Team Adaptation*

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Abstract

We model an organization as a team choosing between a status quo project and a potentially superior alternative. We show that the members' concern for each other's motivation leads to a lack of communication resulting in a failure of adaptation. The status quo is maintained even when evidence for the alternative's superiority has been observed. Adaptation failures are particularly severe when production exhibits strong complementarities. Improving the organization's aggregate information has the adverse effect of reducing communication. In the long run, the organization can become "locked-in" with the status quo, in that adaptation is impaired for *every* adoptable alternative.

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1 Introduction

Adaptation has long been recognized as a prerequisite for economic performance in environments subject to change. Economists have argued that adaptation is vital for both, individual decision makers in market settings (Hayek, 1945), as well as for hierarchical organizations (Barnard, 1938). The importance of adaptation for an organization's success becomes most apparent when dominant firms fail to sustain their position in the event of radical change. Henderson (1993) and Christensen (2013) document examples from various industries alluding to the organizations' inability to adopt technological innovations in spite of their members' awareness of the need for change.

There exists a widespread view amongst organizational psychologists, practitioners, and management scientists that team work may constitute a means to improve an organization's ability to adapt. For example, Burke et al. (2006) state that "structuring work via teams rather than around individuals primes organizations to be more adaptive because collectives have a broader repertoire of experiences to draw on." Similarly, commenting on the traditional top-down organization of the Army, General Stanley McChristal, commander of the US Joint Special Operations in Iraq, expressed his belief that "this approach cant work in a fast-changing world".[1] This view may explain why self-managed work teams have become an integral part of most organizations and teams no longer play the single role of executing a superior's decision but take part in determining an organization's course of action (Manz and Sims, 1993).

In this paper we argue that the presumption that teams are more adaptive should be taken with caution. Our argument is based on the observation that, by the mere nature of team production, team members have an incentive to communicate strategically by withholding information that reduces their colleagues' motivation to implement a common decision. We show that due to the resulting lack of communication, teams fail to adapt in situations where individual decision makers would choose the right course of action.

We analyze a standard model of team production preceded by a project-selection stage in which the team chooses between a status quo project A and an alternative project B.

[1] Stanford GSB presentation available at http://www.gsb.stanford.edu/insights/gen-stanley-mcchrystal-adapt-win-21st-century.

The alternative belongs to the team's *adaptation set* $\mathcal{B}$, containing all projects that are ex ante inferior relative to the status quo but constitute the better choice conditional on the occurrence of an event E. The event E is assumed to represent bad news with respect to the status quo. Each team member may obtain verifiable evidence about the occurrence of E. We are concerned with the members' willingness to disclose such information and the implications for the team's ability to adopt the superior project.

In our model, team members face a basic trade-off between adaptation and motivation. The disclosure of evidence for E leads to the adoption of the better project B whereas its concealment makes uninformed team members more motivated to exert effort on project A because no news represents good news with respect to the status quo. We show that this trade-off implies the existence of a non-empty subset $\mathcal{B}^I \subset \mathcal{B}$ of projects for which adaptation is impaired in the sense that they fail to be adopted (with positive probability) even when evidence for their superiority has been obtained (by some member). Worryingly, adaptation failures turn out to be most severe in those situations where team production is most frequently employed. In particular, we show that the set of projects for which adaptation is impaired is growing with the degree of complementarity of team production. Moreover, improving the team's aggregate information by increasing the likelihood with which evidence is obtained individually has the adverse effect of reducing communication. Hence better informed teams may be less adaptive.

We embed our basic model into a dynamic framework in order to study how the trade-off between adaptation and motivation evolves over time. An important feature of the dynamic setting is that the team members' motivation to work on the status quo increases with the number of periods in which no evidence for E has been observed. We obtain the strong result that for sufficiently long time horizons team adaptation is impaired for *every* adoptable project, i.e. $\mathcal{B}^I = \mathcal{B}$. Hence there exists the possibility that, in the long run, teams can become "locked-in" with the status quo in the sense that there exists no project that will be adopted (with certainty) upon the observation of its superiority. We show that this can happen if and only if the likelihood with which E is expected to occur ex ante is sufficiently high.

As a robustness check we consider a variation of our model in which team members receive non-verifiable signals rather than verifiable evidence about the occurrence of the event E. Although the team members' incentives for truthful communication are strengthened by a propensity to agree that is absent in the model with evidence, our result about the team's inability to adapt remains intact.

Related literature

This paper contributes to a growing literature studying the influence of strategic or imperfect communication on decision making within organizations and its consequences for organizational design.[2] Few papers in this literature share our focus on adaptation. For example, Dessein and Santos (2006) consider an organization consisting of individual decision-makers who aim to adapt their actions to their localized information and to coordinate them with the actions of others. Assuming communication to be imperfect, Dessein and Santos show that there exists a trade-off between adaptation and coordination and study its impact on the organization's degree of specialization. Their finding that "extensive specialization results in organizations that ignore local knowledge" resonates well with the view that team-work improves an organization's adaptiveness. The trade-off between adaptation and coordination is also present in Alonso et al. (2008, 2015) and Rantakari (2008) who consider the influence of strategic communication for an organization's choice between centralized and decentralized decision-making. We differ from these models mainly in that decisions are taken by a group rather than by individuals and that the trade-off is between adaptation and motivation rather than adaptation and coordination.

The trade-off between adaptation and motivation has been a feature of other models but existing work has focused on hierarchical settings where decision-making and execution are the task of separate agents (Zabojnik (2002), Blanes i Vidal and Möller (2007), Landier et al. (2009)). An exception is Blanes i Vidal and Möller (forthcoming) where we used a similar but drastically simplified model (binary efforts, no complementarities, homogeneous team members) to show that a team's failure to adapt cannot be overcome even when it is able to commit to the most sophisticated mechanisms.[3] Here we take

[2] See Gibbons, Matouschek and Roberts (2013) for a recent review.

[3] Another exception is Banal-Estañol and Seldeslachts (2009), who study mergers and show that the concern for the partner's post-merger effort may hinder decision-making at the pre-merger stage.

a complementary approach by assuming that such commitment is not available. This is in line with the view advocated by organizational economists that "if too much is contractible, then the transaction should probably be conducted in a market rather than in an organization" (Gibbons et al. 2013). Both approaches share only the basic insight that motivation hinders adaptation but allow for complementary sets of results.

Our finding that information aggregation can be inefficient arises in a number of articles on group decision-making but for different reasons: Conflicting preferences (Li, Rosen, and Suen, 2001; Dessein 2007); Career concerns (Ottaviani and Sorensen, 2001; Levy, 2007; Visser and Swank, 2007); and Voting (Feddersen and Pesendorfer, 1998; Gersbach 2000). Moreover, in this literature effort typically refers to the acquisition of decision-relevant information (Persico 2004, Gerardi and Yariv 2007, Gershkov and Szentes 2009, Campbell et al. 2013), rather than the execution of a joint decision. Our model offers a complementary approach by highlighting the consequences of a group's desire to maintain high morale at the execution stage, for the communication of information at the decision-making stage, thereby formalizing, partly, the notion of "Groupthink" coined by Janis (1982).[4]

More generally, our paper contributes to the literature on teams which can be decomposed into two distinct branches. The first branch dates back to Marshak and Radner (1972) and has become known as team theory. It is concerned with the analysis of team decision-making when members share a common objective but differ in their information. The second branch, initiated by Holmstrom's (1982) analysis of moral hazard in teams, deals with the question of how to provide team members with incentives to exert effort. While team theory abstracts from the execution of a group's decision, incentive theory has nothing to say about decision making. Our paper lies at the intersection of these two approaches by considering a team whose members take *and* execute a joint decision.

