Formal vs. Informal Monitoring in Teams*

Alex Gershkov and Eyal Winter†

13.03.2014

Abstract

In this paper we analyze a principal's optimal monitoring strategies in team environment. In doing so we study the interaction between formal monitoring and informal (peer) monitoring. We show that if the technology satisfies complementarity, peer monitoring substitutes for the principal's monitoring. However, if the technology satisfies substitution, the principal's optimal monitoring is independent of the peer monitoring. We also show that if the technology satisfies complementarity, then the principal in the optimal contracts will monitor more closely than in the case of substitution.

Teamwork is widespread in both for profit and non-profit organizations. Osterman [9] estimates that self-directed teamwork is present in 54 percent of American organizations. Team production implies a variety of technological characteristics that differ from other structures of organization. One of the

*We wish to thank Mike Borns for his excellent editorial work.

†Gershkov, Department of Economics and Center for the Study of Rationality, The Hebrew University of Jerusalem and School of Economics, University of Surrey, address: Center for the Study of Rationality, Givat Ram 91904, Jerusalem, Israel, email: alexg@huji.ac.il; Winter: Department of Economics and Center for the Study of Rationality, The Hebrew University of Jerusalem, and Department of Economics, University of Leicester, address: Center for the Study of Rationality, Givat Ram 91904, Jerusalem, Israel,email: eyal.winter@huji.ac.il. The authors would like to thank three anonymous referees for their comments. This work was financially supported by German-Israel Foundation Grant #1123 and by the Google Inter-university center for Electronic Markets and Auctions.

main features of team production is that individual success and rewards are strongly, though not exclusively, determined by the aggregate success of the group. This feature arises mostly from the fact that individual efforts or performance are hard to evaluate because of the nature of the production process and the fact that there is no clear allocation of tasks among the agents. This moral hazard effect in teams is expected to make incentive mechanisms more expensive than in other organizational structures because no conditioning on individual efforts or performance is allowed.

To lower this excessive cost of incentives, organizations often resort to two types of monitoring regimes. The first one is formal, noisy, and costly, conducted by the organization itself either directly (as in employees punching in and punching out) or through a supervisor who fills out periodic evaluation reports. The second type of monitoring is spontaneous and random on the one hand, but more accurate on the other. This monitoring is typically done by other agents who collect information about their peers. Peer monitoring is random as it requires a nexus of events that provide information about agents' efforts. They are very often more accurate since once the monitoring opportunity is available peers receive more detailed information and are better than the principal at interpreting it. Furthermore, peer information is costless in that it is a by-product of working together in a team. Finally, unlike formal monitoring which can affect agents' benefits through contracting, peer monitoring cannot affect agents' benefits directly, yet it does so indirectly as it affects the incentives of other agents to exert effort and thus the success of the team.

The purpose of this paper is to study the role of monitoring in teams and in particular the interaction between formal monitoring and informal peer monitoring. We shall consider a sequential production process and model peer monitoring by means of a probability q under which player i observes the effort of player j, where i acts after j (with independence across pairs). We shall also refer to q as the level of transparency within the team as it indicates the propensity with which agents can monitor their predecessors. In contrast, formal monitoring by the principal is modeled as a signal of the level of effort undertaken by agents which the principal can purchase at a cost. The contract can make contingencies on the outcome of this signal, which is noisy, as this outcome is affected by events that have nothing to do with the agents' level of effort.

Our analysis draws a sharp distinction between technologies that satisfy complementarity (super-modularity) and ones satisfying substitution (sub-modularity). We shall show that under complementarity peer monitoring serves as a substitute for formal monitoring, i.e., the higher the transparency among peers, the smaller the set of agents that the principal chooses to monitor directly. This substitution between the two types of monitoring is somewhat surprising as peer monitoring reveals nothing to the principal[1] and even if it did the principal could not offer contracts that make contingencies on the outcomes of peer monitoring. We shall also show that when the principal decides to monitor a particular agent j he must also monitor all the agents who succeed agent j. Both these results build strongly on the implicit incentive to exert effort that is generated by the complementarity property of the technology. Under complementarity, and for a fixed set of rewards, an agent's incentive to exert effort increases the more other players exert effort. This generates a credible threat to shirk as a response to shirking by one's peers. This threat serves as an implicit safeguard that is more effective with more transparency and less effective with late players than with early players (who have much more to lose from the domino effect triggered by their shirking). The stronger the implicit safeguard is, the less the principal needs to use formal monitoring. This will also imply that it is optimal for the principal to monitor later agents more closely than the first agents. We will come back to this intuition later. In contrast to the case of complementarity, under substitution the principal's strategy of monitoring is invariant with respect to the level of transparency in the organization. This is because under the optimal scheme of rewards the threat of shirking in response to observing one's peers shirking is no longer credible. If a player prefers exerting effort to shirking under the belief that all the other players are exerting effort, then all the more so when he observes some of them shirking.

