12}(0,1), e^*_{22}(0,1)) = (0,0)$ as an *NE* in the continuation game. For this to happen, the following conditions must hold (see Fig. 2):

$$\begin{aligned} \text{Player 1's best-response :} \qquad 0 &\geq (p(1,1) - p(0,1))v - c, &(20)\\ 0 &\geq (p(2,1) - p(0,1))v - 2c; &(21)\\ \text{Player 2's best-response :} \qquad 0 &\geq (p(0,2) - p(0,1))v - c. &(22)\end{aligned}$$

Conditions (20) and (21) are guaranteed by (19) and **A2**. To see that (22) is satisfied, rewrite

(18):

$$\begin{aligned} 0 &\geq (p(1,2) - p(1,1))v - c \\ \text{i.e.,} \quad 0 &> (p(0,2) - p(0,1))v - c, \qquad \text{by} \quad \mathbf{A4}. \end{aligned}$$

So, in the *NE*, $(e_{12}^*(0,1), e_{22}^*(0,1)) = (0,0)$, following player 1's deviation in Round 1, player 1 receives an overall payoff in the two rounds combined,

$$u_1(0,1;0,0) = p(0,1)v,$$

which, by (19) and **A2**, exceeds player 1's overall payoff in the originally posited strategy profile:

$$u_1(1,1;0,0) = p(1,1)v - c.$$

Hence player 1 would deviate in Round 1 as claimed and $(1,1;0,0)$ cannot be an *SPE*. This completes the proof that, under transparency, overall efforts of $(1,1)$ cannot be supported in equilibrium. ■

Proof of Lemma 5. (i) If $\mathbf{e}_{\mathcal{G}}^* = (2,2)$, then for every $\mathbf{e_1} = (e_{11}, e_{21}) \in \hat{\mathbf{E}}_\mathbf{1}$, the second-round strategy profile $(2 - e_{11}, 2 - e_{21})$ is an *NE* in the continuation game, denoted by $(e_{12}^*(\mathbf{e_1}), e_{22}^*(\mathbf{e_1}))$. Moreover, all strategy profiles $(\mathbf{e_1}; e_{12}^*(\mathbf{e_1}), e_{22}^*(\mathbf{e_1}))$, $\mathbf{e_1} \in \hat{\mathbf{E}}_\mathbf{1}$, yield:

$$u_i(e_{11}, e_{21}; e_{12}^*(\mathbf{e_1}), e_{22}^*(\mathbf{e_1})) = v - 2c \ \text{ for } \ i = 1, 2.$$

Therefore, for each of these strategy profiles, there exists no profitable first-round deviation for any player i, since the payoffs to the deviating player is the same as what he would get by not deviating. Thus, full cooperation is an *SPE*.

(ii) Corresponding to overall efforts $(1,1)$, the strategy profile in the extensive form is one of the following: $(0,0;1,1)$, $(1,1;0,0)$, $(1,0;0,1)$, $(0,1;1,0)$. Each of these profiles yields player 1 a payoff of $p(1,1)v - c$, and since $v - 2c \geq p(1,2)v - c$ (recall, $\mathbf{e}_{\mathcal{G}}^* = (2,2)$) it follows, using **A3**, that $v - 2c > p(1,1)v - c$. It is now easy to see that none of the strategy profiles will be *SPE*: given a first-round deviation by player 1 to $e_{11} = 2$, in Round 2 player 2 choosing an effort such that overall efforts are $(2,2)$ is an *NE*. This would result in a payoff of $v - 2c$ to player 1, which exceeds his payoff $p(1,1)v - c$ in the posited equilibrium. Thus, under transparency, overall efforts of $(1,1)$ cannot be supported in equilibrium. ■

Proof of Lemma 6. Let $\mathbf{e}_{\mathcal{G}}^* = (1,1)$, and by definition $\mathcal{I}_{(1,1)} = \{(0,0), (1,0), (0,1), (2,0), (0,2)\}$.

By Proposition 1,

$$
\begin{aligned}
(p(1,1)-p(0,1))v-c &\geq 0 && (23)\\
\text{and} \qquad (p(2,1)-p(1,1))v &\leq c. && (24)
\end{aligned}
$$

Fix any $(\tilde{e}_1,\tilde{e}_2)\in\mathcal{I}_{(1,1)}\setminus(0,0)$. By Lemma 1, such $(\tilde{e}_1,\tilde{e}_2)$ cannot be an *SPE* with the strategy profile $(0,0;\tilde{e}_1,\tilde{e}_2)$. This is so because the continuation game following $\mathbf{e_1}=(0,0)$ is strategically equivalent to the one-shot game $\mathcal{G}$.

Consider elimination of overall efforts $(1,0)$. Since $(0,0;1,0)$ cannot be an *SPE*, what remains to be shown is that $(1,0;0,0)$ is *not* subgame-perfect. Player 1's payoff $u_1(1,0;0,0)=p(1,0)v-c$; but then player 1 can deviate in Round 1 to $e_{11}=0$ while player 2 chooses $e_{21}=0$, and with $(1,1)$ being an *NE* in the continuation game (because $\mathbf{e}^*_{\mathcal{G}}=(1,1)$) player 1 will receive an overall payoff of $u_1(0,0;1,1)=p(1,1)v-c$. Thus, player 1 would benefit ($p(1,1)v-c>p(1,0)v-c$, by (23) and **A3**), ruling out $(1,0;0,0)$ as an *SPE*. So, under transparency, overall efforts of $(1,0)$, and by symmetry $(0,1)$, cannot be supported in equilibrium.

Next consider overall efforts $(2,0)$. We know that $(0,0;2,0)$ cannot be an *SPE*. Consider then the strategies $(2,0;0,0)$. By (23) and invoking **A2** and **A4**, $(p(2,1)-p(2,0))v-c>0$, so following $(2,0)$ player 2 will gain by choosing $e_{22}=1$ over $e_{22}=0$ (see Fig. 2). Therefore, $(e^*_{12}(2,0),e^*_{22}(2,0))\neq(0,0)$, hence $(2,0;0,0)$ is not an *SPE*. Finally, consider $(1,0;1,0)$. By (24) and invoking **A4**, $(p(2,0)-p(1,0))v-c<0$: if player 2 chooses $e_{22}=0$, player 1 would choose $e_{12}=0$ instead of $e_{12}=1$, so $(1,0)$ cannot be an *NE* following $(1,0)$; this rules out $(1,0;1,0)$ as an *SPE*. Thus, overall efforts $(2,0)$, and by symmetry $(0,2)$, cannot be supported in equilibrium.

Finally, consider overall efforts $(0,0)$. There are two subcases to be considered.

If $\mathbf{e}^*_{\mathcal{G}}\neq(0,0)$, then by Lemma 4 overall efforts of $(0,0)$ cannot arise in equilibrium of $\widehat{\mathcal{G}}$.

Alternatively suppose $\mathbf{e}^*_{\mathcal{G}}=(0,0)$, in addition to $\mathbf{e}^*_{\mathcal{G}}=(1,1)$. We claim that here too overall efforts of $(0,0)$ cannot be supported in equilibrium of $\widehat{\mathcal{G}}$. To see this, note that by (23) and (24) and invoking **A2**, we can conclude that $(0,1)$ is an *NE* in the continuation game following $\mathbf{e_1}=(1,0)$ (see Fig. 2). Moreover, using (23) directly and invoking **A3**, we see that

$$u_1(1,0;0,1)=p(1,1)v-c\geq p(0,1)v>p(0,0)v=u_1(0,0;0,0).$$

This shows that first-round efforts $(0,0)$ cannot be supported as part of an equilibrium in the extensive-form game, since player 1 (in fact, any player) would have an incentive to undertake a first-round unilateral deviation by choosing $e_{11}=1$ which will be followed up in

Round 2 by $(0,1)$ as an *NE*. Therefore, once again overall efforts, $(0,0)$, cannot be supported in equilibrium of $\widehat{\mathcal{G}}$.

This completes the proof that overall efforts in $\mathcal{I}_{(1,1)}$ cannot be supported in *SPE*. ■

Proof of Lemma 7. Let $\mathbf{e}^*_{\mathcal{G}} = (2,2)$, and by definition

$$\mathcal{I}_{(2,2)} = \{(0,0),(1,0),(0,1),(2,0),(0,2),(1,2),(2,1),(1,1)\}.$$

By Proposition 1,

$$(1-p(1,2))v - c \geq 0 \tag{25}$$

$$\text{and} \quad (1-p(0,2))v - 2c \geq 0. \tag{26}$$

Fix any $(\tilde{e}_1,\tilde{e}_2) \in \mathcal{I}_{(2,2)} \setminus \{(0,0),(1,1)\}$. By Lemma 1, such $(\tilde{e}_1,\tilde{e}_2)$ cannot be supported in an *SPE* with the strategy profile $(0,0;\tilde{e}_1,\tilde{e}_2)$; the continuation game following $\mathbf{e_1} = (0,0)$ is strategically equivalent to the one-shot game $\mathcal{G}$. Note that, by construction $\tilde{e}_1 \neq \tilde{e}_2$.

Consider elimination of overall efforts $(1,0)$. Since $(0,0;1,0)$ cannot be an *SPE*, what remains to be shown is that $(1,0;0,0)$ is *not* subgame-perfect. Player 1's payoff $u_1(1,0;0,0) = p(1,0)v - c$; but then player 1 can deviate in Round 1 to $e_{11} = 0$ while player 2 chooses $e_{21} = 0$, and with $(2,2)$ being an *NE* in the continuation game (because $\mathbf{e}^*_{\mathcal{G}} = (2,2)$) player 1 will receive an overall payoff of $u_1(0,0;2,2) = v - 2c$. This makes player 1 better off since

$$u_1(0,0;2,2) = v - 2c \underbrace{\geq}_{\text{by (25)}} p(1,2)v - c \underbrace{>}_{\text{by } \mathbf{A3}} p(1,0)v - c = u_1(1,0;0,0).$$

Therefore, overall efforts $(1,0)$, and by symmetry $(0,1)$, cannot be supported in *SPE*.

Consider overall efforts $(2,0)$. Aside from $(0,0;2,0)$, which we already argued cannot be an *SPE*, these efforts can also arise via the strategy profiles $(2,0;0,0)$ and $(1,0;1,0)$. First consider $(2,0;0,0)$ in which player 1 receives $p(2,0)v - 2c$. But then player 1 can deviate in Round 1 to $e_{11} = 0$, following which $(e_{12},e_{22}) = (2,2)$ is an *NE* in the continuation game (since $\mathbf{e}^*_{\mathcal{G}} = (2,2)$) and player 1 receives a higher payoff, $u_1(0,0;2,2) = v - 2c$. Hence $(2,0;0,0)$ is not an *SPE*.

Consider next the strategy profile $(1,0;1,0)$. Again, similar to the case just analyzed, player 1 can deviate in Round 1 to $e_{11} = 0$, following which $(e_{12},e_{22}) = (2,2)$ realizes and player 1 is strictly better off compared to his payoff of $u_1(1,0;1,0) = p(2,0)v - 2c$. Hence $(1,0;1,0)$ cannot be an *SPE*.

Thus, overall efforts $(2,0)$, and by symmetry $(0,2)$, cannot be supported in *SPE*.

Consider overall efforts $(1,1)$. By Lemma 5(ii), overall efforts $(1,1)$ cannot be supported in an *SPE*.