[4] Benabou (2013) also emphasizes the importance of group-morale, but does so in a very different model where individuals decide whether to engage in "reality denial" about an exogenously given productivity parameter.

2 Model

We model an organization as a team consisting of two risk-neutral members indexed by $i, j \in \{1, 2\}$, $i \neq j$.[5] Members exert non-contractible efforts to implement a common project. In particular, member i chooses effort $e_i \geq 0$ at cost $C_i(e_i)$. Costs are assumed to be increasing and strictly convex with $\lim_{e_i \to 0} \frac{dC_i}{de_i} = 0$ and $\lim_{e_i \to \infty} \frac{dC_i}{de_i} = \infty$. The team's revenue depends on efforts and the quality, $q > 0$, of the underlying project. It is given by $q \cdot F(e_1, e_2)$ with F being an increasing and concave function.[6] We focus on the case where efforts are complements, i.e. member i's marginal return to effort, $\frac{\partial F}{\partial e_i}$, is assumed to be (weakly) increasing in the effort provided by member j.[7]

There are two mutually exclusive projects, $X \in \{A, B\}$, whose qualities are uncertain. For example, A may represent a firm's strategy of exploiting its dominant position in the industry by focusing on the sale of its traditional product whereas B may consist of the development of a new technology. Let $q_{X|E}$ and $q_{X|\bar{E}}$ denote the expected qualities of project X conditional on an event having occurred (E) or not having occurred ($\bar{E}$) respectively. We let $\rho_0 \in (0, 1)$ be the probability that E occurs and assume, without loss of generality, that ex ante project A is expected to have a higher quality than project B, i.e.

$$\rho_0 q_{A|E} + (1 - \rho_0) q_{A|\bar{E}} > \rho_0 q_{B|E} + (1 - \rho_0) q_{B|\bar{E}}. \tag{C1}$$

Accordingly, we denote project A as the status quo. We further assume that E represents negative news with respect to the status quo, i.e.

$$q_{A|E} < q_{A|\bar{E}}, \tag{C2}$$

and that conditional on E having occurred, project B is expected to be of higher quality than project A, i.e.

$$q_{B|E} > q_{A|E}. \tag{C3}$$

For example, E could be a first step in the development of a new technology taken by a competitor, threatening the profits obtainable from the sale of existing products. Figure

[5] Our results can be easily generalized to a team with more than two members.

[6] The multiplicative functional form simplifies the exposition but is not necessary. Our results are a consequence of the fact that marginal returns to effort are increasing in the project's quality.

[7] The existence of complementarities is commonly considered as a motive for team production.

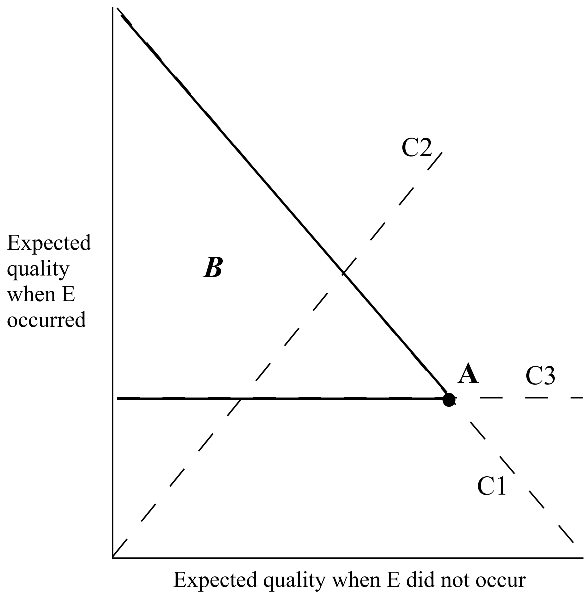

Figure 1: The team's adaptation set $\mathcal{B}$ for a given prior ρ_0 and status quo $A = (q_{A|\bar{E}}, q_{A|E})$ satisfying (C2). $\mathcal{B}$ contains all projects whose quality is expected to be lower than the status quo's ex ante (C1) but higher conditional on the event E being realized (C3).

1 provides a summary of our assumptions with respect to the projects' qualities. Given a status quo A satisfying (C2), the area $\mathcal{B}$ depicts the set of alternative projects B whose state dependent quality $(q_{B|\bar{E}}, q_{B|E})$ satisfies the conditions (C1) and (C3). We refer to $\mathcal{B}$ as the team's *adaptation set*. $\mathcal{B}$ contains all those projects which are ex ante inferior with respect to the status quo but constitute superior choices conditional on the event E having occurred.

Team members may obtain private information concerning the occurrence of event E. We model this by assuming that, conditional on E having occurred, member i obtains verifiable evidence of E's occurrence with probability $\gamma_i \in (0, 1)$.[8] However, it is not

[8]The assumption that information is verifiable has a long tradition in information economics, starting with the seminal work of Milgrom (1981). It guarantees that members cannot misrepresent their information. The fact that information is either perfect or absent simplifies Bayesian updating. In Section 6 we consider a variation of our model in which team members receive non-verifiable and imperfect information.

possible to obtain evidence proving that E has *not* occurred.[9] For example, if a new technology has been developed by a competitor, a sample device might be obtainable whereas otherwise no such sample exists. We will be concerned with the members' incentive to disclose their evidence and the implications for the team's ability to adapt to the event E by adopting the superior project B.

In Blanes–i–Vidal and Möller (2015) we have determined the optimal institution for a team in a simplified setting by assuming that members can commit to a mechanism which selects a project and allocates revenue based on the disclosed information. Here we pursue a complementary approach by assuming that the team is unable to commit to such a mechanism. Instead, we posit that member i obtains a fixed share $\alpha_i > 0$ of revenue and that the team's project choice must be optimal ex post, i.e. conditional on the disclosed evidence.[10] This allows us to investigate team adaptation in an organizational framework that is frequently observed in reality.

The timing is as follows: (I) Nature determines whether the event E occurs and for each member whether he obtains evidence for E. (II) Each member who obtained evidence may either disclose it or conceal it. (III) Based on the disclosed information, the team select the project with the highest (expected) quality. In particular, the status quo is maintained unless evidence for E has been disclosed. (IV) Finally, members choose their efforts.[11] Member i's payoff when a project of quality q was selected and efforts (e_1, e_2) were exerted is given by

$$U_i(e_1, e_2, q) = \alpha_i q F(e_1, e_2) - C_i(e_i). \tag{1}$$

A strategy for member i specifies the probability $d_i \in [0, 1]$ with which he discloses evidence and a rule determining his effort as a function of the selected project and the information available to him.

[9] This assumption simplifies the exposition but is not necessary for our results, as members would have no incentive to conceal evidence that is favorable with respect to the status quo.

[10] Note that we do not require budget balance, i.e. $\alpha_1 + \alpha_2$ may be less than one. Also note that an ex post optimal project choice would be the result of any voting procedure taking place after members had an opportunity to share their private information.

[11] We assume that efforts are chosen simultaneously since otherwise one member may obtain information about the project's quality from his observation of the other member's effort as in Hermalin (1998).