The literature on incentive provision in teams investigates different as-

[1] Deb, Li, and Mukherjee [4] analyzed a problem of repeated contracting with peer monitoring. However, they allowed for the agents' compensation to be conditioned on peer reports.

pects of monitoring. Alchian and Demsetz [1] argue in a seminal paper that the capitalist firm resolves the moral hazard problem in teams by assigning a specialized agent from within the team to monitor the rest of the agents. The central agent is motivated to monitor by the fact that he obtains the team revenue net of the obligations that he has to the remaining members of the team. Miller [8] and Strausz [12] illustrate how monitoring can help to overcome the classical impossibility result of Holmstrom [5] of moral hazard in teams. Baliga [3] shows that the presence of a monitor can reduce the set of equilibria in the environments with private information. McAfee and McMillan [7] show that once we have adverse selection on top of moral hazard monitoring stops being effective in reducing the principal's cost. In the standard principal-agent environment, Strausz [11] illustrates that the delegation of monitoring can have a positive effect on incentive provision and can serve as a commitment device for monitoring strategy. Rahman [10] analyzes incentive provision to the monitor in a team environment. Peer monitoring is discussed in Winter [15], which study the effect of the organization's internal transparency on the principal's revenue. Recently Bag and Pepito [2] extended the study to a dynamic framework. Yet, these papers do not analyze the interplay between formal monitoring by a principal and informal monitoring by peers. Varian [13] analyzed an optimal choice of monitor. In particular, he assumed that there are monitors who lower the costs of the optimal action and monitors who raise the cost of the suboptimal action. It is shown that the principal is better off hiring a monitor who lowers the cost of the optimal effort as it alleviates both the incentive compatibility constraint and the participation constraint of the agent. In addition, the paper provides other rationales for peer monitoring, such as mutual insurance.

The structure of the paper is as follows. Section 2 presents the model. Section 3 characterizes optimal compensation schemes and monitoring policies. Section 4 compares the monitoring intensities of different technologies. The Appendix contains proofs omitted from the text.

1 The Model

A set N of n agents collectively manages a project as a team. Each agent has to decide whether to exert effort/invest in the performance of his tasks or not. Henceforth we interchangeably use the term *investment* to mean the action of exerting effort. The technology of the organization maps a profile of effort decisions into a probability of the project's success. For a group $M \subseteq N$ of investing agents the probability that the project will succeed is $P(M)$. Throughout the paper we assume that P is increasing in the following simple sense: if $T \subset M$, then $P(T) < P(M)$.

We will also make the distinction between technologies satisfying complementarity and those satisfying substitution (both with respect to agents' inputs). Specifically, we say that P satisfies complementarity if the following condition holds:

$P(T \cup \{i\}) - P(T) < P(M \cup \{i\}) - P(M)$ for $T \subset M$ and $i \notin M$.

We say that p satisfies substitution if

$P(T \cup \{i\}) - P(T) \geq P(M \cup \{i\}) - P(M)$ for $T \subset M$ and $i \notin M$.

In the case of symmetric agents, that is, $P(L) = P(L')$ whenever $|L| = |L'|$, complementarity is equivalent to the requirement that $P(n+1) - P(n)$ increases, while substitution requires this expression to decrease.

We assume that agents move sequentially in making their effort decisions and performing their tasks. The cost of effort of agent j is e_j. Without loss of generality we assume that agents are indexed according to the order of moves. At period j, before agent j has made his effort decision, a random event occurs that determines who among j's predecessors, denoted by $F_j = \{1, 2, ..., j-1\}$, can be observed by j in a way that his effort decision is revealed. We assume that agent $i \in F_j$ is observed by $j > i$ with probability $q > 0$ and that observability is statistically independent across players in F_j. Peer monitoring in our model is informal and occasional. It is informal in the sense that this information is not leaked to the principal and therefore the principal cannot make his contract contingent on the outcome of peer monitoring. Precisely because peer monitoring is informal and not institutional we would like to think of it as an outcome of a random process. This randomness reflects the fact that monitoring opportunities are imperfect.