Consider overall efforts $(2,1)$. The strategy profiles that yield these overall efforts are $(2,1;0,0)$, $(2,0;0,1)$, $(1,1;1,0)$, $(1,0;1,1)$, $(0,1;2,0)$, and $(0,0;2,1)$. Note that in each of these profiles player 1 receives a payoff of $p(2,1)v-2c$. First, it has already been established at the beginning that the strategy profile $(0,0;2,1)$ cannot be an *SPE*. Next, examine the strategy profiles $(2,1;0,0)$ and $(2,0;0,1)$. Neither of these strategy profiles will be an *SPE*: given a first-round deviation by player 1 to $e_{11}=1$ in either strategy profile, $(e_{12},e_{22})=(1,2-e_{21})$ is an *NE* in the continuation game that follows (since $\mathbf{e}^*_{\mathcal{G}}=(2,2)$), which results in a payoff of $u_1(1,1;1,1)=u_1(1,0;1,2)=v-2c\geq p(2,1)v-c>p(2,1)v-2c$ (the first inequality follows from (25) and applying **A2**). Now consider the strategy profile $(1,1;1,0)$. For $(1,0)$ to be an *NE* following $\mathbf{e_1}=(1,1)$, and given that $\mathbf{e}^*_{\mathcal{G}}=(2,2)$ (in particular, note condition (25) and property **A2**), the following conditions must hold (see Fig. 2):

$$\begin{aligned}
\text{Player 1's best-response} &: \quad 0\leq (p(2,1)-p(1,1))v-c &&(27)\\
\text{Player 2's best-response} &: \quad (p(2,1)-p(1,1))v=(1-p(1,1))v-c &&\\
&\quad\;\; \text{i.e., } 0=(1-p(2,1))v-c. &&(28)
\end{aligned}$$

However, these conditions are inconsistent, given **A4** and **A2**. Therefore, $(e^*_{12}(1,1),e^*_{22}(1,1))\neq(1,0)$, and $(1,1;1,0)$ is not an *SPE*. Moreover, note that conditions (27) and (28) must also hold for $(2,0)$ to be an *NE* following $\mathbf{e_1}=(0,1)$ and for $(1,1)$ to be an *NE* following $\mathbf{e_1}=(1,0)$. Since these conditions are inconsistent, then $(e^*_{12}(0,1),e^*_{22}(0,1))\neq(2,0)$ and $(e^*_{12}(1,0),e^*_{22}(1,0))\neq(1,1)$, and the strategy profiles $(0,1;2,0)$ and $(1,0;1,1)$ are not *SPE*. Therefore, none of the strategy profiles yielding overall efforts $(2,1)$ can be *SPE*.

What is left now is to show that overall efforts of $(0,0)$ cannot be supported in an *SPE*. There are three subcases to be considered.

First consider the subcase where $\mathbf{e}^*_{\mathcal{G}}\neq(0,0)$. By Lemma 4(i), overall efforts $(0,0)$ cannot arise in an *SPE*.

Next, suppose $\mathbf{e}^*_{\mathcal{G}}=(2,2)$, $\mathbf{e}^*_{\mathcal{G}}=(0,0)$, and $\mathbf{e}^*_{\mathcal{G}}\neq(1,1)$. While $(0,0)$ is clearly an *NE* in the continuation game following $\mathbf{e_1}=(0,0)$, $(0,0;0,0)$ cannot be sustained as an equilibrium in the overall game since a first-round unilateral deviation to $e_{11}=2$ by player 1 is gainful:

$$u_1(2,0;0,2)=v-2c\underbrace{\geq}_{\text{by (26)}}p(0,2)v>p(0,0)v=u_1(0,0;0,0),$$

thus ruling out overall efforts of $(0,0)$ in an equilibrium of $\widehat{\mathcal{G}}$.

Finally, consider the subcase where all symmetric equilibria arise in the one-shot game. By Lemma 6, overall efforts of $(0,0)$ cannot be supported in an equilibrium of $\widehat{\mathcal{G}}$. ■

Proof of Proposition 3. We divide the proof into three parts.

[**1**] First suppose that $\mathbf{e}^*_{\mathcal{G}} = (1,1)$ but $\mathbf{e}^*_{\mathcal{G}} \neq (2,2)$; this equilibrium may be unique or there could be another equilibrium $\mathbf{e}^*_{\mathcal{G}} = (0,0)$. Then, we show that the overall efforts $(1,1)$ can be supported as an *SPE* in the extensive-form game; moreover, the equilibrium (in terms of overall efforts) will be unique.

By Proposition 1, $\mathbf{e}^*_{\mathcal{G}} = (1,1)$ if and only if

$$(p(2,1) - p(1,1))v \leq c \leq (p(1,1) - p(0,1))v. \tag{29}$$

Consider the strategy profile $(1,0;0,1)$. By condition (29), we know that $(0,1)$ is an *NE* in the continuation game following first-round efforts $(1,0)$.

Suppose that player 1 unilaterally deviates in Round 1 to $e_{11} = 0$. Since $\mathbf{e}^*_{\mathcal{G}} = (1,1)$, and the continuation game following $\mathbf{e}_1 = (0,0)$ is simply $\mathcal{G}$, then $(e^*_{12}(0,0), e^*_{22}(0,0)) = (1,1)$. This yields payoffs of $p(1,1)v - c$ to player 1, the same as his payoffs before the deviation. Therefore, deviation to $e_{11} = 0$ is not gainful for player 1.

Moreover, since $\mathbf{e}^*_{\mathcal{G}} \neq (2,2)$, we know that if player 1 deviates unilaterally in Round 1 by choosing $e_{11} = 2$, then player 2 will not choose $e_{22} = 2$. Specifically, player 2 will choose $e_{22} = 1$: the right-hand side (weak) inequality in (29) implies that $(p(2,1) - p(2,0))v - c > 0$, by **A2** and **A4**. Consequently, this deviation is not gainful for player 1 since, by (29),

$$u_1(2,0;0,1) = p(2,1)v - 2c \leq p(1,1)v - c = u_1(1,0;0,1).$$

Thus, there is no profitable deviation for player 1.

There is also no profitable deviation for player 2 in Round 1. To see this, suppose player 2 deviates in Round 1 to $e_{21} = 2$. Recall that $(p(1,2) - p(0,2))v - c > 0$ (as argued in the above paragraph), or $p(1,2)v - c > p(0,2)v$. Since $\mathbf{e}^*_{\mathcal{G}} \neq (2,2)$, then $p(1,2)v - c > v - 2c$ (because $p(1,2)v - c > p(0,2)v$), i.e., $(1 - p(1,2))v - c < 0$. Therefore, player 1 chooses $e_{12} = 0$ following $\mathbf{e_1} = (1,2)$, and

$$u_2(1,2;0,0) = p(1,2)v - 2c \underbrace{\leq}_{(\mathbf{e}^*_{\mathcal{G}} = (1,1))} p(1,1)v - c = u_2(1,0;0,1).$$

Next, suppose player 2 deviates to $e_{21} = 1$. Note that $(e_{12}, e_{22}) = (0,0)$ is the only *NE* of the continuation game following $\mathbf{e_1} = (1,1)$, since $(1 - p(1,2))v - c < 0$ (as established above) and **A2** and **A4** apply. So,

$$u_2(1,1;0,0) = p(1,1)v - c = u_2(1,0;0,1).$$

Therefore, overall efforts $(1,1)$ can be supported in an *SPE* with $(1,0;0,1)$ (and by symmetry, $(0,1;1,0)$ is also an *SPE*).[28]

Note that in this case overall efforts of $(2,2)$ cannot be supported in an *SPE* of $\widehat{\mathcal{G}}$, by Lemma 2. Moreover, by Lemma 6, none of the overall efforts that are inferior to $(1,1)$ are subgame-perfect. Also, overall efforts $(2,1)$ (and by symmetry, $(1,2)$) cannot be supported in *SPE*. To show this, consider first overall efforts $(2,1)$ which can result from any of the following strategy profiles: $(0,0;2,1)$, $(1,1;1,0)$, $(1,0;1,1)$, $(0,1;2,0)$, $(2,0;0,1)$, and $(2,1;0,0)$. By Lemma 1, $(e^*_{12}(0,0), e^*_{22}(0,0)) \neq (2,1)$, hence $(0,0;2,1)$ cannot be an *SPE*. Next, consider $(1,1;1,0)$. If $(1,0)$ is an *NE* in the continuation game following $\mathbf{e_1} = (1,1)$, then by **A4** and **A2** respectively,

$$(p(2,1) - p(1,1))v - c \geq 0, \quad \text{i.e.,} \quad (p(2,2) - p(1,2))v - c > 0 \tag{30}$$

$$\text{and} \;\; (p(2,1) - p(1,1))v \geq (1 - p(1,1))v - c, \quad \text{i.e.,} \quad 0 \geq (1 - p(1,2))v - c. \tag{31}$$

However, these conditions are inconsistent. Therefore, $(e^*_{12}(1,1), e^*_{22}(1,1)) \neq (1,0)$, and $(1,1;1,0)$ cannot be an *SPE*. By the same argument, the profiles $(1,0;1,1)$ and $(0,1;2,0)$ cannot be *SPE*: both $(e^*_{12}(1,0), e^*_{22}(1,0)) = (1,1)$ and $(e^*_{12}(0,1), e^*_{22}(0,1)) = (2,0)$ require that conditions (30) and (31) simultaneously hold, an impossibility. Next, the strategy profile $(2,0;0,1)$ is an *SPE* only if $(e^*_{12}(2,0), e^*_{22}(2,0)) = (0,1)$, which in turn requires

$$(p(2,1) - p(2,0))v - c \geq (1 - p(2,0))v - 2c, \quad \text{i.e.,} \quad 0 \geq (1 - p(2,1))v - c.$$

Consequently, by **A2** and then **A4**, $0 > (p(2,1) - p(1,1))v - c$, i.e., $p(1,1)v - c > p(2,1)v - 2c$, thus player 1 gains from a unilateral first-round deviation to $e_{11} = 1$: following $\mathbf{e_1} = (1,0)$, in the continuation game $(0,1)$ is an *NE* (since $\mathbf{e}^*_{\mathcal{G}} = (1,1)$), and $u_1(1,0;0,1) = p(1,1)v - c > p(2,1)v - 2c = u_1(2,0;1,0)$. Therefore, $(2,0;1,0)$ cannot be an *SPE*. Finally, consider the strategy profile $(2,1;0,0)$. For $(e^*_{12}(2,1), e^*_{22}(2,1)) = (0,0)$ to arise, it must be that

$$0 \geq (1 - p(2,1))v - c,$$

which implies that, by **A2** and **A4**, $0 > (p(2,1) - p(1,1))v - c$, or that $p(1,1)v - c > p(2,1)v - 2c$. But then player 1 will find unilateral deviation to $e_{11} = 1$ gainful, because

[28] In fact, all strategy profiles leading to $(1,1)$ are *SPE*, a result derived in an earlier version of this paper.

$(e^*_{12}(1,1), e^*_{22}(1,1)) = (0,0)$ (why? $\mathbf{e}^*_{\mathcal{G}} = (1,1)$) and

$$u_1(1,1;0,0) = p(1,1)v - c > p(2,1)v - 2c = u_1(2,1;0,0).$$

Thus $(2,1;0,0)$ cannot be an *SPE* either.

This achieves (weak) domination of partial cooperation in the game $\mathcal{G}$ by partial cooperation in the game $\widehat{\mathcal{G}}$, through elimination of any inferior equilibrium. Moreover, this is the only overall equilibrium efforts possible in the game $\widehat{\mathcal{G}}$.