In the following section we explain why communication is strategic in our model and show that the amount of information that is disclosed in equilibrium can be characterized as a function of a single parameter

$$\Delta q \equiv q_{B|E} - q_{A|E}. \tag{2}$$

The parameter Δq measures the gain in project quality from abandoning the status quo A in exchange for the alternative project B in the presence of evidence proving B's superiority. We denote this parameter as the *value of adaptation*.

3 Communication

To understand the strategic nature of communication in our setup it is instructive to consider the possibility of an equilibrium in which both team members disclose their information fully, i.e. $d_1 = d_2 = 1$. Suppose that member $i \in \{1, 2\}$ observed evidence that E occurred. If member i discloses his evidence then project B is selected and both members expect the project's quality to be $q_{B|E}$. Equilibrium efforts $(\hat{e}_1^{E,E}, \hat{e}_2^{E,E})$ are thus defined by the requirement that $\hat{e}_k^{E,E}$ solves

$$\max_{e_k} \alpha_k q_{B|E} F(e_k, \hat{e}_l^{E,E}) - C_k(e_k) \tag{3}$$

for $k, l \in \{1, 2\}$, $k \neq l$.[12] Here we use the superscript (E, E) to express the fact that both members know about the occurrence of event E. Member i's expected payoff from disclosing his evidence is given by $U_i(\hat{e}_1^{E,E}, \hat{e}_2^{E,E}, q_{B|E})$.

If, instead, member i conceals his evidence then two possibilities arise. The first possibility is that member j has also received evidence and discloses it in accordance with his strategy of full disclosure. In this case the concealment of evidence by member i has no effect on member i's payoff. The second possibility is that member j has failed to receive evidence. In this case, project A is selected and member j is induced to believe

[12] Since efforts are complementary, the simultaneous effort choice constitutes a supermodular game. Milgrom and Roberts (1990) have shown that a supermodular game has a smallest and a largest pure Nash equilibrium. Since revenue is increasing in efforts, the largest equilibrium is Pareto preferred to all other equilibria. We assume that members are able to coordinate on their preferred equilibrium thereby selecting the largest equilibrium as the unique outcome of the simultaneous effort choice game.

that no evidence has been observed. Member j therefore updates his belief about the likelihood of the occurrence of event E to

$$\rho_1 = \frac{\rho_0(1-\gamma_1)(1-\gamma_2)}{\rho_0(1-\gamma_1)(1-\gamma_2)+1-\rho_0}. \tag{4}$$

Note for future reference that, due to the unavailability of evidence for the non-occurrence of E, no news represents good news for the status quo, i.e. $\rho_1 < \rho_0$ implying $\rho_1 q_{A|E} + (1-\rho_1)q_{A|\bar{E}} > \rho_0 q_{A|E} + (1-\rho_0)q_{A|\bar{E}}$. This property will play a role for the evolution of adaptation over time in the dynamic extension of our model in Section 5.

Member j presumes (wrongly) that member i shares his updated belief and thus chooses the effort level $\hat{e}_j^{\emptyset,\emptyset}$ forming part of the equilibrium effort vector $(\hat{e}_1^{\emptyset,\emptyset}, \hat{e}_2^{\emptyset,\emptyset})$ that would occur if *both* members had failed to observe evidence. $(\hat{e}_1^{\emptyset,\emptyset}, \hat{e}_2^{\emptyset,\emptyset})$ is defined by the requirement that $\hat{e}_k^{\emptyset,\emptyset}$ solves

$$\max_{e_k} \alpha_k[\rho_1 q_{A|E} + (1-\rho_1)q_{A|\bar{E}}]F(e_k, \hat{e}_l^{\emptyset,\emptyset}) - C_k(e_k) \tag{5}$$

for $k, l \in \{1, 2\}$, $k \neq l$. Since the deviating member i has observed evidence for the event E, he expects project A's quality to be given by $q_{A|E}$ and therefore chooses a best reply to member j's effort level $\hat{e}_j^{\emptyset,\emptyset}$ by selecting the effort $\hat{e}_i^{E,\emptyset}$ that solves

$$\max_{e_i} \alpha_i q_{A|E} F(e_i, \hat{e}_j^{\emptyset,\emptyset}) - C_i(e_i). \tag{6}$$

The superscript $(E, \emptyset)$ denotes the fact that member i knows that E has occurred whereas member j believes that no evidence has been observed. The disclosure of evidence is optimal for member i if and only if

$$\Delta U_i \equiv U_i(\hat{e}_i^{E,E}, \hat{e}_j^{E,E}, q_{B|E}) - U_i(\hat{e}_i^{E,\emptyset}, \hat{e}_j^{\emptyset,\emptyset}, q_{A|E}) \geq 0. \tag{7}$$

Condition (7) highlights the team members' trade-off between adaptation and motivation. On the one hand, disclosure leads to an increase in project quality due to the positive value $\Delta q = q_{B|E} - q_{A|E}$ of adopting the superior project. On the other hand, disclosure leads to a change in member j's effort from $\hat{e}_j^{\emptyset,\emptyset}$ to $\hat{e}_j^{E,E}$. Disclosure decreases member j's motivation to exert effort when project B's expected quality conditional on the occurrence of event E is smaller than the quality project A is expected to have in the absence of

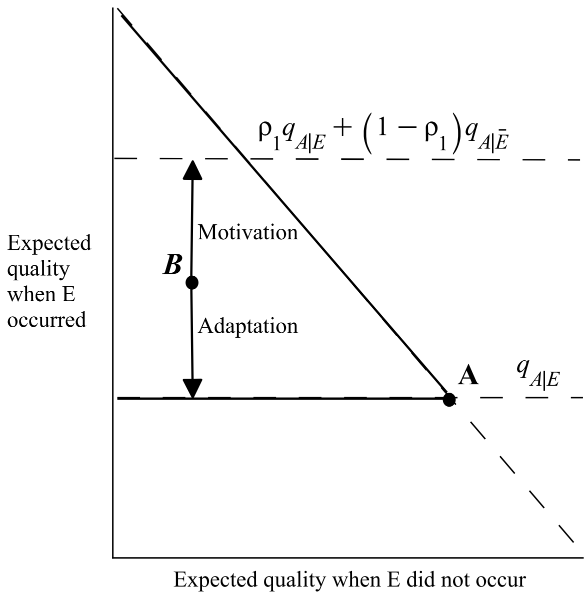

Figure 2: The basic trade-off. Disclosure of E induces the adoption of the superior project B with quality $q_{B|E} > q_{A|E}$. Concealment motivates uninformed members to exert higher effort as they expect project A to offer higher quality $\rho_1 q_{A|E} + (1-\rho_1) q_{A|\bar{E}} > q_{B|E}$.

evidence, i.e. $q_{B|E} < \rho_1 q_{A|E} + (1-\rho_1) q_{A|\bar{E}}$. We depict these two effects in Figure 2. The downward pointing arrow of length Δq is a measure of the adaptation effect. Similarly, the upward pointing arrow of length $\rho_1 q_{A|E} + (1-\rho_1) q_{A|\bar{E}} - q_{B|E}$ is a measure of the motivation effect. The team members' incentive to disclose information depends on the size of the adaptation effect relative to the motivation effect.