This imperfection may arise from a variety of organizational features: the architecture of the workplace may impede perfect observation among peers. The lack of sufficient overlap in working hours among peers may result in a similar imperfection. Finally, social aspects may introduce stochastic constraints on the degree of interaction among peers and thus on the possibility of monitoring. We note that our assumption of a constant probability of monitoring across all pairs is not essential and is taken only for the sake of simplifying the notations. All our results apply to the more descriptive model in which this probability can vary across different pairs of agents. Internal monitoring gives rise to an information structure in the effort game. Any strategic environment in which players possess some information about the actions of others requires the game to be modeled as an extensive form game and any extensive form game implicitly assumes some order of moves. The full sequentiality of our model simply reflects the fact that exerting effort is modeled as a single action. An alternative model in which effort exertion by an agent is gradual and involves multiple actions is more complex to analyze but is unlikely to deliver any additional insight. The results of such a model will be quantitatively the same.

While we assume monitoring opportunities to be stochastic we also assume that once the monitoring opportunity is available peer monitoring is accurate. This reflects the idea that peers can interpret signals regarding each other's effort better than the principal can. This is clearly the case if the agents are engaged in the same production process and are performing similar tasks. But even agents who perform quite different tasks are part of a rich network of peers from which they can potentially extract information and from which the principal is typically excluded.

In addition to internal monitoring among agents, the principal can monitor agents for their effort decision. However, in contrast to peer monitoring which is random and accurate, monitoring by the principal is strategic and noisy. Specifically, each agent can be monitored by the principal at a cost $c(\pi)$ through signals with quality π. This means that the principal's type 1 and type 2 errors have a probability $(1-\pi)$ (again the uniformity of both c and π is without loss of generality). We assume that $\pi \in [1/2, 1]$. Since $\pi = 1/2$ corresponds to no-monitoring, we assume that $c(1/2) = c'(1/2) = 0$, and $c'(\pi) > 0$ and $c''(\pi) > 0$ for $\pi \in (1/2, 1)$. Finally, in addition to the information revealed through monitoring, the principal is always costlessly informed about the outcome of the project.

The principal offers a contract to the agents to induce them to exert effort. The contract is designed and offered ex-ante before any agent makes his effort decision. The principal decides on the monitoring levels in advance and the chosen monitoring precisions are revealed to the agents.[2] The contract can make contingencies on the monitoring outcome of the agent as well as the project's outcome. Specifically, a contract to agent j is a 4-tuple $\mathbf{v}_j = (v_j^{e,s}, v_j^{ne,s}, v_j^{e,f}, v_j^{ne,f})$ specifying payments under each monitoring signal (e for effort and ne for no-effort) and each outcome of the project (s for success and f for failure).[3] We adopt the standard assumption of limited liability which means that all these payments are nonnegative. For a mechanism $\mathbf{v}(q) = (v_1, ..., v_n)$ we denote by $G(\mathbf{v})$ the underlying sequential game among the players. Player j's pure strategy in this game is a function $s_j : 2^{M(j)} \longrightarrow \{0, 1\}$, where $M(j)$ is the set of players whose effort has been observed by agent j. A mechanism $\mathbf{v}$ is said to be incentive-inducing (IIN) if there exists a perfect Bayesian equilibrium of $G(\mathbf{v})$ in which all players exert effort. We say that $\mathbf{v}$ is an optimal incentive-inducing mechanism if it is an IIN mechanism and there exists no other IIN mechanism with a smaller expected payment by the principal. Our assumption that the principal wishes to incentivize the entire set of agents should be viewed as the crucial step of the more general problem in which the principal maximizes his net payoff, i.e., the difference between the expected benefit from the successful completion of the project and the cost of incentivizing the optimal group of agents. Thus we are mainly

[2] Alternatively, we can assume that the principal commits in advance to the monitoring precision. Otherwise, it is not sequantially rational for the principal to monitor the agents.

[3] The principal can further increase his utility by conditioning the payment to agent j on the monitoring outcome of all the later agents or on the reports of the later agents. However, we design the contract to be simple in the sense that it is based only on the results of the whole project and on the results of the personal monitoring. In addition to its simplicity, it guarantees that the contract is not based on contingencies that are hard to verify. Moreover, contracts that condition the compensation of agent j on the monitoring outcomes of some other agents may not be applicable in many situations. Therefore, we do not consider these types of payment schemes here.

concerned with the properties of the optimal contracts offered to the optimal group and not so much with the problem of selecting the optimal group.

2 Optimal Monitoring Schemes

We start this section by showing that under complementarity peer monitoring can serve as a substitute for direct monitoring by the principal. Proposition 1 asserts that as the organization becomes more transparent in terms of monitoring opportunities among peers, the principal will monitor the agents with lower precisions. We find this result particularly surprising given the different nature of peer monitoring and monitoring by the principal namely, formal vs. informal and strategic vs. random. In particular, in spite of the fact that none of the information available to peers leaks to the principal, greater transparency among peers reduces the incentive of the principal to monitor the agents directly. The basic intuition behind this result is that with increasing transparency the implicit incentive to exert effort grows. This incentive arises from the fact that the success of the project induces benefits to agents beyond the benefits that can be attained by a positive effort signal to the principal. Since the technology is one of complementarity it implies that players can credibly threaten each other (in equilibrium) that they will not exert effort if they encounter someone else shirking. This credible threat has a similar effect as in direct monitoring and makes the latter partly dispensable.