[**2**] Suppose that $\mathbf{e}^*_{\mathcal{G}} = (2,2)$ (possibly unique). Then in the transparent environment overall efforts of $(2,2)$ can also be supported in an *SPE* (by Lemma 5(i)). Moreover, by Lemma 7, none of the overall efforts that are inferior to $(2,2)$ can be supported in an *SPE*. Therefore, full cooperation in $\mathcal{G}$ is (weakly) dominated by full cooperation as the unique overall equilibrium efforts in the game $\widehat{\mathcal{G}}$.

[**3**] Finally, suppose the unique one-shot equilibrium is $\mathbf{e}^*_{\mathcal{G}} = (0,0)$. By Lemma 4($ii$), partial cooperation cannot arise in an *SPE*. However, by Proposition 2, full cooperation can arise in equilibrium in the extensive-form game. Therefore, shirking in $\mathcal{G}$ can be dominated by full cooperation in $\widehat{\mathcal{G}}$. ■

Derivation of Table 1

The equilibrium (or equilibria) reported in Table 1 are exhaustive. We start with a preliminary result that will be used repeatedly.

Lemma 9. *Suppose* $\mathbf{e}^*_{\mathcal{G}} = (0,0)$ *is unique. Then,*

(i) $c > (p(1,0) - p(0,0))v$;

(ii) $\mathbf{e}^*_{\widehat{\mathcal{G}}} \neq (1,0)$;

(iii) $\mathbf{e}^*_{\widehat{\mathcal{G}}} \neq (2,0)$;

(iv) *Further, if* $p(0,2)v > p(1,2)v - c$, *then* $\mathbf{e}^*_{\widehat{\mathcal{G}}} \neq (2,1)$.

Proof. (i) Uniqueness of $\mathbf{e}^*_{\mathcal{G}} = (0,0)$ implies the following conditions must hold: $p(0,0)v \geq p(1,0)v - c$, $p(1,1)v - c < \max\{p(0,1)v, p(2,1)v - 2c\}$, and $v - 2c < \max\{p(0,2)v, p(1,2)v - c\}$. We claim that $\max\{p(0,1)v, p(2,1)v - 2c\} = p(0,1)v$. Suppose not. Then $p(0,1)v < p(2,1)v - 2c$ and $p(1,1)v - c < p(2,1)v - 2c$, i.e., $c < \frac{p(2,1)-p(0,1)}{2}v$ and $c < (p(2,1) - p(1,1))v$. By **A4**, these conditions further imply that $c < \frac{1-p(0,2)}{2}v$ and $c < (1 - p(1,2))v$, or that

$\mathbf{e}^*_{\mathcal{G}} = (2,2)$, a contradiction. So $\max\{p(0,1)v, p(2,1)v - 2c\} = p(0,1)v$, which in turn implies that $p(0,1)v > p(1,1)v - c$, or $c > (p(1,1) - p(0,1))v$. Applying **A4** on this last inequality yields $c > (p(1,0) - p(0,0))v$.

(ii) Note that $(1,0)$ cannot be supported in *SPE* through the profile $(0,0;1,0)$, by Lemma 1. Thus the only way $(1,0)$ can be an *SPE* is through $(1,0;0,0)$, but this is not possible either: if player 1 deviates to $e_{11} = 0$, then $(0,0)$ is an *NE* in the continuation game, and player 1 receives $u_1(0,0;0,0) = p(0,0)v > p(1,0)v - c = u_1(1,0;0,0)$, by part *(i)*.

(iii) By Lemma 1, $(2,0)$ cannot be supported in *SPE* through $(0,0;2,0)$. Next, note that in part *(i)* we had established that $p(0,1)v \geq p(2,1)v - 2c$. By **A4**, this implies that $p(0,0)v > p(2,0)v - 2c$. Therefore, $(2,0;0,0)$ cannot be an *SPE*: player 1 can deviate to $e_{11} = 0$, following which $(e^*_{12}(0,0), e^*_{22}(0,0)) = (0,0)$ arises (since $\mathbf{e}^*_{\mathcal{G}} = (0,0)$), and he receives $u_1(0,0;0,0) = p(0,0)v > p(2,0)v - 2c = u_1(2,0;0,0)$, a profitable deviation. Finally, consider the strategy profile $(1,0;1,0)$. If player 1 deviates to $e_{11} = 0$, in the continuation game $(0,0)$ is an *NE* and he thus obtains $u_1(0,0;0,0) = p(0,0)v > p(2,0)v - 2c = u_1(1,0;1,0)$.

(iv) Since $\mathbf{e}^*_{\mathcal{G}} \neq (2,2)$, either $p(0,2)v > v - 2c$ or $p(1,2)v - c > v - 2c$ must hold. But then the condition $p(0,2)v > p(1,2)v - c$ implies that $p(0,2)v > v - 2c$.

This part will rely on Fig. 2. By Lemma 1, $(0,0;2,1)$ is not an *SPE*. The profile $(2,1;0,0)$ is not an *SPE* either: if player 2 deviates to $e_{21} = 0$, then by $p(0,2)v > p(1,2)v - c$, $p(0,2)v > v - 2c$ and **A2**, player 2's unique best response in Round 2 is $e_{22} = 0$. This results in $u_2(2,0;0,0) = p(2,0)v > p(2,1)v - c$, so player 2 would deviate in Round 1. Also, $(2,0;0,1)$ is not an *SPE*; following $\mathbf{e_1} = (2,0)$, player 2's unique best response is $e_{22} = 0$.

The profile $(0,1;2,0)$ is not an *SPE* as well. Applying **A4** on $p(0,2)v > v - 2c$ (established above) yields $p(0,1)v > p(2,1)v - 2c$ which, together with $p(0,1)v > p(1,1)v - c$ (part *(i)*), imply that player 1's unique best response, if player 2 chooses $e_{22} = 0$ in the continuation game following $\mathbf{e_1} = (0,1)$, is $e_{12} = 0$. Hence, $(e^*_{12}(0,1), e^*_{22}(0,1)) \neq (2,0)$. The profile $(1,1;1,0)$ is not an *SPE*: if $(1,0)$ is an *NE* following $\mathbf{e_1} = (1,1)$, then by player 1's best-response property $(p(2,1) - p(1,1))v \geq c$, which, by **A4**, implies that $(1 - p(1,2))v > c$, i.e., if player 1 chooses $e_{12} = 1$ then player 2 chooses $e_{22} = 1$ and *not* $e_{22} = 0$. Finally, $(1;0;1,1)$ cannot be an *SPE*: following $\mathbf{e_1} = (1,0)$, if player 1 chooses $e_{12} = 1$ then player 2 would prefer $e_{22} = 0$ over $e_{22} = 1$ (since $p(0,2)v > p(1,2)v - c$, by hypothesis). ||

We now verify the equilibria reported in Table 1. The analysis consists of two sets of conditions – the main condition and the subsidiary conditions – and it is developed in order of ascending costs.

1. Suppose that $c < (p(2,0) - p(1,0))v$. By **A4**, $c < (p(2,1) - p(1,1))v$; thus, if $c < (p(2,0) - p(1,0))v$, $\mathbf{e}^*_{\mathcal{G}} \neq (1,1)$ (see Proposition 1). Therefore, the only equilibrium

possibilities in the one-shot game are $(0,0)$ only, $(2,2)$ only, and the multiple equilibria of $(0,0)$ and $(2,2)$. We consider the following additional conditions.

(a) Suppose further that $c \leq (p(1,0)-p(0,0))v$. This condition and the main condition imply, respectively, that $p(1,0)v-c \geq p(0,0)v$ and $p(2,0)v-2c > p(1,0)v-c$; therefore, $p(2,0)v-2c > p(0,0)v$, or $c < \frac{p(2,0)-p(0,0)}{2}v$, which by Proposition 1 implies $\mathbf{e}^*_{\mathcal{G}} \neq (0,0)$. Since there always exists a pure strategy equilibrium in the game $\mathcal{G}$, it must be that $\mathbf{e}^*_{\mathcal{G}} = (2,2)$. Then by Proposition 3, the unique *SPE* is $\mathbf{e}^*_{\widehat{\mathcal{G}}} = (2,2)$.

Now suppose that

$$(p(1,0)-p(0,0))v < c.$$

We consider three subcases (configurations (b), (c), and (d)):

(b) Suppose that $(p(1,0)-p(0,0))v < c$ and $c < \frac{(p(2,0)-p(0,0))}{2}v$. From the latter condition it follows that $\mathbf{e}^*_{\mathcal{G}} \neq (0,0)$, hence, as in (a), it follows that $\mathbf{e}^*_{\mathcal{G}} = (2,2)$, and by Proposition 3 the unique *SPE* is $\mathbf{e}^*_{\widehat{\mathcal{G}}} = (2,2)$.

(c) Suppose that $(p(1,0)-p(0,0))v < c$ and $\frac{p(2,0)-p(0,0)}{2}v \leq c \leq \frac{1-p(0,2)}{2}v$. By **A4**, the main condition $c < (p(2,0)-p(1,0))v$ implies that $c < (1-p(1,2))v$; this, together with the additional condition $c \leq \frac{1-p(0,2)}{2}v$, implies that $\mathbf{e}^*_{\mathcal{G}} = (2,2)$. Also, the additional conditions $(p(1,0)-p(0,0))v < c$ and $\frac{p(2,0)-p(0,0)}{2}v \leq c$ imply that $\mathbf{e}^*_{\mathcal{G}} = (0,0)$. Since $\mathbf{e}^*_{\mathcal{G}} = (2,2)$, by Proposition 3 the unique *SPE* is $\mathbf{e}^*_{\widehat{\mathcal{G}}} = (2,2)$.

(d) Suppose that $(p(1,0)-p(0,0))v < c$ and $\frac{1-p(0,2)}{2}v < c$. The latter condition implies that $\mathbf{e}^*_{\mathcal{G}} \neq (2,2)$. Moreover, applying **A4** on this condition yields $\frac{p(2,0)-p(0,0)}{2}v < c$; this and $(p(1,0)-p(0,0))v < c$ imply that $\mathbf{e}^*_{\mathcal{G}} = (0,0)$.

We claim that $\mathbf{e}^*_{\widehat{\mathcal{G}}} = (0,0)$, i.e., $\mathbf{e}^*_{\widehat{\mathcal{G}}} = (0,0;0,0)$. First observe that following $\mathbf{e_1} = (0,0)$, (0,0) is an *NE* given that $\mathbf{e}^*_{\mathcal{G}} = (0,0)$. Now go back to Round 1. Suppose player 1 deviates to $e_{11} = 1$. By **A4**, the main condition implies $c < (1-p(1,2))v$, which, together with $\frac{1-p(0,2)}{2}v < c$, implies $((p(1,2)-p(0,2))v < c$. This and $\frac{1-p(0,2)}{2}v < c$ (defining player 2's best response) and the main condition $c < (p(2,0)-p(1,0))v$ (defining player 1's best response) imply that following $\mathbf{e_1} = (1,0)$, (1,0) is an *NE*, yielding player 1 the payoff $u_1(1,0;1,0) = p(2,0)v-2c < p(0,0)v = u_1(0,0;0,0)$ (by the inequality in the previous paragraph). Finally, suppose player 1 deviates to $e_{11} = 2$. From $((p(1,2)-p(0,2))v < c$ and $\frac{1-p(0,2)}{2}v < c$, we know that player 2 would choose $e_{22} = 0$, yielding player 1 the payoff

$u_1(2,0;0,0) = p(2,0)v - 2c < p(0,0)v = u_1(0,0;0,0)$. By symmetry, there is no profitable deviation for player 2.