While (7) provides necessary and sufficient conditions for the existence of a full disclosure equilibrium, deriving the corresponding conditions for an equilibrium in which evidence is concealed (with positive probability) is more complicated. This is due to the fact that in such an equilibrium the simultaneous effort choice in the absence of evidence constitutes a Bayesian game in which members do not know whether or not their colleague has observed (and concealed) evidence. We have relegated the corresponding analysis to the Appendix where we prove the following result:

Proposition 1 *There exist thresholds Δq^C and Δq^D such that $0 < \Delta q^C < \Delta q^D$ and the* *following holds:*

1. *Full disclosure of evidence,* $d_1 = d_2 = 1$*, is an equilibrium if and only if* $\Delta q \geq \Delta q^D$.
2. *Full concealment of evidence,* $d_1 = d_2 = 0$*, is an equilibrium if and only if* $\Delta q \leq \Delta q^C$.
3. *For* $\Delta q \in (\Delta q^C, \Delta q^D)$*, disclosure is partial,* $(0,0) \neq (d_1, d_2) \neq (1,1)$*, and (weakly) increasing in* Δq*, i.e. if* (d_1, d_2) *and* (d_1', d_2') *are equilibria for* Δq *and* $\Delta q'$ *respectively then* $(d_1', d_2') > (d_1, d_2)$ *implies* $\Delta q' > \Delta q$.

Proposition 1 provides a complete characterization of the communication equilibria of our model. One way to summarize the result is the observation that team communication deteriorates (monotonically) as the value of adaptation decreases. In the following section we state the implications for the team's ability to adapt and consider how adaptation depends on the team's characteristics.

4 Team adaptation

When a team obtains evidence proving the superiority of an alternative over the status quo, a natural question to ask is whether the team is able to adapt. If evidence was observed *publicly*, the team would certainly adopt the alternative since members have a common preference for the project with the highest quality. In contrast, when evidence is observed privately, information sharing becomes a prerequisite for adaptation. A lack of communication may result in team adaptation being impaired. To be precise we make the following:

Definition 1 *Team adaptation is said to be impaired for an adoptable project* $B \in \mathcal{B}$*, if conditional on evidence for* B*'s superiority having been obtained by some member, the team maintains the status quo* A *with positive probability.*

The following corollary is a direct consequence of our characterization of team communication contained in the previous section.

Corollary 1 *The team's adaptation set* $\mathcal{B}$ *contains a non-empty subset* $\mathcal{B}^I \subset \mathcal{B}$ *of projects for which team adaptation is impaired.*

Team adaptation is impaired if and only if the full disclosure of evidence fails to be an equilibrium. Hence

$$\mathcal{B}^I = \{B \in \mathcal{B} | \Delta q < \Delta q^D\}. \tag{8}$$

Corollary 1 reveals a potential obstacle to team production. Teams fail to adopt projects that are known to be superior alternatives, due to the members' tendency to conceal information in conflict with the status quo.[13] Given that this problem exists under fairly general conditions it is surprising that it has remained unnoticed by the literature. Moreover, our next result shows that the problem is particularly severe in those settings where team production is most likely to emerge.

Proposition 2 *Let* $F(e_1, e_2) = e_1 + e_2 + \eta e_1 e_2$ *with* $\eta > 0$, $C_i(e_i) = \frac{1}{4}e_i^2$, *and* $\alpha_i = \frac{1}{2}$. *The team's ability to adapt is decreasing in the complementarity of team production, i.e.* $\eta' > \eta$ *implies* $\mathcal{B}^I(\eta) \subset \mathcal{B}^I(\eta')$.

Proposition 2 shows that an increase in the complementarity of team production leads to an expansion of the set of projects for which adaptation is impaired. This result highlights the downside of choosing team production over individual production in settings characterized by strong complementarities.

The intuition for the result is as follows. Stronger complementarities lead to an increase in the uninformed member's effort both after the concealment as well as the disclosure of evidence. However, since the uninformed member j expects member i to exert a higher effort upon concealment than upon disclosure, $\hat{e}_j^{\emptyset,\emptyset}$ increases more strongly than $\hat{e}_j^{E,E}$. As a consequence member i's incentive to conceal evidence increases.

If team adaptation is obstructed by the members' failure to share information, a potential remedy might be to increase the information of each individual member. Indeed, an increase in member i's individual informedness γ_i makes the team become more likely to obtain evidence on aggregate. In particular, the team's *aggregate* informedness

$$\Gamma \equiv 1 - (1 - \gamma_1)(1 - \gamma_2) \tag{9}$$

[13] It is worth emphasizing that, in contrast to Li et al. (2001), in our model there never exists disagreement at the project selection stage. When no evidence was disclosed even those members who concealed evidence are in favor of selecting the status quo.

increases. A team with access to better information has a greater potential to adopt the right course of action. However, the following result shows that there exists an adverse effect.

Proposition 3 *The set of projects for which adaptation is impaired is increasing in the team's aggregate informedness, i.e.* $\Gamma' > \Gamma$ *implies* $\mathcal{B}^I(\Gamma) \subset \mathcal{B}^I(\Gamma')$.

To understand this result, first note from (4) that an increase in the team's aggregate informedness, Γ, lowers the probability ρ_1 with which uninformed members believe that E has occurred when no evidence is being disclosed. Intuitively, for a higher Γ, the absence of evidence for E represents more positive news with respect to the status quo. As a consequence, team members are willing to exert higher efforts on the status quo in the absence of evidence, giving members a stronger incentive to conceal information. This leads to an expansion of the set of projects for which adaptation is impaired.

Our analysis so far has shown that, in a general team framework, a team's ability to adapt to news in conflict with the status quo is sub-optimal, and that this problem is particularly severe when production exhibits strong complementarities and the team is regarded as well informed on aggregate. In the next section we use a dynamic extension of our model to show that in the long run adaptation failures can become generic (in a sense to be made precise below).

5 Adaptation in the long run

In this section we adopt a dynamic perspective of team production by allowing for more than one round of adaptation. This enables us to investigate how a team's ability to adapt evolves with time. Our model formalizes the notion that a team may become "locked-in" with the status quo and sheds light on the conditions under which this is most likely to happen.

We extend our baseline model by assuming that there exist $T > 1$ adaptation periods. Whether or not the event E occurs is determined at time $t = 0$. In each period $t \in \{1, 2, \dots, T\}$, team members face the same situation as in the baseline model described in Section 2. In particular, conditional on E having occurred, member i obtains evidence for E's occurrence with probability γ_i, chooses whether to disclose or conceal, and exerts (unobservable) effort $e_{i,t}$ on the selected project $X_t \in \{A, B\}$. We abstract from the possibility that members learn about their project's quality q_{X_t} from their colleague's previous efforts or the realization of revenue by assuming that efforts are unobservable and that all revenue is realized at the end of period T. In the absence of discounting, member i's payoff is thus given by

$$U_i^T = \sum_{t=1}^{T} U_i(e_{1,t}, e_{2,t}, q_{X_t}) = \alpha_i \sum_{t=1}^{T} q_{X_t} F(e_{1,t}, e_{2,t}) - \sum_{t=1}^{T} C_i(e_{i,t}). \tag{10}$$

An important property of the dynamic setting is that the members' beliefs about the occurrence of the event E and hence their expectations about the status quo's quality evolve over time. More specifically, in period $t \in \{1, 2, \ldots, T\}$ of a full disclosure equilibrium, the members' belief about the likelihood of E in the absence of evidence is determined recursively by

$$\rho_t = \frac{\rho_{t-1}(1-\gamma_1)(1-\gamma_2)}{\rho_{t-1}(1-\gamma_1)(1-\gamma_2) + 1 - \rho_{t-1}}. \tag{11}$$

Note that $\rho_t < \rho_{t-1}$, i.e. the members' expectations about the status quo's quality increases in the number of periods during which no evidence for the occurrence of E has been obtained.[14]

As before we are concerned with the influence of the privacy of information on the team's ability to adapt. If evidence was observed publicly, then in the dynamic setting, the team would adopt the alternative as soon as it obtained evidence of its superiority. Hence our notion of impaired adaptation given in Definition 1 extends to the dynamic setting. As in the static setting, the full disclosure of evidence is necessary to prevent adaptation from being impaired.