Proposition 1 *Assume that the technology P satisfies complementarity. If $q_1 > q_2$ then $\pi_j^1 \leq \pi_j^2$ for every agent $j < n$, where π_j^i is a monitoring precision of agent j if the quality of the peer monitoring is q_i. The equality may hold only if $\pi_j^1 = 1$.*[4] *For the last agent $\pi_n^1 = \pi_n^2$.*

To prove the proposition above we shall make use of three lemmata that characterize some properties of the optimal IIN mechanism. The first two lemmata characterize the optimal compensation scheme for an arbitrary agent conditional on the principal's monitoring strategy, while the third lemma uses the property of technological complementarity to show that for

[4] Alternatively, in order to exclude the corner solution we can assume that $c(1) = \infty$.

any fixed monitoring policy of the principal better peer-review technology implies a higher probability of the failure of the project if agent j shirks, while all the other agents play the equilibrium strategies.

In deriving the optimal payments of agent j in any IIN mechanism, we keep fixed the payment scheme and the monitoring of all the other agents. To suppress some notation we denote by $Q(j)$ the probability that the project will succeed if agent j shirks, while others play the equilibrium strategy for a given payment scheme of the IIN mechanism and the monitoring decisions of the principal. Notice that monotonicity of $P(\cdot)$ implies that $P(N) > Q(j)$. The lemma below characterizes the properties of the optimal payment scheme as a function of the principal's monitoring strategy regarding agent j in any IIN mechanism.

Lemma 1 *If the principal monitors agent j with precision π_j, then the compensation scheme of that agent in any incentive-inducing mechanism satisfies*

$$v_j^{e,s}\left[\pi_j P(N) - (1-\pi_j) Q(j)\right] + v_j^{e,f}\left[\pi_j (1-P(N)) - (1-\pi_j)(1-Q(j))\right] + \tag{1}$$
$$v_j^{ne,s}\left[(1-\pi_j) P(N) - \pi_j Q(j)\right] + v_j^{ne,f}\left[(1-\pi_j)(1-P(N)) - \pi_j (1-Q(j))\right] \geq e_j.$$

Proof. If the principal monitors the agent with precision π, then the expected utility of the agent if he invests effort is

$$-e_j + \pi_j P(N) v_j^{e,s} + v_j^{e,f} \pi_j (1-P(N)) + v_j^{ne,s}(1-\pi_j) P(N) + v_j^{ne,f}(1-\pi_j)(1-P(N)).$$

If, however, the agent shirks, then his utility is

$$v_j^{e,s}(1-\pi_j) Q(j) + v_j^{e,f}(1-\pi_j)(1-Q(j)) + v_j^{ne,s} \pi_j Q(j) + v_j^{ne,f} \pi_j (1-Q(j)).$$

In any IIN mechanism, the agent should prefer to exert effort. That is,

$$\begin{aligned} & -e_j + \pi_j P(N) v_j^{e,s} + v_j^{e,f} \pi_j (1-P(N)) + v_j^{ne,s}(1-\pi_j) P(N) + v_j^{ne,f}(1-\pi_j)(1-P(N)) \\ \geq\ & v_j^{e,s}(1-\pi_j) Q(j) + v_j^{e,f}(1-\pi_j)(1-Q(j)) + v_j^{ne,s} \pi_j Q(j) + v_j^{ne,f} \pi_j (1-Q(j)). \end{aligned}$$

Rearranging gives us the required inequality. ■

Note that the expected payment of the principal to agent j in an IIN mechanism if he monitors that agent with precision π_j is given by

$$v_j^{e,s} \pi_j P(N) + v_j^{e,f} \pi_j (1-P(N)) + v_j^{ne,s}(1-\pi_j) P(N) + v_j^{ne,f}(1-\pi_j)(1-P(N)). \tag{2}$$

The next lemma specifies the optimal payment scheme for a given level of monitoring. More precisely, any agent gets a compensation if and only if the project succeeded and the principal's monitoring did not detect shirking. The intuition is rather simple: paying in the case of the failure of the project and observing shirking decrease incentives. While positive payments in the case of only one negative signal (either the success of the project and shirking by the agent, or the failure of the project and observing effort exertion) may improve the incentives of the agents, these payments ignore some of the available information. On the other hand reducing these payments while adjusting the payments when both signals are positive (project completion and monitoring by the principal) is always beneficial.