We claim that $\mathbf{e}^*_{\widehat{\mathcal{G}}} \neq (2,2)$. Note that by Proposition 2, full cooperation arises in this case only through $(1,1;1,1)$; applying **A4** on the main condition allows us to conclude that $(1,1)$ is an *NE* following $\mathbf{e_1} = (1,1)$. However, the sequence of efforts $(1,1;1,1)$ is not an *SPE* because player 2 (say) can profitably deviate to $e_{21} = 0:$ following $\mathbf{e_1} = (1,0)$, we know (from the argument above) that (1,0) is an *NE*, so player 2 would receive $u_2(1,0;1,0) = p(2,0)v > v - 2c = u_2(1,1;1,1)$.

Since $\mathbf{e}^*_{\mathcal{G}} = (0,0)$ is unique, by Lemma 9 $\mathbf{e}^*_{\widehat{\mathcal{G}}} \neq (1,0)$ and $\mathbf{e}^*_{\widehat{\mathcal{G}}} \neq (2,0)$; and by Lemma 4$(ii)$, $\mathbf{e}^*_{\widehat{\mathcal{G}}} \neq (1,1)$. Finally, rewrite $((p(1,2) - p(0,2))v < c$ (as shown above) as $p(1,2)v - c < p(0,2)v$, which, by Lemma 9(iv), implies $\mathbf{e}^*_{\widehat{\mathcal{G}}} \neq (2,1)$.

Therefore, the unique *SPE* is $\mathbf{e}^*_{\widehat{\mathcal{G}}} = (0,0)$.

2. Suppose that the main condition is now $(p(2,0) - p(1,0))v \leq c < (p(2,1) - p(1,1))v$. From the right-hand side inequality, we conclude that $\mathbf{e}^*_{\mathcal{G}} \neq (1,1)$ by Proposition 1. Therefore, the only equilibrium possibilities in the one-shot game are $(0,0)$ only, $(2,2)$ only, and the multiple equilibria of $(0,0)$ and $(2,2)$. Moreover, note that the right-hand side inequality also implies that $c < (1 - p(1,2))v$.

   (e) Suppose that $c < (p(1,0) - p(0,0))v$ holds at the same time; thus $\mathbf{e}^*_{\mathcal{G}} \neq (0,0)$. Since there always exists a pure strategy equilibrium in the game $\mathcal{G}$, it must be that $\mathbf{e}^*_{\mathcal{G}} = (2,2)$. By Proposition 3, the unique *SPE* is $\mathbf{e}^*_{\widehat{\mathcal{G}}} = (2,2)$.

   (f) Next, suppose that $c = (p(1,0) - p(0,0))v$. This condition and the left-hand side inequality of the main condition imply that $p(0,0)v = p(1,0)v - c \geq p(2,0)v - 2c$, i.e., $\mathbf{e}^*_{\mathcal{G}} = (0,0)$. Applying **A4** on the subsidiary condition yields $p(0,2)v < p(1,2)v - c$. Likewise, by **A4**, the right-hand side inequality of the main condition implies that $p(1,2)v - c < v - 2c$. Therefore, $p(0,2)v < p(1,2)v - c < v - 2c$, i.e., $\mathbf{e}^*_{\mathcal{G}} = (2,2)$. By Proposition 3, the unique *SPE* is $\mathbf{e}^*_{\widehat{\mathcal{G}}} = (2,2)$.

   Now suppose that

$$(p(1,0) - p(0,0))v < c.$$

   From this condition and the left-hand side inequality of the main condition, we see that $p(0,0)v > p(1,0)v - c \geq p(2,0)v - 2c$, i.e., $\mathbf{e}^*_{\mathcal{G}} = (0,0)$. We consider three subcases (configurations (g), (h), and (i)):

   (g) Consider $(p(1,0) - p(0,0))v < c$ and $c \leq \frac{1-p(0,2)}{2}v$. The latter condition and applying **A4** on the right-hand side inequality of the main condition yield $\mathbf{e}^*_{\mathcal{G}} =$

$(2,2)$. Moreover, $\mathbf{e}^*_{\mathcal{G}} = (0,0)$, once by the left-hand side inequality of the main condition, then a second time again by the left-hand side inequality of the main condition together with the left-hand side inequality of the subsidiary condition. By Proposition 3, the unique *SPE* is $\mathbf{e}^*_{\widehat{\mathcal{G}}} = (2,2)$.

(h) Consider $(p(1,0) - p(0,0))v < c$ and $\frac{1-p(0,2)}{2}v < c \leq \frac{1-p(0,1)}{2}v$. By the left-hand side inequality of the latter relation, $\mathbf{e}^*_{\mathcal{G}} \neq (2,2)$. Since there always exists a pure strategy equilibrium in the game $\mathcal{G}$, it must be that $\mathbf{e}^*_{\mathcal{G}} = (0,0)$. By Lemma 3, using the main condition and the subsidiary conditions listed in Table 1 and applying **A4** we can conclude that $\mathbf{e}^*_{\widehat{\mathcal{G}}} = (0,0)$ and $\mathbf{e}^*_{\widehat{\mathcal{G}}} = (2,2)$. The right-hand side inequality of the main condition implies that $c < (1 - p(1,2))v$, or $p(1,2)v - c < v - 2c$; together with the left-hand side inequality of the second subsidiary condition, this yields $p(1,2)v-c < v-2c < p(0,2)v$, thus $\mathbf{e}^*_{\widehat{\mathcal{G}}} \neq (2,1)$, by Lemma 9$(iv)$. Since $\mathbf{e}^*_{\mathcal{G}} = (0,0)$ is unique, by Lemma 9 it follows that $\mathbf{e}^*_{\widehat{\mathcal{G}}} \neq (1,0)$ and $\mathbf{e}^*_{\widehat{\mathcal{G}}} \neq (2,0)$; and by Lemma 4$(ii)$, $\mathbf{e}^*_{\widehat{\mathcal{G}}} \neq (1,1)$.

(i) Finally, suppose that $(p(1,0) - p(0,0))v < c$ and $\frac{1-p(0,1)}{2}v < c$. By **A3**, the latter implies that $\frac{1-p(0,2)}{2}v < c$, i.e., $\mathbf{e}^*_{\mathcal{G}} \neq (2,2)$. Therefore, shirking is the unique one-shot equilibrium.

Note that because of the subsidiary condition $\frac{1-p(0,1)}{2}v < c$, Lemma 3 does not apply. We establish that $\mathbf{e}^*_{\widehat{\mathcal{G}}} = (0,0)$, i.e. $(0,0;0,0)$ is an *SPE*, as follows. That following $\mathbf{e_1} = (0,0)$, $(0,0)$ is an *NE* is clear. So consider the beginning of Round 1. Suppose player 2 deviates to $e_{21} = 1$. The right-hand side inequality of the main condition combined with $\frac{1-p(0,2)}{2}v < c$ and **A4** result in $p(0,2)v > v - 2c > p(1,2)v - c$, i.e., $c > \frac{1-p(0,2)}{2}v$ and $c > (p(1,2) - p(0,2))v$. Applying **A4** on these two conditions yields $c > \frac{p(2,1)-p(0,1)}{2}v$ and $c > (p(1,1) - p(0,1))v$, or $p(0,1)v > p(2,1)v - 2c$ and $p(0,1)v > p(1,1)v - c$; thus in the continuation game following $(0,1)$ in the first round, $e_{12} = 0$ is player 1's best response when player 2 chooses $e_{22} = 0$. Further, if player 1 chooses $e_{12} = 0$, player 2's best response is $e_{22} = 0$, by the left-hand side inequality of the main condition. Thus $(0,0)$ is an *NE* in the said continuation game, resulting in the payoff $u_2(0,1;0,0) = p(0,1)v - c < p(0,0)v = u_2(0,0;0,0)$ (from condition $(p(1,0)-p(0,0))v < c$). If player 2 deviates to $e_{21} = 2$, we know that $e_{12} = 0$ (since $p(0,2)v > v - 2c > p(1,2)v - c$, as argued above); therefore, $u_2(0,2;0,0) = p(0,2)v - 2c < p(0,0)v = u_2(0,0;0,0)$ (from condition $v - 2c < p(0,2)v$ and **A4**). By symmetry, there is no profitable deviation for player 1.

We claim that in the extensive form, $\mathbf{e}^*_{\widehat{\mathcal{G}}} \neq (2,2)$. To see this, note that by

Proposition 2, full cooperation in this case only arises through $(1,1;1,1)$. The right-hand side inequality of the main condition, with **A4** applied to it, guarantees that $(1,1)$ is an *NE* following $(1,1)$. However, suppose that player 1 deviates to $e_{11}=0$. As we have shown above, in the continuation game following $(0,1)$ in the first round, $(0,0)$ is an *NE*, thus player 1 receives $u_1(0,1;0,0)=p(0,1)v > v-2c = u_1(1,1;1,1)$ (since by hypothesis, $\frac{1-p(0,1)}{2}v < c$), a profitable deviation.

Since $\mathbf{e}^*_{\mathcal{G}}=(0,0)$ is unique, by Lemma 9 it follows that $\mathbf{e}^*_{\widehat{\mathcal{G}}} \neq (1,0)$ and $\mathbf{e}^*_{\widehat{\mathcal{G}}} \neq (2,0)$; and by Lemma 4($ii$), $\mathbf{e}^*_{\widehat{\mathcal{G}}} \neq (1,1)$.

By **A4**, the right-hand side inequality of main condition implies that $p(1,2)v - c < v-2c$. Together with $\frac{1-p(0,2)}{2}v < c$ (as shown above), we conclude that $p(1,2)v-c < p(0,2)v$. Therefore, by Lemma 9(iv), $\mathbf{e}^*_{\widehat{\mathcal{G}}} \neq (2,1)$.

3. Suppose that the main condition is now $(p(2,1)-p(1,1))v \leq c \leq (1-p(1,2))v$. First, consider the case where c also satisfies

$$c \leq \frac{1-p(0,2)}{2}v.$$

We analyze three subcases (configurations (j), (k), and (l)).

(j) Suppose that $c \leq \frac{1-p(0,2)}{2}v$ and $c < (p(1,0)-p(0,0))v$. The right-hand side inequality of the main condition and $c \leq \frac{1-p(0,2)}{2}v$ imply that $\mathbf{e}^*_{\mathcal{G}}=(2,2)$. Applying **A4** on $c < (p(1,0)-p(0,0))v$ and combining it with the left-hand side of the main condition yields $(p(2,1)-p(1,1))v \leq c < (p(1,1)-p(0,1))v$, i.e, $\mathbf{e}^*_{\mathcal{G}}=(1,1)$. The condition $c < (p(1,0)-p(0,0))v$ implies that $\mathbf{e}^*_{\mathcal{G}} \neq (0,0)$. By Proposition 3, the unique *SPE* is $\mathbf{e}^*_{\widehat{\mathcal{G}}}=(2,2)$.

(k) Next, suppose that $c \leq \frac{1-p(0,2)}{2}v$ and $(p(1,0)-p(0,0))v \leq c \leq (p(1,1)-p(0,1))v$. As in case ($j$) above we have $\mathbf{e}^*_{\mathcal{G}}=(2,2)$, while the left-hand side inequality of the main condition and $c \leq (p(1,1)-p(0,1))v$ imply that $\mathbf{e}^*_{\mathcal{G}}=(1,1)$. Applying **A4** on the left-hand side inequality of the main condition yields $p(2,0)v-2c < p(1,0)v-c$; this and the fact that $(p(1,0)-p(0,0))v \leq c$ result in $p(2,0)v-2c < p(1,0)v-c \leq p(0,0)v$, i.e., $\mathbf{e}^*_{\mathcal{G}}=(0,0)$. By Proposition 3, the unique *SPE* is $\mathbf{e}^*_{\widehat{\mathcal{G}}}=(2,2)$.