In order to determine the conditions under which full disclosure constitutes an equilibrium in the dynamic setting, suppose that both members' strategies call for full disclosure in every period. Consider member i's incentive to conceal evidence in period τ when no evidence has been disclosed in periods $1, \ldots, \tau - 1$. If member i discloses evidence then

[14] A sufficient condition for this property to hold is that team members are more likely to obtain evidence for the occurrence than for the non-occurrence of the event E.

from period τ onwards, the team will work on project B and members will exert efforts $\hat{e}_i^{E,E}$ as defined by (3) in Section 4. If member i conceals his evidence in period τ (and ever after) then what happens in period $t \geq \tau$ depends on whether or not member j obtains evidence himself in periods $\tau, \ldots, t$. Concealment by member i in period τ has an effect on payoffs in period $t \geq \tau$ only when member j fails to observe evidence in periods $\tau \ldots t$. This happens with probability $(1-\gamma_j)^{t-\tau+1}$. Member i will therefore prefer disclosure over concealment in period τ if and only if

$$\sum_{t=\tau}^{T}(1-\gamma_j)^{t-\tau+1}[U_i(\hat{e}_i^{E,E}, \hat{e}_j^{E,E}, q_{B|E}) - U_i(\hat{e}_{i,t}^{E,\emptyset}, \hat{e}_{j,t}^{\emptyset,\emptyset}, q_{A|E})] \geq 0. \tag{12}$$

The effort levels $\hat{e}_{i,t}^{E,\emptyset}$ and $\hat{e}_{j,t}^{\emptyset,\emptyset}$ are determined as in Section 4 from (5) and (6) with ρ_t playing the role of the updated prior.

Since the members' expectation of the status quo's quality is increasing over time, the effort member j is willing to exert on the status quo in the absence of evidence, $\hat{e}_{j,t}^{\emptyset,\emptyset}$, is increasing from period to period. It follows that member i's incentive to disclose evidence is decreasing over time, i.e. (12) holds for all $\tau \in \{1, 2, \ldots, T\}$ if and only if it holds for $\tau = T$. Hence full disclosure constitutes an equilibrium of the dynamic setting if and only if

$$\Delta U_i^T \equiv U_i(\hat{e}_i^{E,E}, \hat{e}_j^{E,E}, q_{B|E}) - U_i(\hat{e}_{i,T}^{E,\emptyset}, \hat{e}_{j,T}^{\emptyset,\emptyset}, q_{A|E}) \geq 0. \tag{13}$$

Letting $\mathcal{B}^I(T)$ denote the set of alternatives for which adaptation is impaired with a horizon of length T, we obtain the following result:

Proposition 4 *Suppose there are $T > 1$ periods of adaptation and all revenue materializes at the end of the last period.*

1. *The set of projects for which team adaptation is impaired is growing with the time horizon, i.e. $T' > T$ implies $\mathcal{B}^I(T) \subset \mathcal{B}^I(T')$.*

2. *If the event E is sufficiently likely, i.e. $\rho_0 > \bar{\rho}_0 \in (0,1)$, then in the long run team adaptation is impaired for* every *adoptable alternative, i.e. there exists a $\bar{T}$ such that $\mathcal{B}^I(T) = \mathcal{B}$ for all $T \geq \bar{T}$.*

The first part of Proposition 4 is an immediate consequence of the fact that the team members' confidence in the status quo, and hence their motivation to exert effort in the absence of evidence, is increasing over time. In order to guarantee full adaptation, members must find it optimal to disclose evidence in favor of the alternative even when their colleague has become maximally confident with respect to the superiority of the status quo. A longer time horizon raises the maximum level of confidence team members may obtain. Hence a larger value of adaptation Δq is required to guarantee full disclosure and adaptation.

Now consider what happens as T tends to infinity. When in a full disclosure equilibrium, no evidence has been disclosed for many periods, member j will eventually believe that the event E must not have occurred, i.e. $\lim_{T\to\infty} \rho_T = 0$, and that this belief is shared by member i. In the long run member j will therefore work on the status quo as if it was common knowledge that its quality was $q_{A|\bar{E}}$, exerting the effort $\hat{e}_j^{\bar{E},\bar{E}}$ where $(\hat{e}_1^{\bar{E},\bar{E}}, \hat{e}_2^{\bar{E},\bar{E}})$ solves

$$\max_{e_k} \alpha_k q_{A|\bar{E}} F(e_k, \hat{e}_l^{\bar{E},\bar{E}}) - C_k(e_k). \tag{14}$$

In the limit, a deviating member i, upon concealing his evidence, would choose a best reply against $\hat{e}_j^{\bar{E},\bar{E}}$ by selecting the effort $\hat{e}_i^{E,\bar{E}}$ solving

$$\max_{e_i} \alpha_i q_{A|E} F(e_i, \hat{e}_j^{\bar{E},\bar{E}}) - C_i(e_i). \tag{15}$$

As the team members' incentive to disclose evidence is increasing in the value of adaptation, Δq, the incentive to disclose is maximal for the alternative $B = (q_{B|\bar{E}}, q_{B|E}) = (0, q_{A|E} + \frac{1-\rho_0}{\rho_0} q_{A|\bar{E}})$ located in the upper left corner of the team's adaptation set $\mathcal{B}$ (see Figure 1). Hence, in the long run, adaptation must be impaired for every project $B \in \mathcal{B}$ if and only if

$$\Delta U_i^\infty \equiv U_i(\hat{e}_i^{E,E}, \hat{e}_j^{E,E}, q_{A|E} + \frac{1-\rho_0}{\rho_0} q_{A|\bar{E}}) - U_i(\hat{e}_i^{E,\bar{E}}, \hat{e}_j^{\bar{E},\bar{E}}, q_{A|E}) < 0 \tag{16}$$

for some member $i \in \{1, 2\}$. In the proof of Proposition 4 we show that this condition holds if and only if ρ_0 is above a certain threshold $\bar{\rho}_0 \in (0, 1)$. If $\rho_0 > \bar{\rho}_0$ then in the long run, member j's expectation of the status quo's quality and hence his motivation to exert effort increase by so much, that member i benefits from concealing evidence even when the alternative was expected to have the same quality at time $t = 0$ and evidence is maximally favorable with respect to the alternative in the sense that $q_{B|\bar{E}} = 0$.

This last result formalizes the notion that organizations may become "locked-in" with the status quo. To see this, consider a variation of our model in which the team faces a (potentially) different project $B_t \in \mathcal{B}$ in each period. Recall that the team's adaptation set $\mathcal{B}$ contains all projects which are ex ante inferior relative to the status quo but constitute superior choices conditional on the occurrence of the event E. Proposition 4 shows that if E is sufficiently likely and the team has maintained the status quo for a sufficient number of periods (either because no evidence for E was obtained or because evidence was concealed) then in subsequent periods the team will fail to adapt (with positive probability) *any* of the adoptable projects it may encounter.