Lemma 2 *For a given monitoring precision π_j of agent j, in an IIN mechanism the compensation scheme of agent j that minimizes the expected payment of the principal to agent j is given by*

$$\left(v_j^{e,s}, v_j^{ne,s}, v_j^{e,f}, v_j^{ne,f}\right) = \left(\frac{e_j}{\pi_j P(N) - (1-\pi_j)\, Q\,(j)}, 0, 0, 0\right).$$

Proof. See Appendix. ■

The expected payment of the principal, in an IIN mechanism if he monitors the agent with precision π_j is given by

$$\frac{\pi_j P(N) e_j}{\pi_j P(N) - (1-\pi_j)\, Q\,(j)}.$$

Lemma 2 implies that each agent is exactly indifferent between investing and shirking, given that all the predecessors of this agent exerted effort. In particular, the assumed technological complementarity implies that in the optimal IIN mechanism an agent will shirk after observing the shirking of at least one of his predecessors independently of the monitoring strategy of the principal.

The next lemma shows that in the case of complementarity in the optimal IIN mechanism more precise peer monitoring reduces the probability of completing the project if agent j shirks and does not invest effort, while all the other agents stick to their equilibrium strategies. The reason is that in the case of more precise peer monitoring, shirking by agent j will be detected by more successors of agent j. This generates further shirking by the later agents. We denote by $Q^q(j)$ the probability that in the optimal compensation scheme the project will be successful if agent j shirks, while the peer monitoring parameter is q. Notice that since in the optimal IIN mechanism if the technology satisfies complementarity, an agent exerts effort only if he does not observe any shirking by the previous agents, $Q^q(j)$ is independent of the monitoring strategy of the principal.

Lemma 3 *Under complementarity, in the optimal compensation scheme, $Q^q(j)$ is strictly decreasing in q for any $j < n$.*

Proof. See Appendix. ■

Proof of Proposition 1. Observe that if agent j is monitored with precision $\pi_j \in [1/2, 1]$, then Lemma 2 implies that the expected payment to this agent is

$$\frac{\pi_j P(N) e_j}{\pi_j P(N) - (1-\pi_j) Q(j)}.$$

Therefore, the principal chooses π_j to minimize his expected payment and monitoring costs:

$$\min_{\pi_j \in [1/2,1]} \frac{\pi_j P(N) e_j}{\pi_j P(N) - (1-\pi_j) Q(j)} + c(\pi_j).$$

The first-order condition gives us that for $\pi_j < 1$

$$\pi_j^2 \frac{P(N)}{Q(j)} - 2\pi_j (1-\pi_j) + (1-\pi_j)^2 \frac{Q(j)}{P(N)} = \frac{e_j}{c'(\pi_j)}.$$

Notice that

$$\frac{\partial}{\partial Q}\left[\pi_j^2 \frac{P}{Q} + (1-\pi_j)^2 \frac{Q}{P}\right] = -\pi_j^2 \frac{P}{Q^2} + (1-\pi_j)^2 \frac{1}{P} < 0,$$

where the last inequality follows since $\pi > 1/2$ and $Q < P$. To complete the proof recall that the previous lemma implies that if $q_1 > q_2$ then $Q^{q_1}(j) < Q^{q_2}(j)$. Therefore, from the first-order condition and the convexity of c we get that if $q_1 > q_2$ and $\pi_j^1 < 1$ then $\pi_j^1 < \pi_j^2$. If $\pi_j^1 = 1$, then a similar proof implies that $\pi_j^2 = 1$. ■

Our next result refers to the case where all the agents are symmetric.

Definition 1 *All agents are symmetric if $e_j = e$ for any j, and for any two sets of agents $T, T' \subseteq N$ holds $P(T) = P(T')$ whenever $|T| = |T'|$.*

That is, in the symmetric case the efforts of all the agents cost the same and the probability of success depends only on the number of agents that exert effort, not on their identities.

Lemma 4 *If all agents are symmetric, then for any q we have that $j_1 > j_2$ implies that $Q(j_1) > Q(j_2)$.*

Proof. Note that it is sufficient to show that $Q(j) > Q(j+1)$ holds for any $q \in (0,1)$ and $j \in \{1, ..., n-1\}$. That is, we compare two cases. In the first one, agent j is the first agent that shirks and all his successors that observed his shirking do not exert effort. The second case refers to agent $j+1$. Since the probability of peer review is q, the only difference for any realization of peer reviews of the $n-j-2$ agents that follow the shirking agent is that in the first case one additional agent shirks with positive probability, while in the second case, this agent shirks with probability 0. Therefore, $Q(j) > Q(j+1)$. ■