(l) Finally, suppose that $c \leq \frac{1-p(0,2)}{2}v$ and $(p(1,1)-p(0,1))v < c$. From the latter condition, it follows that $\mathbf{e}^*_{\mathcal{G}} \neq (1,1)$. As in case ($j$), we have $\mathbf{e}^*_{\mathcal{G}}=(2,2)$. Applying **A4**, the left-hand side inequality of the main condition and $(p(1,1)-p(0,1))v < c$ imply, respectively, that $p(2,0)v-2c < p(1,0)v-c$ and $p(1,0)v-c < p(0,0)v$, i.e., $\mathbf{e}^*_{\mathcal{G}}=(0,0)$. By Proposition 3, the unique *SPE* is $\mathbf{e}^*_{\widehat{\mathcal{G}}}=(2,2)$.

Now we consider the case where

$$\frac{1-p(0,2)}{2}v < c.$$

This implies that $\mathbf{e}^*_{\mathcal{G}} \neq (2,2)$. Note that the right-hand side inequality of the main condition can be rewritten as $p(1,2)v - c \leq v - 2c$, while the condition $\frac{1-p(0,2)}{2}v < c$ can be rewritten as $v - 2c < p(0,2)v$. Combining the two we obtain $p(1,2)v - c < p(0,2)v$, i.e, $(p(1,2) - p(0,2))v < c$. Applying **A4** on this condition we obtain $(p(1,0) - p(0,0))v < c$, and applying **A4** on the subsidiary condition $\frac{1-p(0,2)}{2}v < c$ yields $\frac{p(2,0)-p(0,0)}{2}v < c$. By Proposition 1, these two conditions imply that $\mathbf{e}^*_{\mathcal{G}} = (0,0)$. We now analyze three subcases (configurations (m), (n), (o)).

(m) Suppose that $\frac{1-p(0,2)}{2}v < c \leq \frac{1-p(0,1)}{2}v$ and $c \leq (p(1,0) - p(0,0))v$. This set is empty. To see why, note that by **A4**, the condition $c \leq (p(1,0) - p(0,0))v$ implies that $p(0,2)v < p(1,2)v - c$. Together with the right-hand side inequality of the main condition, it must be that $p(0,2)v < p(1,2)v - c \leq v - 2c$, contradicting the fact that $\frac{1-p(0,2)}{2}v < c$.

(n) Suppose $\frac{1-p(0,2)}{2}v < c \leq \frac{1-p(0,1)}{2}v$ and $(p(1,0) - p(0,0))v < c \leq (p(1,1) - p(0,1))v$. The left-hand side inequality of the main condition and $c \leq (p(1,1) - p(0,1))v$ imply that $\mathbf{e}^*_{\mathcal{G}} = (1,1)$. By Proposition 3, the unique *SPE* is $\mathbf{e}^*_{\widehat{\mathcal{G}}} = (1,1)$.

(o) Suppose that $\frac{1-p(0,2)}{2}v < c \leq \frac{1-p(0,1)}{2}v$ and $(p(1,1) - p(0,1))v < c$. The latter condition implies that $\mathbf{e}^*_{\mathcal{G}} \neq (1,1)$. By Lemma 3 – using the main condition, **A4**, and the subsidiary conditions – we can conclude that $\mathbf{e}^*_{\widehat{\mathcal{G}}} = (0,0)$ and $\mathbf{e}^*_{\widehat{\mathcal{G}}} = (2,2)$. The right-hand side inequality of the main condition and the left-hand side inequality of the first subsidiary condition together yield $p(1,2)v - c \leq v - 2c < p(0,2)v$, thus $\mathbf{e}^*_{\widehat{\mathcal{G}}} \neq (2,1)$, by Lemma 9$(iv)$. Since $\mathbf{e}^*_{\mathcal{G}} = (0,0)$ is unique, by Lemma 9 it follows that $\mathbf{e}^*_{\widehat{\mathcal{G}}} \neq (1,0)$ and $\mathbf{e}^*_{\widehat{\mathcal{G}}} \neq (2,0)$; and by Lemma 4$(ii)$, $\mathbf{e}^*_{\widehat{\mathcal{G}}} \neq (1,1)$.

Now we consider the case where

$$\frac{1-p(0,1)}{2}v < c.$$

Since it follows by **A3** that $\frac{1-p(0,2)}{2}v < c$, we can conclude as in the above subcases that $\mathbf{e}^*_{\mathcal{G}} \neq (2,2)$ and $\mathbf{e}^*_{\mathcal{G}} = (0,0)$. Let us then consider two subcases.

(p) Suppose that $\frac{1-p(0,1)}{2}v < c$ and $c \leq (p(1,1) - p(0,1))v$. The latter condition and the left-hand side inequality of the main condition imply that $\mathbf{e}^*_{\mathcal{G}} = (1,1)$. By Proposition 3, the unique *SPE* is $\mathbf{e}^*_{\widehat{\mathcal{G}}} = (1,1)$.

(q) Finally, suppose that $\frac{1-p(0,1)}{2}v < c$ and $(p(1,1) - p(0,1))v < c$. Then by the latter condition, $\mathbf{e}^*_{\mathcal{G}} \neq (1,1)$. Hence $\mathbf{e}^*_{\mathcal{G}} = (0,0)$, which is already guaranteed, is unique. However, because of the condition $\frac{1-p(0,1)}{2}v < c$, we cannot use Lemma 3. Note that the subsidiary condition $\frac{1-p(0,1)}{2}v < c$ implies that $\frac{1-p(0,2)}{2}v < c$; combining with the right-hand side inequality of the main condition, we obtain $p(1,2)v - c \leq v - 2c < p(0,2)v$. Therefore, using the same argument as in configuration (i), we can show that $\mathbf{e}^*_{\widehat{\mathcal{G}}} = (0,0)$ and $\mathbf{e}^*_{\widehat{\mathcal{G}}} \neq (2,2)$.

Since $\mathbf{e}^*_{\mathcal{G}} = (0,0)$ is unique, by Lemma 9 it follows that $\mathbf{e}^*_{\widehat{\mathcal{G}}} \neq (1,0)$ and $\mathbf{e}^*_{\widehat{\mathcal{G}}} \neq (2,0)$; and by Lemma 4$(ii)$, $\mathbf{e}^*_{\widehat{\mathcal{G}}} \neq (1,1)$.

From $p(1,2)v - c \leq v - 2c < p(0,2)v$ already established above, conclude that $p(1,2)v - c < p(0,2)v$. Therefore, by Lemma 9(iv), $\mathbf{e}^*_{\widehat{\mathcal{G}}} \neq (2,1)$.

4. Suppose that the main condition is now $(1-p(1,2))v < c$. Then $\mathbf{e}^*_{\mathcal{G}} \neq (2,2)$. Therefore, the only possible equilibria are $(1,1)$ only, $(0,0)$ only, and the multiple equilibria of $(1,1)$ and $(0,0)$. We consider the following subsidiary conditions.

(r) Suppose that $c < (p(1,0) - p(0,0))v$; thus $\mathbf{e}^*_{\mathcal{G}} \neq (0,0)$. Since there always exists a pure strategy equilibrium in the game $\mathcal{G}$, it must be that $\mathbf{e}^*_{\mathcal{G}} = (1,1)$. By Proposition 3, the unique *SPE* is $\mathbf{e}^*_{\widehat{\mathcal{G}}} = (1,1)$.

(s) Suppose now that $(p(1,0) - p(0,0))v \leq c \leq (p(1,1) - p(0,1))v$. The condition $c \leq (p(1,1) - p(0,1))v$ and the main condition (where **A4** is used) imply that $\mathbf{e}^*_{\mathcal{G}} = (1,1)$. Applying **A4** on the main condition, we obtain $p(1,0)v - c > p(2,0)v - 2c$; combining this with the condition $(p(1,0) - p(0,0))v \leq c$ yields $p(0,0)v \geq p(1,0)v - c > p(2,0)v - 2c$; thus $\mathbf{e}^*_{\mathcal{G}} = (0,0)$. By Proposition 3, the unique *SPE* is $\mathbf{e}^*_{\widehat{\mathcal{G}}} = (1,1)$.

Now we consider the case where

$$(p(1,1) - p(0,1))v < c \leq (p(1,2) - p(0,2))v,$$

which is analyzed in three subcases (configurations (t), (u), and (v)). The left-hand side inequality of the above condition implies that $\mathbf{e}^*_{\mathcal{G}} \neq (1,1)$. Since a pure-strategy *NE* must exist in $\mathcal{G}$, it must be that the unique one-shot equilibrium is $\mathbf{e}^*_{\mathcal{G}} = (0,0)$.

Note that by Proposition 2, full cooperation in this case only arises through $(1,1;1,1)$. However, the main condition implies that $(e^*_{11}(1,1), e^*_{21}(1,1)) \neq (1,1)$, thus $\mathbf{e}^*_{\widehat{\mathcal{G}}} \neq (2,2)$.

Consider the profile $(0,0;0,0)$, and the continuation game following the first-round deviation of player 2 (this argument applies to player 1 as well, by symmetry) to $e_{21}=1$. Applying **A4** on the main condition yields $(p(2,1)-p(1,1))v<c$; this and the subsidiary condition $(p(1,1)-p(0,1))v<c$ together imply that $p(2,1)v-2c<p(1,1)v-c<p(0,1)v$, i.e., following $\mathbf{e_1}=(0,1)$, $e_{12}=0$ is the best response of player 1 to $e_{22}=0$. Moreover, applying **A4** on the main condition and then **A2** yields $(p(0,2)-p(0,1))v<c$, i.e., following $\mathbf{e_1}=(0,1)$, $e_{22}=0$ is the best response of player 2 to $e_{12}=0$. Thus $(e^*_{12}(0,1),e^*_{22}(0,1))=(0,0)$, and player 2's deviation results in the payoff $u_2(0,1;0,0)=p(0,1)v-c<p(0,0)v=u_2(0,0;0,0)$ (by applying **A4** on condition $(p(1,1)-p(0,1))v<c$). Now consider player 2's deviation to $e_{21}=2$. By the condition $c\leq(p(1,2)-p(0,2))v$ and the main condition, player 1 can choose $e_{12}=0$ (if $c\leq(p(1,2)-p(0,2))v$ holds as an equality) or $e_{12}=1$ (if it holds strictly) in the continuation game. If he chooses $e_{12}=0$, then player 2 receives the payoff $u_2(0,2;0,0)=p(0,2)v-2c$. Applying **A4** on the main condition and on the left-hand side inequality of the subsidiary condition yields, respectively, $(p(2,0)-p(1,0))v<c$ and $(p(1,0)-p(0,0))v<c$, i.e., $p(2,0)v-2c<p(1,0)v-c$ and $p(1,0)v-c<p(0,0)v$. Thus $p(2,0)v-2c<p(0,0)v$, and $u_2(0,2;0,0)=p(0,2)v-2c<p(0,0)v=u_2(0,0;0,0)$, an unprofitable deviation. On the other hand, suppose that following $\mathbf{e_1}=(0,2)$, player 1 chooses $e_{12}=1$ such that player 2 receives $u_2(0,2;1,0)=p(1,2)v-2c$. Consider two subcases:

(t) Suppose that $(p(1,1)-p(0,1))v<c\leq(p(1,2)-p(0,2))v$ and $\frac{p(1,2)-p(0,0)}{2}v<c$. Then $u_2(0,2;1,0)=p(1,2)v-2c<p(0,0)v=u_2(0,0;0,0)$. Therefore, there does not exist a profitable deviation for player 2 (and by symmetry, for player 1), and hence $\mathbf{e}^*_{\widehat{\mathcal{G}}}=(0,0)$.