6 Non-verifiable information

Although the assumptions about information have lend tractability to our model, we do not pretend that they come without loss of generality. In particular, our model cannot cover the notion that team members may be more motivated to work on a given project when their "opinions" agree rather than disagree. In this section we consider a situation where team members receive non-verifiable and imperfect information about the projects' qualities. It turns out that the team's inability to share information and the corresponding adaptation failure continue to exist under these more standard assumptions.

Suppose that each member observes a private signal $s_i \in \{E, \bar{E}\}$ about the occurrence of the event E. The signals' precision is denoted as $p \in (\frac{1}{2}, 1)$, i.e.

$$p \equiv Prob(s_i = E|E) = Prob(s_i = \bar{E}|\bar{E}) \tag{17}$$

for $i \in \{1, 2\}$. In order to simplify the algebra, we set $q_{A|E} = q_{B|\bar{E}} = 0$ and $\rho_0 = 1/2$ and assume that efforts are independent, i.e. $F(e_1, e_2) = e_1 + e_2$.

In the communication stage (II), team members send non–verifiable messages $m_i \in \{E, \bar{E}\}$ to each other. We maintain our assumption about the ex-post optimality of the team's project choice. In particular, in stage (III) the team selects the project $X(m_i, m_j)$

with the highest expected quality based on the communicated messages. We focus on the case where ex-post optimality requires project B to be selected if and only if *both* members observed signal E. In particular, we restrict attention to the area of the parameter space where

$$\frac{(1-p)^2}{p^2} q_{A|\bar{E}} < q_{B|E} < q_{A|\bar{E}}. \tag{18}$$

In the following we explore the possibility of a truth-telling equilibrium in which each member issues $m_i = s_i$. For this purpose, let $q_{X|s_i,s_j}$ denote project X's expected quality conditional on the signals s_i and s_j. If member i expects project X's quality to be given by q_X then he will exert effort $\hat{e}_i(q_X) = \frac{dC_i}{de_i}^{-1}(\alpha_i q_X)$ on project X. If in a truth-telling equilibrium signals (s_i, s_j) have been observed and member i issues message m_i then member i's expected payoff is given by

$$u_i = \alpha_i q_{X(m_i,s_j)|s_i,s_j}[\hat{e}_i(q_{X(m_i,s_j)|s_i,s_j}) + \hat{e}_j(q_{X(m_i,s_j)|m_i,s_j})] - C_i(\hat{e}_i(q_{X(m_i,s_j)|s_i,s_j})). \tag{19}$$

When choosing his message, member i does not know whether $s_j = \bar{E}$ or $s_j = E$. Member j's signal s_j determines how member i's message m_i influences member j's effort and whether it alters the team's project choice. For $s_j = \bar{E}$ the team will maintain the status quo independently of member i's message. However, member j will exert higher effort if member i issues $m_i = \bar{E}$ since member j's confidence in the status quo is reinforced when messages agree. For $s_j = E$ the team will select the alternative project B if $m_i = E$ and maintain the status if $m_i = \bar{E}$. Member j will exert more effort on the status quo than on the alternative if and only if

$$q_{A|\bar{E}} \cdot \frac{1}{2} > q_{B|E} \cdot \frac{q^2}{q^2 + (1-q)^2}. \tag{20}$$

Hence for $q_{B|E}$ sufficiently small, team members have to compromise between maximizing project quality by issuing $m_i = s_i$ and maximizing motivation by issuing $m_i = \bar{E}$. The same trade-off that drives our results in the setting with verifiable evidence is also present in the model with non-verifiable signals. In the Appendix we prove the following:

Proposition 5 *An equilibrium in which all team members report their signals truthfully exists if and only if the value of adaptation Δq is higher than some threshold $\Delta q^D \in (\frac{(1-p)^2}{p^2} q_{A|\bar{E}}, q_{A|\bar{E}})$.*

Proposition 5 extends Proposition 1 and the corresponding Corollary 1 to settings with non-verifiable information. In the model with signals the economic mechanisms involved are similar to the ones in the model with evidence. However, there exists one additional mechanism. This mechanism is similar to the subordinates' incentive to conform with the views of their superiors in Prendergast (1993), or to the leader's propensity to follow hard rather than soft information in Blanes i Vidal and Möller (2007). Each team member has an incentive to issue a message that reinforces rather than contradicts the other member's signal. Since messages are issued simultaneously and signals are more likely to coincide than to contradict each other, members therefore have an additional incentive to tell the truth. It is reassuring that our results remain unchanged even in the presence of such a *propensity to agree*.

7 Conclusion

In this paper we have provided a new explanation for the common perception that organizations find it difficult to adapt to new circumstances, even while some of their members are privately aware of the need for change. We have argued that team production may actually be a cause rather than a solution of this problem. A key ingredient of our model has been the individuals' dual task of communicating decision-relevant information and executing the corresponding decisions. In an environment with incomplete contracts, this dual role creates a trade-off between adaptation and motivation, leading to inefficient information sharing and sub-optimal adaptation. Our theory shows that adaptation failures are particularly likely in organizations that exhibit strong complementarities of production, view themselves as well informed on aggregate, and have maintained a certain strategy for a long time.

In our theory we have focused on the influence of strategic communication on the organization's ability to adapt. One aspect of our model, that we have left aside, is the fact that, from a welfare perspective, the concealment of information within teams may have the positive effect of increasing efforts, which, because of free-riding, are inefficiently low. These effort effects must be taken into account by a theory aiming to derive results about optimal organizational design. We see our model as a first step into this direction.

Appendix

Proof of Proposition 1:

Part 1: In accordance with Milgrom and Roberts (1990), let $(\hat{e}_1, \hat{e}_2)$ denote the largest pure Nash equilibrium of the simultaneous effort choice game when members have the (common) expectation that the selected project's quality is q. We first show that $\hat{e}_1$ and $\hat{e}_2$ are continuous, strictly increasing functions of q. Continuity follows from the concavity of the members' payoffs, $\alpha_i q F(e_i, e_j) - C_i(e_i)$, and the fact that efforts are chosen from the interior of a convex set. As the members' payoffs have increasing differences in (q, e_i) and efforts are complements, Theorem 6 of Milgrom and Roberts (1990) implies that $\hat{e}_1$ and $\hat{e}_2$ are both non-decreasing in q. Hence, an increase in q must raise each member's marginal return to effort evaluated at the equilibrium, and, due to the strict convexity of the members' cost functions, must therefore lead to strictly higher equilibrium efforts.

Consider member i's incentive to disclose evidence as defined by ΔU_i in (7). From the above it follows that $\hat{e}_2^{E,E}$ and hence ΔU_i are continuous, strictly increasing functions of $q_{B|E}$. Consider the limit as $q_{B|E} \to q_{A|E}$. From $q_{A|E} < \rho_1 q_{A|E} + (1-\rho_1) q_{A|\bar{E}}$ it follows that $\hat{e}_2^{E,E} < \hat{e}_2^{\emptyset,\emptyset}$ which implies that $\Delta U_i < 0$. In contrast for $q_{B|E} \to \rho_1 q_{A|E} + (1-\rho_1) q_{A|\bar{E}}$ it must hold that $\hat{e}_2^{E,E} \to \hat{e}_2^{\emptyset,\emptyset}$ and hence $q_{B|E} > q_{A|E}$ implies that $\Delta U_i > 0$. Hence there must exist a unique $q_{B|E}$ for which $q_{A|E} < q_{B|E} < \rho_1 q_{A|E} + (1-\rho_1) q_{A|\bar{E}}$ and $\Delta U_i = 0$. Denote the corresponding value of adaptation $\Delta q = q_{B|E} - q_{A|E}$ as Δq_i and define $\Delta q^D = \max(\Delta q_1, \Delta q_2)$. Full disclosure of evidence constitutes an equilibrium if and only if $\Delta q \geq \Delta q^D$.