Proposition 1 asserted that the principal will typically only partially monitor the agents and this monitoring will be more extensive as the level of transparency among peers declines. We are now interested in the identity of the agents who will be more closely monitored by the principal. Proposition 2 asserts that if all agents are symmetric, then the last agents will be exposed to higher levels of monitoring. In other words, the optimal allocation of monitoring resources is such that agents who appear later in the order of moves are monitored with greater precisions than those who appear earlier. The principal gains more from the monitoring of late movers compared with early movers because later movers are less exposed to the implicit incentives generated by peer monitoring. An early mover affects the decisions of many agents and by shirking he may trigger a domino effect that will potentially induce all his followers to shirk as well, which will greatly diminish the expected return he will get from the principal. In contrast a late mover affects the behavior of only a small number of agents and therefore has a greater incentive to shirk unless monitored by the principal.

Proposition 2 *Assume that technology satisfies complementarity and all agents are symmetric. If* $j_1 > j_2$ *and* $\pi_{j_2} < 1$*, then* $\pi_{j_1} > \pi_{j_2}$*.*

Proof. Recall that if agent j gets monitored with precision $\pi \in [1/2, 1]$, then Lemma 2 implies that the expected payment to this agent is

$$\frac{\pi P(N)e}{\pi P(N) - (1-\pi)\,Q\,(j)}.$$

Therefore, the principal chooses π to minimize his disutility

$$\min_{\pi\in[1/2,1]} \frac{\pi P(N)e}{\pi P(N) - (1-\pi)\,Q\,(j)} + c(\pi).$$

The first-order condition for $\pi < 1$ gives us

$$\pi^2 \frac{P(N)}{Q\,(j)} - 2\pi\,(1-\pi) + (1-\pi)^2 \,\frac{Q\,(j)}{P(N)} = \frac{e}{c'(\pi)}.$$

Notice that

$$\frac{\partial}{\partial Q}\left[\pi^2 \frac{P}{Q} + (1-\pi)^2 \,\frac{Q}{P}\right] = -\pi^2 \frac{P}{Q^2} + (1-\pi)^2 \,\frac{1}{P} < 0$$

where the last inequality follows since $\pi > 1/2$ and $Q < P$.

From Lemma 4 follows that $j_1 > j_2$ implies that $Q\,(j_1) > Q\,(j_2)$. Therefore,

$$\pi^2 \frac{P(N)}{Q\,(j_1)} - 2\pi\,(1-\pi) + (1-\pi)^2 \,\frac{Q\,(j_1)}{P(N)} <$$
$$\pi^2 \frac{P(N)}{Q\,(j_2)} - 2\pi\,(1-\pi) + (1-\pi)^2 \,\frac{Q\,(j_2)}{P(N)}.$$

This inequality implies that $c'\,(\pi_{j_1}) > c'\,(\pi_{j_2})$. The convexity of the monitoring costs implies that $\pi_{j_1} > \pi_{j_2}$. ■

2.1 Technological substitution

In this subsection we characterize the optimal compensation scheme and monitoring strategy if the technology satisfies substitution. In the case of technological substitution, without monitoring, observing any predecessor shirking, increases the incentives of the other agents. That is, shirking by any agent does not induce shirking by later agents and hence the effect on the probability of the successful accomplishment of the project is rather insignificant, since it does not generate a domino effect. Therefore, peer monitoring is not an effective way to incentivize agents. Hence, in the optimal IIN mechanism, under the assumed substitution, it is sufficient to generate incentives when all the other agents exert effort. It will guarantee effort exertion in all the other cases. Hence, independently of the observed history, in the IIN mechanism the principal should provide incentives to agent j if all the other agents exert effort.

The next corollary states formally that in the case of substitution, two types of monitoring are unrelated.

Corollary 3 *In the case of technological substitution, the optimal level of monitoring is independent of* q*.*

Proof. Note that Lemma 2 does not use any assumption of complementarity. That is, this lemma holds in the case of both technological complementarity and substitution. In the case of technological substitution, shirking by any agent, if detected, increases the incentives of any later agents. Therefore, shirking by agent j leads to the completion of the project with probability $P(N\backslash j)$. Plugging $Q(j) = P(N\backslash j)$ into the expressions in the statement of Lemma 2 leads to

$$\left(v_j^{e,s}, v_j^{ne,s}, v_j^{e,f}, v_j^{ne,f}\right) = \left(\frac{e_j}{\pi_j P(N) - (1-\pi_j) P(N\backslash j)}, 0, 0, 0\right).$$

■

3 The Optimal Level of Monitoring and the Technology

Our last results compares the precision of the monitoring for different types of technologies. They yield the testable implication that technologies of substitution admit more intensive monitoring than ones of complementarity. In the case of complementarity, the motivation of the agents is rather significant, since in the optimal IIN mechanism shirking by any agent causes shirking by all the later agents that observed his or anyone else's shirking. Therefore, a relatively low level of monitoring and small payments are sufficient to generate incentives. However, in the case of substitution, shirking by any agent amplifies the incentives of the other agents. Therefore, peer monitoring is not instrumental in providing incentives and substitution technology requires closer monitoring by the principal.