We claim that $\mathbf{e}^*_{\widehat{\mathcal{G}}}\neq(2,1)$. By Lemma 1, the profile $(0,0;2,1)$ cannot be an *SPE*. Applying **A4** on the main condition yields $(p(2,1)-p(1,1))v<c$; by this condition, $(e^*_{12}(1,1),e^*_{22}(1,1))=(0,0)$. This implies that $(2,1;0,0)$ cannot be an *SPE*: if player 1 deviates to $e_{11}=1$, then he receives $u_1(1,1;0,0)=p(1,1)v-c>p(2,1)v-2c=u_1(2,1;0,0)$ (by the condition $(p(2,1)-p(1,1))v<c$). Next check that $(2,0;0,1)$ cannot be an *SPE*. Since $\mathbf{e}^*_{\mathcal{G}}=(0,0)$, following $\mathbf{e_1}=(0,0)$, $(0,0)$ is an *NE*, which implies that player 1 can profitably deviate to $e_{11}=0$: $u_1(0,0;0,0)=p(0,0)v>p(2,1)v-2c=u_1(2,0;0,1)$, by the subsidiary condition $\frac{p(1,2)-p(0,0)}{2}v<c$. The profile $(0,1;2,0)$ cannot be an *SPE* either: following $\mathbf{e_1}=(0,1)$, if player 2 chooses $e_{22}=0$ then $e_{12}=0$ yields player 1 strictly higher payoff than $e_{12}=2$, by $(p(2,1)-p(1,1))v<c$ and the left-hand side inequality of the

first subsidiary condition. Also $(1,1;1,0)$ cannot be an *SPE*: following $\mathbf{e_1} = (1,1)$, if player 2 chooses $e_{22} = 0$ then player 1 is strictly better off choosing $e_{12} = 0$ than $e_{12} = 1$, by $(p(2,1) - p(1,1))v < c$. Finally, $(1,0;1,1)$ cannot be an *SPE*: following $\mathbf{e_1} = (1,0)$, player 1 would strictly prefer $e_{12} = 0$ over $e_{12} = 1$ if player 2 chooses $e_{22} = 1$, by the main condition and **A4**.

Since $\mathbf{e}^*_{\mathcal{G}} = (0,0)$ is unique, by Lemma 9 it follows that $\mathbf{e}^*_{\widehat{\mathcal{G}}} \neq (1,0)$ and $\mathbf{e}^*_{\widehat{\mathcal{G}}} \neq (2,0)$; and by Lemma 4$(ii)$, $\mathbf{e}^*_{\widehat{\mathcal{G}}} \neq (1,1)$.

(u) Suppose that $(p(1,1) - p(0,1))v < c \leq (p(1,2) - p(0,2))v$ and $\frac{p(1,2)-p(0,0)}{2}v = c$. Then $u_2(0,2;1,0) = p(1,2)v - 2c = p(0,0)v = u_2(0,0;0,0)$. Therefore, there does not exist a profitable deviation for player 2 (and by symmetry, for player 1), and hence $\mathbf{e}^*_{\widehat{\mathcal{G}}} = (0,0)$.

We claim that $\mathbf{e}^*_{\widehat{\mathcal{G}}} = (2,1)$, through the strategy profile $(2,0;0,1)$. Player 1's first-round deviation to $e_{11} = 0$ is not profitable: $u_1(0,0;0,0) = p(0,0)v = p(2,1)v - 2c = u_1(2,0;0,1)$, by $\frac{p(1,2)-p(0,0)}{2}v = c$. Earlier we had shown that $(0,0)$ is an *NE* following $\mathbf{e_1} = (1,0)$. Therefore, a first-round deviation by player 1 to $e_{11} = 1$ is also not profitable: $u_1(1,0;0,0) = p(1,0)v - c < p(0,0)v = p(2,1)v - 2c = u_1(2,0;0,1)$, where the strict inequality follows from applying **A4** on the left-hand side inequality of the first subsidiary condition. Now consider first-round deviations by player 2. If he deviates to $e_{21} = 1$, by the main condition we know that $e_{22} = 0$, which does not alter his payoff: $u_2(2,1;0,0) = p(2,1)v - c = u_2(2,0;0,1)$. If, on the other hand, he deviates to $e_{21} = 2$, then by the main condition he is worse off: $u_2(2,2;0,0) = v - 2c < p(2,1)v - c = u_2(2,0;0,1)$.

(v) Suppose that $(p(1,1) - p(0,1))v < c \leq (p(1,2) - p(0,2))v$ and $c < \frac{p(1,2)-p(0,0)}{2}v$. Then $u_2(0,2;1,0) = p(1,2)v - 2c > p(0,0)v = u_2(0,0;0,0)$, i.e., player 2 can profitably deviate to $e_{21} = 2$, so $\mathbf{e}^*_{\mathcal{G}} \neq (0,0)$. (Following $\mathbf{e_1} = (0,2)$, it is optimal for player 1 to choose $e_{12} = 1$.)

We claim that $\mathbf{e}^*_{\widehat{\mathcal{G}}} = (2,1)$, with the profile $(0,2;1,0)$. Note that if player 2 deviates to $e_{21} = 1$, then $(e^*_{12}(0,1), e^*_{22}(0,1)) = (0,0)$, as established earlier, and he receives $u_2(0,1;0,0) = p(0,1)v - c$. This implies that the deviation is unprofitable, since $p(0,1)v - c < p(0,0)v$ (this follows from applying **A4** on the subsidiary condition $(p(1,1) - p(0,1))v < c$), and $p(0,0)v < p(1,2)v - 2c = u_2(0,2;1,0)$ (by the second subsidiary condition). If he instead deviates to $e_{21} = 0$, then $(e^*_{11}(0,0), e^*_{21}(0,0)) = (0,0)$, and he receives $u_2(0,0;0,0) = p(0,0)v < p(1,2)v - 2c = u_2(0,2;1,0)$. Therefore, there exists no profitable deviation for player 2. Now consider player 1. He can deviate to $e_{11} = 1$, following which he will choose $e_{12} = 0$

(by the main condition), resulting in the payoff $u_1(1,2;0,0) = p(1,2)v - c = u_1(0,2;1,0)$. He can also deviate to $e_{11} = 2$ and receive $u_1(2,2;0,0) = v - 2c < p(1,2)v - c = u_1(0,2;1,0)$ (by the main condition). Therefore, there also does not exist any profitable deviation for player 1.

(w) Finally, suppose that $(p(1,2) - p(0,2))v < c$. By **A4**, this implies that $(p(1,1) - p(0,1))v < c$, or that $\mathbf{e}^*_{\mathcal{G}} \neq (1,1)$. Since a pure-strategy *NE* must exist in $\mathcal{G}$, it must be that the unique one-shot equilibrium is $\mathbf{e}^*_{\mathcal{G}} = (0,0)$.

Consider the profile $(0,0;0,0)$. We need to consider only first-round deviations; there will be no deviation incentive in the second round. Applying **A4** on $(p(1,2) - p(0,2))v < c$ and on the main condition yields, respectively, $(p(1,1) - p(0,1))v < c$ and $(p(2,1) - p(1,1))v < c$, implying that $p(2,1)v - 2c < p(1,1)v - c < p(0,1)v$, and applying **A4** on the main condition and then **A2** yields $(p(0,2) - p(0,1))v < c$. Therefore, following $\mathbf{e_1} = (0,1)$, $(0,0)$ is an *NE*, thus the deviation by player 2 to $e_{21} = 1$ is unprofitable: $u_2(0,1;0,0) = p(0,1)v - c < p(0,0)v = u_2(0,0;0,0)$ (by applying **A4** on the subsidiary condition $(p(1,2) - p(0,2))v < c$). Player 2's deviation to $e_{21} = 2$ is likewise unprofitable since in the continuation game player 1 chooses $e_{12} = 0$ (by the main and the subsidiary conditions), and $u_2(0,2;0,0) = p(0,2)v - 2c < p(0,0)v$ (by applying **A4** both on the main condition and on the subsidiary condition). By symmetry, there is no profitable deviation for player 1. Therefore, $\mathbf{e}^*_{\widehat{\mathcal{G}}} = (0,0)$.

Since $\mathbf{e}^*_{\mathcal{G}} = (0,0)$ is unique, by Proposition 2 the only way $(2,2)$ can be supported in an *SPE* is through the profile $(1,1;1,1)$. But the main condition implies that $(e^*_{11}(1,1), e^*_{21}(1,1)) \neq (1,1)$, so $\mathbf{e}^*_{\widehat{\mathcal{G}}} \neq (2,2)$.

Also, uniqueness of $\mathbf{e}^*_{\mathcal{G}} = (0,0)$ implies, by Lemma 9, that $\mathbf{e}^*_{\widehat{\mathcal{G}}} \neq (1,0)$ and $\mathbf{e}^*_{\widehat{\mathcal{G}}} \neq (2,0)$; and by Lemma 4$(ii)$, $\mathbf{e}^*_{\widehat{\mathcal{G}}} \neq (1,1)$.

Finally, rewriting the subsidiary condition yields $p(1,2)v - c < p(0,2)v$. Therefore, by Lemma 9(iv), $\mathbf{e}^*_{\widehat{\mathcal{G}}} \neq (2,1)$. ■

Existence of (possibly asymmetric) pure strategy NE in $\mathcal{G}_{\mathcal{S}}$. *The one-shot game, $\mathcal{G}_{\mathcal{S}}$, has at least one pure-strategy Nash equilibrium.*

Proof. Suppose that $\mathbf{e}^*_{\mathcal{G}_{\mathcal{S}}} \neq (0,0)$. Then (refer to Fig. 4),

$$\rho(0,0)v < \max\{\rho(1,0)v - c, \rho(2,0)v - 2c\}. \tag{32}$$

If $\max\{\rho(1,0)v-c, \rho(2,0)v-2c\} = \rho(1,0)v-c$, then

$$\begin{aligned} & \rho(1,0)v - c \geq \rho(2,0)v - 2c, \qquad \text{i.e.,} \qquad c \geq (\rho(2,0)-\rho(1,0))v && (33)\\ \text{and} \qquad & \rho(1,0)v - c > \rho(0,0)v, \qquad \text{i.e.,} \qquad (\rho(1,0)-\rho(0,0))v > c, && (34)\end{aligned}$$

from which we can infer, using **A4′** in (33), that

$$c > (\rho(2,1)-\rho(1,1))v. \tag{35}$$

Now if

$$(\rho(1,0)-\rho(0,0))v \underbrace{>}_{\text{by } \mathbf{A4'}} (\rho(1,1)-\rho(0,1))v \underbrace{\geq}_{\text{by hypothesis}} c,$$

then this and (35) imply that

$$(\rho(1,1)-\rho(0,1))v \geq c > (\rho(2,1)-\rho(1,1))v,$$

i.e, $\rho(1,1)v-c \geq \rho(0,1)v$ and $\rho(1,1)v-c > \rho(2,1)v-2c$, thus $\mathbf{e}^*_{\mathcal{G}_\mathcal{S}} = (1,1)$. On the other hand, if alternative to our initial hypothesis (see above)

$$(\rho(1,0)-\rho(0,0))v > c > (\rho(1,1)-\rho(0,1))v,$$

then using the right-hand side inequality, (35) and **A2** yield

$$\rho(1,0)v > \rho(1,1)v-c > \rho(1,2)v-2c.$$

This, as well as (33) and (34), imply that $\mathbf{e}^*_{\mathcal{G}_\mathcal{S}} = (1,0)$.