Part 2 and 3: Suppose that $d_j < 1$. The novelty with respect to Part 1 is that when member j fails to disclose evidence, member i cannot distinguish between the case in which member j has failed to obtain evidence and the case in which member j has obtained evidence but concealed it. When no evidence is disclosed, the simultaneous effort choice therefore constitutes a Bayesian game, in which each team member's *type* represents whether or not he has obtained evidence. Van Zandt and Vives (2007) show that the insights of Milgrom and Roberts (1990) extend to Bayesian games. In case of a multiplicity of equilibria we can therefore select the equilibrium with the highest efforts as the Pareto preferred outcome. Let this equilibrium be denoted as $((\hat{e}_1^{E,\emptyset}, \hat{e}_1^{\emptyset,\emptyset}), (\hat{e}_2^{E,\emptyset}, \hat{e}_2^{\emptyset,\emptyset}))$ where $\hat{e}_i^{E,\emptyset}$ and $\hat{e}_i^{\emptyset,\emptyset}$ are member i's efforts when he did or did not obtain evidence, respectively.

In the absence of evidence, member i must believe that member j has obtained evidence with probability $\tilde{\gamma}_j = \frac{\gamma_j(1-d_j)}{\gamma_j(1-d_j)+1-\gamma_j}$ and that E has occurred with probability $\rho_{1,i} = \frac{\rho_0(1-\gamma_i)[1-\gamma_j+\gamma_j(1-d_j)]}{\rho_0(1-\gamma_i)[1-\gamma_j+\gamma_j(1-d_j)]+1-\rho_0}$. The effort $\hat{e}_i^{E,\emptyset}$ must therefore solve the program

$$\max_{e_i} \alpha_i q_{A|E}[\tilde{\gamma}_j F(e_i, \hat{e}_j^{E,\emptyset}) + (1-\tilde{\gamma}_j)F(e_i, \hat{e}_j^{\emptyset,\emptyset})] - C_i(e_i), \tag{21}$$

whereas $\hat{e}_i^{\emptyset,\emptyset}$ must solve

$$\max_{e_i} \alpha_i\{(1-\rho_{1,i})q_{A|\bar{E}}F(e_i, \hat{e}_j^{\emptyset,\emptyset}) + \rho_{1,i}q_{A|E}[\tilde{\gamma}_j F(e_i, \hat{e}_j^{E,\emptyset}) + (1-\tilde{\gamma}_j)F(e_i, \hat{e}_j^{\emptyset,\emptyset})]\} - C_i(e_i). \tag{22}$$

It follows from $q_{A|\bar{E}} > q_{A|E}$ and the complementarity of efforts that $\hat{e}_1^{\emptyset,\emptyset} > \hat{e}_1^{E,\emptyset}$ and $\hat{e}_2^{\emptyset,\emptyset} > \hat{e}_2^{E,\emptyset}$. Disclosure is optimal for member i if and only if $\Delta U_i(d_j) \geq 0$ with

$$\Delta U_i(d_j) \equiv U_i(\hat{e}_i^{E,E}, \hat{e}_j^{E,E}, q_{B|E}) - [\tilde{\gamma}_j U_i(\hat{e}_i^{E,\emptyset}, \hat{e}_j^{E,\emptyset}, q_{A|E}) + (1-\tilde{\gamma}_j)U_i(\hat{e}_i^{E,\emptyset}, \hat{e}_j^{\emptyset,\emptyset}, q_{A|E})]. \tag{23}$$

We now show that $\Delta U_i(d_j)$ is strictly decreasing. An increase in d_j leads to a decrease in $\tilde{\gamma}_j$ and to an increase in $\rho_{1,i}$. Both effects lead to an increase in $\hat{e}_i^{\emptyset,\emptyset}$ and $\hat{e}_i^{E,\emptyset}$ and due to the complementarity of efforts to an increase in $\hat{e}_j^{\emptyset,\emptyset}$ and $\hat{e}_j^{E,\emptyset}$. Hence member i's incentive to disclose evidence, $\Delta U_i(d_j)$, decreases in the likelihood with which member j discloses. The same argument as in Part 1 therefore implies that there exists a $\Delta q^C > 0$ such that $\Delta U_i(0) \leq 0 \Leftrightarrow \Delta q \leq \Delta q^C$ and $\Delta q^C < \Delta q^D$. Full concealment constitutes an equilibrium if and only if $\Delta q \leq \Delta q^C$.

Finally, to prove the monotonicity of disclosure for $\Delta q \in (\Delta q^C, \Delta q^D)$ note that, for similar reasons as above, $\Delta U_i(d_j)$ is decreasing not only in d_j but also in d_i. Hence if (d_1, d_2) and (d_1', d_2') are equilibria for Δq and $\Delta q'$ respectively and $(d_1', d_2') > (d_1, d_2)$ then the fact that $\Delta U_i(d_j)$ is increasing in the value of adaptation implies that $\Delta q' > \Delta q$. ■

Proof of Proposition 2: If member i expects the project's quality to be given by q, then his reaction function in the simultaneous effort choice game is given by $R_i(e_j) = q(1+\eta e_j)$. Given identical expectations the equilibrium is the unique solution to the linear system of equations $R_i(e_j^*) = e_i^*$ leading $e_1^* = e_2^* = \frac{q}{1-\eta q}$. Existence of equilibrium can be guaranteed for all relevant expectations by assuming that $\eta < \frac{1}{q_{A|\bar{E}}}$. Normalizing by setting $\rho_1 q_{A|E} + (1-\rho_1) q_{A|\bar{E}} = 1$, we therefore obtain the effort levels $e_j^{\emptyset,\emptyset} = \frac{1}{1-\eta}$, $e_j^{E,E} = \frac{q_{B|E}}{1-\eta q_{B|E}}$ and $e_i^{\emptyset,E} = q_{A|E}(1+\eta\frac{1}{1-\eta})$. Substituting these efforts into (7) gives

$$\Delta U_1 = \Delta U_2 = \frac{\frac{3}{2}q_{B|E}^2 - \eta q_{B|E}^3}{2(1-\eta q_{B|E})^2} - \frac{\frac{1}{2}q_{A|E}^2 + (1-\eta)q_{A|E}}{2(1-\eta)^2}. \tag{24}$$

Solving $\Delta U_1 = \Delta U_2 = 0$ for $q_{A|E}$ we can express the critical value of adaptation as a function of $q_{B|E}$:

$$\Delta q^I = q_{B|E} - (1-\eta)\left(\sqrt{1 + \frac{3q_{B|E}^2 - 2\eta q_{B|E}^3}{(1-\eta q_{B|E})^2}} - 1\right). \tag{25}$$

The threshold Δq^I is increasing in η. ■

Proof of Proposition 3: Consider the effect of an increase in the team's aggregate informedness $\Gamma = 1 - (1-\gamma_1)(1-\gamma_2)$. Note from (4) that an increase in Γ leads to a decrease in the likelihood ρ_1 with which members believe E to have occurred in the absence of evidence. From $q_{A|E} < q_{A|\bar{E}}$ and the fact that equilibrium efforts are strictly increasing in the project's expected quality (see proof of Proposition 1) it follows that $\hat{e}_j^{\emptyset,\emptyset}$ becomes larger. This decreases member i's incentive to disclose information ΔU_i leading to an increase in the threshold Δq^I. ■

Proof of Proposition 4:

Part 1: Consider the effect of an increase in the time horizon T. It follows from (11) that an increase in T decrease the likelihood ρ_T with which members believe E to have occurred when no evidence was disclosed over the full duration of T periods. From $q_{A|E} < q_{A|\bar{E}}$ and the fact that equilibrium efforts are strictly increasing in the project's expected quality (see proof of Proposition 1) it follows that $\hat{e}_{j,T}^{\emptyset,\emptyset}$ in (13) becomes larger. This decreases member i's incentive to disclose information ΔU_i^T leading to an expansion of the set $\mathcal{B}^I(T)$.