Denote by $P^{sub}(k)$ $(P^{com}(k))$ two symmetric technologies such that P^{sub} satisfies the substitution condition and P^{com} satisfies complementarity. In order to conduct a meaningful comparison of the monitoring levels, we normalize the technologies to satisfy

$$P^{sub}(n) = P^{com}(n).$$

Proposition 4 *Assume that in both technologies all agents are symmetric. Then in the optimal IIN mechanism for any j and any q, we have $\pi_j^{sub} \geq \pi_j^{com}$ where the inequality is strict whenever $j < n$ and $\pi_j^{com} < 1$.*

Proof. Recall that in the case of substitution the optimal monitoring is independent of the precision of the peer review, while in the case of complementarity the precision of the principal's monitoring (strictly) decreases with the precision of the peer monitoring (for $j < n$). Therefore, it is sufficient to prove the proposition for $q = 0$. Recall that for $q = 0$ peer monitoring does not exist. Therefore, the incentive provision is based solely on the principal's monitoring and the principal's expected payment to agent j in the case of complementarity is given by

$$\frac{\pi_j P^{com}(n)e}{\pi_j P^{com}(n) - (1-\pi_j)\, P^{com}(n-1)}.$$

Therefore, the first-order condition if $\pi_j^{com} < 1$ is

$$e\frac{\left(P^{com}(n)\right)^2}{\left(\pi_j^{com} P^{com}(n) - \left(1-\pi_j^{com}\right) P^{com}(n-1)\right)^2} = c'\left(\pi_j^{com}\right).$$

Similarly, the first-order condition for the technology that satisfies substitution if π_j^{sub} is

$$e\frac{\left(P^{sub}(n)\right)^2}{\left(\pi_j^{sub} P^{sub}(n) - \left(1-\pi_j^{sub}\right) P^{sub}(n-1)\right)^2} = c'\left(\pi_j^{sub}\right).$$

Since $c''(\cdot) > 0$ and $P^{sub}(n) = P^{com}(n)$, it is sufficient to show that for any $\pi_j \in [1/2, 1]$ $\pi_j P^{com}(n) - (1-\pi_j) P^{com}(n-1) > \pi_j P^{sub}(n) - (1-\pi_j) P^{sub}(n-1)$, which holds, since $P^{sub}(n-1) > P^{com}(n-1)$. ■

4 Discussion

Agents' incentives in organizations are influenced by the nature and the degree of monitoring. In this paper we studied the interaction between the formal monitoring carried out by the principal (management) and the informal monitoring that agents carry out sporadically vis-à-vis their peers. We have shown that if the team's production function satisfies complementarity, then the agents' monitoring substitutes for the principal's monitoring; i.e. as transparency increases among peers, the (optimal) level of monitoring carried out by the principal declines. This holds in spite of the fact that the information the peers possess about each other never leaks to the principal. If, on the other hand, the production technology satisfies substitution, then the principal's optimal level of monitoring is independent of the availability of peer monitoring, and it is generically higher than the (optimal) level of monitoring under complementarity.

Team environments based on a "weak link" type of technology, possess a high degree of complementarity. In these teams the outcome of some task is used as the input of some other task. Our testable implication is that in such teams the formal monitoring of workers will be responsive to the degree of internal information among peers. In contrast teams in which agents perform identical tasks on different units of production (and are therefore substitutes as production factors) will be monitored at a higher level and independently of the level of transparency within the team.

We believe these results can serve as the basis for further investigation on monitoring in teams using both empirical data and results from laboratory experiments.

5 Appendix

Proof of Lemma 2. First, we can claim that the incentive constraint in the optimal IIN mechanism (1) holds with equality, as otherwise it is possible to decrease at least one payment and still satisfy the constraint.