We assumed above that $\mathbf{e}^*_{\mathcal{G}_\mathcal{S}} \neq (0,0)$ and $\max\{\rho(1,0)v-c, \rho(2,0)v-2c\} = \rho(1,0)v-c$. If, on the other hand, $\mathbf{e}^*_{\mathcal{G}_\mathcal{S}} \neq (0,0)$ and $\rho(1,0)v-c < \rho(2,0)v-2c$, then it must be that

$$\begin{aligned} & (\rho(2,0)-\rho(1,0))v \;>\; c && (36)\\ \text{and} \qquad & \rho(2,0)v-2c \;>\; \rho(0,0)v, \quad \text{i.e.,} \quad [(\rho(2,0)-\rho(0,0))v]/2 > c. && (37)\end{aligned}$$

For this last scenario (i.e., (36) and (37)), consider further the following possibilities.

[1] Suppose that

$$\begin{aligned} & (1-\rho(1,2))v \;\geq\; c && (38)\\ \text{and} \qquad & [(1-\rho(0,2))v]/2 \;\geq\; c. && (39)\end{aligned}$$

(Note that (38) and (39) are not inconsistent with (36) and (37)). Then $v - 2c \geq \rho(1,2)v - c$ and $v - 2c \geq \rho(0,2)v$, i.e., $\mathbf{e}^*_{\mathcal{G}_\mathcal{S}} = (2,2)$.

[2] Next, suppose (38) holds but (39) does not so that

$$c > [(1 - \rho(0,2))v]/2. \tag{40}$$

Conditions (38) and (40) imply, using **A2**,

$$\rho(2,0)v > v - 2c \geq \rho(2,1)v - c.$$

This, together with (36) and (37), imply that $\mathbf{e}^*_{\mathcal{G}_\mathcal{S}} = (2,0)$.

[3] Another possibility is that (39) holds, i.e., $v - 2c \geq \rho(0,2)v$, but (38) does not. Then,

$$\rho(1,2)v - c > v - 2c \geq \rho(0,2)v. \tag{41}$$

Condition (41) has the following implications:

$$\begin{array}{rclll} [(1-\rho(0,2))v]/2 & > & c, & \text{i.e.,} \quad [(\rho(2,1)-\rho(0,1))v]/2 > c & (\text{by } \mathbf{A4'}) \quad (42) \\ (\rho(1,2)-\rho(0,2))v & > & c, & \text{i.e.,} \quad (\rho(1,1)-\rho(0,1))v > c & (\text{by } \mathbf{A4'}) \quad (43) \\ \text{and} \qquad\qquad c & > & (1-\rho(1,2))v. & & (44) \end{array}$$

Consider condition (44). If $c > (\rho(2,1) - \rho(1,1))v > (1 - \rho(1,2))v$, then this, together with (43), imply that $(\rho(1,1) - \rho(0,1))v > c > (\rho(2,1) - \rho(1,1))v$, i.e., $\mathbf{e}^*_{\mathcal{G}_\mathcal{S}} = (1,1)$. On the other hand, suppose that $(\rho(2,1) - \rho(1,1))v \geq c > (1 - \rho(1,2))v$. Then using the left-hand side inequality and (42), and applying **A2** for both yield, respectively,

$$\begin{array}{rrcl} & \rho(1,2)v - 2c & \geq & \rho(1,1)v - c \\ \text{and} & \rho(1,2)v - 2c & > & \rho(1,0)v. \end{array}$$

These and (41) imply that $\mathbf{e}^*_{\mathcal{G}_\mathcal{S}} = (1,2)$.

[4] Next suppose that both (38) and (39) fail to hold:

$$\begin{array}{rrcl} & c > (1-\rho(1,2))v, & \text{i.e.,} & \rho(1,2)v - c > v - 2c \qquad (45) \\ \text{and} & c > [(1-\rho(0,2))v]/2, & \text{i.e.,} & \rho(0,2)v > v - 2c. \qquad (46) \end{array}$$

If $\rho(0,2)v > \rho(1,2)v - c$, then $\rho(0,2)v > \rho(1,2)v - c > v - 2c$, or $\rho(2,0)v > \rho(2,1)v - c > v - 2c$ (by **A2**) and this, along with conditions (36) and (37), imply that $\mathbf{e}^*_{\mathcal{G}_\mathcal{S}} = (2,0)$. On the other hand, if $\rho(1,2)v - c \geq \rho(0,2)v$, then

$$\rho(1,2)v - c \geq \rho(0,2)v > v - 2c, \tag{47}$$

and $(\rho(1,2) - \rho(0,2))v > c$. This last inequality implies, applying **A4′**, that

$$(\rho(1,1) - \rho(0,1))v > c. \tag{48}$$

Recall now that condition (45) holds. If

$$(\rho(2,1) - \rho(1,1))v \underbrace{\geq}_{\text{by hypothesis}} c \underbrace{>}_{\text{by (45)}} (1 - \rho(1,2))v,$$

then the left-hand side inequality implies $\rho(2,1)v - 2c \geq \rho(1,1)v - c$, and using **A2** and (48) we have $\rho(1,2)v - 2c \geq \rho(1,1)v - c > \rho(1,0)v$. This condition, combined with (47), imply that $\mathbf{e}^*_{\mathcal{G}_\mathcal{S}} = (1,2)$. However, if alternative to our initial hypothesis (see above)

$$c > (\rho(2,1) - \rho(1,1))v \underbrace{>}_{\text{by } \mathbf{A4'}} (1 - \rho(1,2))v$$

holds, then $\rho(1,1)v - c > \rho(2,1)v - 2c$. This, along with (48), imply that $\mathbf{e}^*_{\mathcal{G}_\mathcal{S}} = (1,1)$.

Finally, if our initial position fails then $\mathbf{e}^*_{\mathcal{G}_\mathcal{S}} = (0,0)$, completing the proof that there is at least one pure strategy *NE* in the game $\mathcal{G}_\mathcal{S}$. ■

Proof of Lemma 8. Suppose, contrary to the claim, $\mathbf{e}^*_{\mathcal{G}_\mathcal{S}} = (0,0)$ and $\mathbf{e}^*_{\mathcal{G}_\mathcal{S}} = (1,1)$. Then (refer to Fig. 4) it must be that

$$c \geq (\rho(1,0) - \rho(0,0))v \tag{49}$$

$$\text{and} \quad c \leq (\rho(1,1) - \rho(0,1))v. \tag{50}$$

However, by **A4′**, (49) implies that $c > (\rho(1,1) - \rho(0,1))v$, contradicting (50).

Next, suppose that $\mathbf{e}^*_{\mathcal{G}_\mathcal{S}} = (0,0)$ and $\mathbf{e}^*_{\mathcal{G}_\mathcal{S}} = (2,2)$. This requires that

$$c \geq [(\rho(2,0) - \rho(0,0))v]/2 \tag{51}$$

$$\text{and} \quad c \leq [(1 - \rho(0,2))v]/2. \tag{52}$$

Condition (51) contradicts (52), since by $\mathbf{A4'}$, (51) implies that $c > [(1-\rho(0,2))v]/2$.

It is also not possible for $\mathbf{e}^*_{\mathcal{G_S}} = (1,1)$ and $\mathbf{e}^*_{\mathcal{G_S}} = (2,2)$ to arise simultaneously. This would require

$$\begin{aligned} (\rho(2,1)-\rho(1,1))v &\leq c \qquad (53) \\ \text{and} \qquad c &\leq (1-\rho(1,2))v, \qquad (54) \end{aligned}$$

but using $\mathbf{A4'}$ in (53) yields $1-\rho(1,2))v < c$, which contradicts (54). ■

Proof of Proposition 5. Let η_i denote the aggregate efforts of player i in $\mathcal{G_S}$, the game under non-transparency. By definition, $\mathbf{e}^*_{\mathcal{G_S}} = (\eta_1^*, \eta_2^*)$ satisfies

$$\rho(\eta_i^*, \eta_j^*)v - c\eta_i^* \geq \rho(\eta_i, \eta_j^*)v - c\eta_i, \quad \forall \eta_i, \ \forall i. \tag{55}$$

Denote the first-round efforts (e_{11}, e_{21}) in the game with transparency by $\mathbf{e_1}$, and recall that we defined (in section 3) incremental gains from second-round actions (e_{i2}, e_{j2}) given history $\mathbf{e_1}$, as

$$\hat{u}_{i2}(e_{i2}, e_{j2}|\mathbf{e_1}) = u_i(e_{i1}+e_{i2}, e_{j1}+e_{j2}) - \hat{u}_{i1}(e_{i1}, e_{j1}).$$

We now claim that for any *NE* (symmetric or asymmetric) in the non-transparency game, there is a strategy profile in the extensive-form game (under transparency) with the same aggregate efforts that will be an equilibrium in the two-round game. Specifically, for any $\mathbf{e}^*_{\mathcal{G_S}} = (\eta_1^*, \eta_2^*)$, the following strategies form an *SPE* in the extensive form:

1. In the first round, $e^*_{i1} = \eta^*_i$ for each player i, and

2. In the second round, for $i = 1, 2$,

$$e^*_{i2} = \begin{cases} 0 & \text{if} \quad \mathbf{e_1} = (\tilde{\eta}_i, \tilde{\eta}_j) \ \text{ and } \ \tilde{\eta}_i \geq \eta_i^*; \\ \eta_i^* - \tilde{\eta}_i & \text{if} \quad \mathbf{e_1} = (\tilde{\eta}_i, \tilde{\eta}_j), \ \tilde{\eta}_i < \eta_i^*, \ \text{and} \ \tilde{\eta}_j \leq \eta_j^*; \\ e^{**}_{i2} & \text{if} \quad \mathbf{e_1} = (\tilde{\eta}_i, \tilde{\eta}_j), \ \tilde{\eta}_i < \eta_i^*, \ \text{and} \ \tilde{\eta}_j > \eta_j^*, \end{cases} \tag{56}$$

   where $e^{**}_{i2} = \arg\max_{e_{i2} \in \hat{\mathbf{E}}_{\mathbf{i2}}} \hat{u}_{i2}(e_{i2}, 0|(\tilde{\eta}_i, \tilde{\eta}_j))$, $\hat{\mathbf{E}}_{\mathbf{i2}}$ being player i's set of admissible second-round effort choices, and $j \neq i$.

Actually, we will not fully verify the Nash equilibrium property of all continuation strategies – both on- and off-the-equilibrium path – specified in (56). (The mutual best-response property of the two players' continuation strategies pretty much follows by construction.) All we need is to confirm that for the specific strategies $(\eta_1^*, \eta_2^*; 0, 0)$, the continuation strategies will be an *NE* and there is no profitable deviation in Round 1.