Part 2: Consider (16) and note that ΔU_i^∞ is strictly decreasing in ρ_0. This follows from the fact that, in the limit, member j's effort $\hat{e}_j^{\bar{E},\bar{E}}$ on project A is independent of ρ_0 and that the expected quality of the critical project $B = (q_{B|\bar{E}}, q_{B|E}) = (0, q_{A|E} + \frac{1-\rho_0}{\rho_0} q_{A|\bar{E}})$ is decreasing in ρ_0. For $\rho_0 \to 1$ it follows from $\hat{e}_j^{\bar{E},\bar{E}} > \hat{e}_j^{E,E}$ that $\Delta U_i^\infty < 0$. In contrast, for $\rho_0 \to 0$ it holds that $\Delta U_i^\infty > 0$. Hence there exists a unique $\rho_{0,i} \in (0,1)$ that solves $\Delta U_i^\infty = 0$. Define $\bar{\rho_0} = \min_{i\in\{1,2\}} \rho_{0,i}$. It then follows from Part 1 that for every $\rho_0 > \bar{\rho_0}$ there exists a time horizon $\bar{T}$ such that $\mathcal{B}^I(T) = \mathcal{B}$ for all $T \geq \bar{T}$. ■

Proof of Proposition 5: Consider the possibility of a truth-telling equilibrium. Member i's payoff $U_i = U_{i,i} + U_{i,j}$ can be decomposed into his own contribution $U_{i,i} = \alpha_i q e_i - C_i(e_i)$ and his colleague's contribution $U_{i,j} = \alpha_i q e_j$. We consider both parts separately and denote by $\Delta U_{i,i}$ and $\Delta U_{i,j}$ the corresponding differences between expected payoffs from truth-telling and from deviating. For $s_i = \bar{E}$ we have

$$\begin{aligned}\Delta U_{i,i} &= 2p(1-p)[\alpha_i q_{A|\bar{E},E}\hat{e}_i(q_{A|\bar{E},E}) - C_i(\hat{e}_i(q_{A|\bar{E},E})) \\ &\quad -\alpha_i q_{B|\bar{E},E}\hat{e}_i(q_{B|\bar{E},E}) + C_i(\hat{e}_i(q_{B|\bar{E},E}))].\end{aligned} \tag{26}$$

It follows from $q_{A|\bar{E},E} = \frac{1}{2} q_{A|\bar{E}} > \frac{1}{2} q_{B|E} = q_{B|\bar{E},E}$ and the optimality of $\hat{e}(q_{A|\bar{E},E})$ that $\Delta U_{i,i} > 0$. Moreover,

$$\begin{aligned}\Delta U_{i,j} &= p(2p-1)\alpha_i q_{A|\bar{E}}[\hat{e}_j(q_{A|\bar{E},\bar{E}}) - \hat{e}_j(q_{A|E,\bar{E}})] \\ &\quad +p(1-p)\alpha_i[q_{A|\bar{E}}\hat{e}_j(q_{A|\bar{E},\bar{E}}) - q_{B|E}\hat{e}_j(q_{B|E,E})].\end{aligned} \tag{27}$$

Note that $\hat{e}_j(q_{A|\bar{E},\bar{E}}) > \hat{e}_j(q_{A|E,\bar{E}})$ and that $q_{A|\bar{E}} > q_{B|E}$ implies that $\hat{e}_j(q_{A|\bar{E},\bar{E}}) > \hat{e}_j(q_{B|E,E})$. It follows that $\Delta U_{i,j} > 0$. We have therefore shown that truth-telling is optimal if $s_i = \bar{E}$. It remains to consider the case where $s_i = E$. We find

$$\begin{aligned}\Delta U_{i,i} &= [p^2 + (1-p)^2][\alpha_i q_{B|E,E}\hat{e}_i(q_{B|E,E}) - C_i(\hat{e}_i(q_{B|E,E})) \\ &\quad -\alpha_i q_{A|E,E}\hat{e}_i(q_{A|E,E}) + C_i(\hat{e}_i(q_{A|E,E}))].\end{aligned} \tag{28}$$

Note that $\Delta U_{i,i}$ is strictly increasing in $q_{B|E,E}$ and hence in $q_{B|E}$. For $q_{B|E} \to \frac{(1-p)^2}{p^2} q_{A|\bar{E}}$, $\hat{e}_i(q_{B|E,E}) \to \hat{e}_i(q_{A|E,E})$ and thus $\Delta U_{i,i} \to 0$. Finally, we have

$$\begin{aligned}\Delta U_{i,j} &= \alpha_i[p^2 q_{B|E}\hat{e}_j(q_{B|E,E}) + (1-p)p q_{A|\bar{E}}\hat{e}_j(q_{A|\bar{E},E}) \\ &\quad -(1-p)^2 q_{A|\bar{E}}\hat{e}_j(q_{A|E,\bar{E}}) - (1-p)p q_{A|\bar{E}}\hat{e}_j(q_{A|\bar{E},\bar{E}})]\end{aligned} \tag{29}$$

Again, $\Delta U_{i,j}$ is strictly increasing in $q_{B|E}$. Furthermore,

$$\lim_{q_{B|E}\to q_{A|\bar{E}}} \Delta U_{i,j} = (2p-1)\alpha_i q_{A|\bar{E}}[p\hat{e}_j(q_{A|\bar{E},\bar{E}}) + (1-p)\hat{e}_j(q_{A|E,\bar{E}})] > 0 \tag{30}$$

and

$$\begin{aligned} \lim_{q_{B|E}\to \frac{(1-p)^2}{p^2} q_{A|\bar{E}}} \Delta U_{i,j} &= \alpha_i q_{A|\bar{E}}\{(1-p)^2[\hat{e}_j(q_{B|E,E}) - \hat{e}_j(q_{A|E,\bar{E}})] \\ &\quad +(1-p)p[\hat{e}_j(q_{A|E,\bar{E}}) - \hat{e}_j(q_{A|\bar{E},\bar{E}})]\} < 0 \end{aligned} \tag{31}$$

where the last inequality arises from the fact that in the limit $\hat{e}_j(q_{B|E,E}) \to \hat{e}_j(q_{A|E,E})$ and $\hat{e}_j(q_{A|E,E}) < \hat{e}_j(q_{A|E,\bar{E}}) < \hat{e}_j(q_{A|\bar{E},\bar{E}})$. Taken together these results imply that there exists a Δq_i such that truth telling is optimal for member i if and only if $\Delta q = q_{B|E} \geq \Delta q_i$. Defining $\Delta q^D = \max(\Delta q_1, \Delta q_2)$ we have therefore shown that mutual truth-telling constitutes an equilibrium if and only if $\Delta q \geq \Delta q^D$. ■

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