So let us first establish that the second-round strategies $(0, 0)$ following $\mathbf{e_1} = (\eta_i^*, \eta_j^*)$ form an *NE* in the continuation game. Consider player i's second-round strategies. In the second round player j would choose, as specified by (56), $e_{j2}^* = 0$, to which we claim that player i's best response is also to set $e_{i2}^* = 0$. To see this, note that i's incremental gains in the second round from choosing $e_{i2} = 0$ is

$$\hat{u}_{i2}(0, 0|(\eta_i^*, \eta_j^*)) = [\rho(\eta_i^* + 0, \eta_j^* + 0) - \rho(\eta_i^*, \eta_j^*)]v - c \times 0,$$

whereas choosing any $e_{i2} > 0$ yields

$$\hat{u}_{i2}(e_{i2}, 0|(\eta_i^*, \eta_j^*)) = [\rho(\eta_i^* + e_{i2}, \eta_j^* + 0) - \rho(\eta_i^*, \eta_j^*)]v - ce_{i2}.$$

Thus, $$\begin{aligned} \hat{u}_{i2}(0, 0|(\eta_i^*, \eta_j^*)) - \hat{u}_{i2}(e_{i2}, 0|(\eta_i^*, \eta_j^*)) &= [\rho(\eta_i^*, \eta_j^*) - \rho(\eta_i^* + e_{i2}, \eta_j^*)]v - c[\eta_i^* - (\eta_i^* + e_{i2})] \\ &\underbrace{\geq}_{\text{by (55)}} 0. \end{aligned}$$

By similar reasoning, $\hat{u}_{j2}(0, 0|(\eta_i^*, \eta_j^*)) \geq \hat{u}_{j2}(0, e_{j2}|(\eta_i^*, \eta_j^*))$. Therefore, $(0, 0)$ forms an *NE* in the continuation game following $\mathbf{e_1} = (\eta_i^*, \eta_j^*)$.

Let us now return to the first round and consider the overall strategies $(\eta_i^*, \eta_j^*; 0, 0)$. This profile yields a payoff to player i of $u_i(\eta_i^*, \eta_j^*; 0, 0) = \rho(\eta_i^*, \eta_j^*)v - c\eta_i^*$. It is clear that there does not exist any profitable first-round deviation for any player: if i lowers his first-round contribution to $\tilde{\eta}_i < \eta_i^*$, he receives $u_i(\tilde{\eta}_i, \eta_j^*; \eta_i^* - \tilde{\eta}_i, 0) = \rho(\eta_i^*, \eta_j^*)v - c\eta_i^*$,[29] which is equal to his payoff from not deviating, and if he increases it to $\tilde{\eta}_i > \eta_i^*$, he receives $u_i(\tilde{\eta}_i, \eta_j^*; 0, 0) = \rho(\tilde{\eta}_i, \eta_j^*)v - c\tilde{\eta}_i \leq \rho(\eta_i^*, \eta_j^*)v - c\eta_i^*$ (by condition (55));[30] similar argument is applicable to player j. Therefore, $\mathbf{e}^*_{\widehat{\mathcal{G}_S}} = (\eta_1^*, \eta_2^*; 0, 0)$. ■

Proof of Proposition 6. Suppose not so that one of the players, say player 1, would benefit by deviating from the claimed equilibrium strategy under non-transparency. So there must be some $\eta_1 \neq \eta_1^*$ such that

[29] It is easy to see why player i restoring his total contribution back to η_i^* and player j contributing zero should constitute an *NE* in the continuation game following $\mathbf{e_1} = (\tilde{\eta}_i, \eta_j^*)$.

[30] Again, it is easy to see why $(0, 0)$ is an *NE* in the continuation game following $\mathbf{e_1} = (\tilde{\eta}_i, \eta_j^*)$, where $\tilde{\eta}_i > \eta_i^*$.

$$\begin{aligned} u_1(\eta_1, \eta_2^*) &> u_1(\eta_1^*, \eta_2^*) \\ \text{i.e.,} \qquad \rho(\eta_1, \eta_2^*)v - c\eta_1 &> \rho(\eta_1^*, \eta_2^*)v - c\eta_1^*. \end{aligned} \tag{57}$$

Claim 1. $\eta_1 \geq e_{11}^*$ is not possible.

To see why, let $\eta_1 = e_{11}^* + e_{12}$ where $e_{12} \in \{0, 1, 2\}$ with the restriction that $e_{12} \leq 2 - e_{11}^*$. Now rewrite (57) as:

$$\begin{aligned} [\rho(e_{11}^* + e_{12}, e_{21}^* + e_{22}^*) - \rho(e_{11}^*, e_{21}^*)]v - ce_{12} &> [\rho(e_{11}^* + e_{12}^*, e_{21}^* + e_{22}^*) - \rho(e_{11}^*, e_{21}^*)]v - ce_{12}^*, \\ \text{i.e.,} \qquad \hat{u}_{12}(e_{12}, e_{22}^* | (e_{11}^*, e_{21}^*)) &> \hat{u}_{12}(e_{12}^*, e_{22}^* | (e_{11}^*, e_{21}^*)), \end{aligned}$$

but this contradicts the fact that $(e_{11}^*, e_{21}^*; e_{12}^*(e_{11}^*, e_{21}^*), e_{22}^*(e_{11}^*, e_{21}^*))$ is an *SPE* in the extensive-form game under transparency. $\quad ||$

Next consider the possibility of profitable deviation in the one-shot game (under non-transparency) with $\eta_1 < e_{11}^*$.

First note that $e_{11}^* \geq 1$, for deviation to a lower effort level to be feasible. Also observe that for the *SPE*, $\mathbf{e}_{\widehat{\mathcal{G}_S}}^*$, it must be that $e_{22}^* \geq 1$, because otherwise profitable deviation to η_1 in the one-shot game is not consistent with the equilibrium $\mathbf{e}_{\widehat{\mathcal{G}_S}}^*$. (We write the strategies $\mathbf{e}_{\widehat{\mathcal{G}_S}} = (e_{11}^*, e_{21}^*; e_{12}^*(e_{11}^*, e_{21}^*), e_{22}^*(e_{11}^*, e_{21}^*))$ as $\mathbf{e}_{\widehat{\mathcal{G}_S}}^*$.)

Since $(e_{11}^*, e_{21}^*; e_{12}^*(e_{11}^*, e_{21}^*), e_{22}^*(e_{11}^*, e_{21}^*))$ is an *SPE*, the following two best-response conditions will be satisfied:

[1] (**Optimality of Round 2 decisions**) In the second round player 1 will not deviate from his equilibrium effort, that is,

$$\begin{aligned} & [\rho(e_{11}^* + e_{12}^*, e_{21}^* + e_{22}^*) - \rho(e_{11}^*, e_{21}^*)]v - ce_{12}^* \\ \geq \ & [\rho(e_{11}^* + e_{12}, e_{21}^* + e_{22}^*) - \rho(e_{11}^*, e_{21}^*)]v - ce_{12}, \end{aligned} \tag{58}$$

for any $0 \leq e_{12} \leq 2 - e_{11}^*$. A similar condition can be stated for player 2.

[2] (**Optimality of Round 1 decisions**) It must be that player 1 will not find deviation by lowering his first-round effort profitable. That is, for any $e_{11} < e_{11}^*$,

$$\begin{aligned} & \rho(e_{11}^* + e_{12}^*, e_{21}^* + e_{22}^*)v - c[e_{11}^* + e_{12}^*] \\ \geq \ & \rho(e_{11} + e_{12}^*(e_{11}, e_{21}^*), e_{21}^* + e_{22}^*(e_{11}, e_{21}^*))v - c[e_{11} + e_{12}^*(e_{11}, e_{21}^*)], \end{aligned} \tag{59}$$

for all Nash equilibria, $(e^*_{12}(e_{11}, e^*_{21}), e^*_{22}(e_{11}, e^*_{21}))$, in the continuation game following $\mathbf{e_1} = (e_{11}, e^*_{21})$. Again, a similar condition can be written for player 2.

Following on the optimality of first-round decisions, we further claim:

The *best deviation* payoff for player 1 when he lowers his first-round effort e_{11} below e^*_{11} is same as his original *SPE* payoff.

We show this result by establishing the following steps.

First, let player 1, upon deviation in Round 1, increase his second-round effort by $\Delta = e^*_{11} - e_{11} > 0$ to $e^*_{12} + \Delta$, and restore his total efforts to $e_{11} + e^*_{12} + \Delta = e^*_{11} + e^*_{12}$.

Second, with player 1's total efforts equalling η^*_1, player 2's best response in Round 2 continues to be e^*_{22}; this follows from $\mathbf{e}_{\widehat{\mathcal{G}_S}}$ being *SPE* (i.e., by writing a condition for player 2 similar to (58)).

Third, with total efforts by player 2 over the two rounds equalling η^*_2 (shown in the second step), below we reconfirm that player 1's best response in Round 2 (after Round 1 deviation to e_{11}) will indeed be to choose $e^*_{12} + \Delta$. To see this, recall (58) which can be written as:

$$\begin{aligned}
& [\rho(\eta^*_1, \eta^*_2) - \rho(e_{11}, e^*_{21})]v - ce^*_{12} \\
\geq \;& [\rho(e^*_{11} + e_{12}, \eta^*_2) - \rho(e_{11}, e^*_{21})]v - ce_{12}, \quad \text{for any } \; 0 \leq e_{12} \leq 2 - e^*_{11} \\
\text{i.e.,} \quad & [\rho(\eta^*_1, \eta^*_2) - \rho(e_{11}, e^*_{21})]v - c[\eta^*_1 - e_{11}] + c[\eta^*_1 - e_{11} - e^*_{12}] \\
\geq \;& [\rho(e_{11} + \tilde{e}_{12}, \eta^*_2) - \rho(e_{11}, e^*_{21})]v - c[e_{11} + \tilde{e}_{12} - e^*_{11}], \quad \text{for } \; e_{11} + \tilde{e}_{12} = e^*_{11} + e_{12} \leq 2 \\
\text{i.e.,} \quad & [\rho(\eta^*_1, \eta^*_2) - \rho(e_{11}, e^*_{21})]v - c[\eta^*_1 - e_{11}] \\
\geq \;& [\rho(e_{11} + \tilde{e}_{12}, \eta^*_2) - \rho(e_{11}, e^*_{21})]v - c\tilde{e}_{12} \\
& \qquad\qquad + \{-c[e_{11} - e^*_{11}] - c[\eta^*_1 - e_{11} - e^*_{12}]\}, \quad \text{for } \; 0 \leq \tilde{e}_{12} \leq 2 - e_{11} \\
\text{i.e.,} \quad & [\rho(\eta^*_1, \eta^*_2) - \rho(e_{11}, e^*_{21})]v - c[\eta^*_1 - e_{11}] \\
\geq \;& [\rho(e_{11} + \tilde{e}_{12}, \eta^*_2) - \rho(e_{11}, e^*_{21})]v - c\tilde{e}_{12}, \quad \text{for } \; 0 \leq \tilde{e}_{12} \leq 2 - e_{11}.
\end{aligned} \tag{60}$$

(The last inequality is the optimality of Round 2 decision by player 2 after cutting back on Round 1 effort.)

The second and third steps, together, establish that player 1 choosing $e^*_{12} + \Delta$ and player 2 choosing e^*_{22} form an *NE* in the continuation game following the deviation by player 1 in Round 1.

Now, by (60),

$$\begin{aligned}
\rho(\eta^*_1, \eta^*_2)v - c[\eta^*_1 - e_{11}] \;&\geq\; \rho(e_{11}, \eta^*_2)v \\
\text{i.e.,} \quad \rho(\eta^*_1, \eta^*_2)v - c\eta^*_1 \;&\geq\; \rho(e_{11}, \eta^*_2)v - ce_{11}, \quad \text{for any } \; e_{11} < e^*_{11},
\end{aligned}$$

contradicting (57).

We have thus shown that in the one-shot game under non-transparency, if player 2 chooses η_2^* then deviation by player 1 (as in (57)) is not possible. Similarly, if player 1 chooses η_1^*, deviation by player 2 is not possible. Thus, (η_1^*, η_2^*) is an *NE* under non-transparency. ■

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