Next, we will show that in the optimal IIN mechanism $v_j^{ne,s} = v_j^{e,f} = v_j^{ne,f} = 0$. First, we claim that in the optimal mechanism $v_j^{ne,f} = 0$. Assume for a moment that in the optimal mechanism $v_j^{ne,f} > 0$. Setting $v_j^{ne,f} = 0$ still satisfies inequality (1) and decreases the expected payment (2). It contradicts the assumed optimality of the original mechanism. Assume now that in the optimal mechanism $v_j^{e,f} > 0$. Consider the following changes: decrease $v_j^{e,f}$ by ε and increase $v_j^{e,s}$ by $\varepsilon \frac{\pi_j(1-P(N))-(1-\pi_j)(1-Q(j))}{\pi_j P(N)-(1-\pi_j)Q(j)}$. The effect of these changes on the incentive constraint (1) is

$$-\varepsilon\left[\pi_j\left(1-P(N)\right)-\left(1-\pi_j\right)\left(1-Q\left(j\right)\right)\right]+\varepsilon\frac{\pi_j\left(1-P\left(N\right)\right)-\left(1-\pi_j\right)\left(1-Q\left(j\right)\right)}{\pi_j P\left(N\right)-\left(1-\pi_j\right)Q\left(j\right)}\left[\pi_j P\left(N\right)-\left(1-\pi_j\right)Q\left(j\right)\right]=0.$$

Therefore, these changes preserve the incentive constraint (1).

We will now show that these changes reduce the principal's expected payment. If $\pi_j\left(1-P\left(N\right)\right)-\left(1-\pi_j\right)\left(1-Q\left(j\right)\right) \leq 0$, then the changes decrease both payments and hence they decrease the principal's expected payment. Assume now that $\pi_j\left(1-P\left(N\right)\right)-\left(1-\pi_j\right)\left(1-Q\left(j\right)\right) > 0$. The effect of the changes on the principal's expected payment is

$$\begin{aligned}
& \varepsilon\frac{\pi_j\left(1-P\left(N\right)\right)-\left(1-\pi_j\right)\left(1-Q\left(j\right)\right)}{\pi_j P\left(N\right)-\left(1-\pi_j\right)Q\left(j\right)}\pi_j P\left(N\right)-\varepsilon\pi_j\left(1-P\left(N\right)\right) \\
= \; & \varepsilon\left[\pi_j\left(1-P(N)\right)-\left(1-\pi_j\right)\left(1-Q\left(j\right)\right)\right]\times \\
& \left(\frac{\pi_j P\left(N\right)}{\pi_j P\left(N\right)-\left(1-\pi_j\right)Q\left(j\right)}-\frac{\pi_j\left(1-P\left(N\right)\right)}{\pi_j\left(1-P(N)\right)-\left(1-\pi_j\right)\left(1-Q\left(j\right)\right)}\right) \\
= \; & \varepsilon\left[\pi_j\left(1-P(N)\right)-\left(1-\pi_j\right)\left(1-Q\left(j\right)\right)\right]\left(\frac{1}{1-\frac{1-\pi_j}{\pi_j}\frac{Q(j)}{P(N)}}-\frac{1}{1-\frac{1-\pi_j}{\pi_j}\frac{1-Q(j)}{1-P(N)}}\right)<0
\end{aligned}$$

where the last inequality follows from the fact that $P\left(N\right) > Q\left(j\right)$ and the assumed inequality $\pi_j\left(1-P\left(N\right)\right)-\left(1-\pi_j\right)\left(1-Q\left(j\right)\right) > 0$. Therefore, these changes preserve the agent's incentives and decrease the principal's expected payment. It contradicts the assumed optimality of the original mechanism.[5]

Finally, we will show that in the optimal IIN mechanism $v_j^{ne,s} = 0$. Assume for a moment that in the optimal mechanism $v_j^{ne,s} > 0$. Consider the following changes: decrease $v_j^{ne,s}$ by ε and increase $v_j^{e,s}$ by $\varepsilon\frac{(1-\pi_j)P(N)-\pi_j Q(j)}{\pi_j P(N)-(1-\pi_j)Q(j)}$. The effect of these changes on the incentive constraint (1) is

$$-\varepsilon\left[(1-\pi_j)P(N)-\pi_j Q(j)\right]+\varepsilon\frac{(1-\pi_j)P(N)-\pi_j Q(j)}{\pi_j P(N)-(1-\pi_j)Q(j)}\left[\pi_j P(N)-(1-\pi_j)Q(j)\right]=0.$$

Therefore, these changes preserve the incentive constraint (1).

We will now show that these changes reduce the principal's expected payment. If $(1-\pi_j)P(N)-\pi_j Q(j) < 0$, then the changes decrease both payments and hence these changes decrease the principal's expected payment. Therefore assume that $(1-\pi_j)P(N)-\pi_j Q(j) > 0$. The effect of the changes on the principal's expected utility is

$$\begin{aligned}
& \varepsilon\frac{(1-\pi_j)P(N)-\pi_j Q(j)}{\pi_j P(N)-(1-\pi_j)Q(j)}\pi_j P(N)-\varepsilon(1-\pi_j)P(N) \\
= \; & \varepsilon\left[(1-\pi_j)P(N)-\pi_j Q(j)\right]\times \\
& \left(\frac{\pi_j P(N)}{\pi_j P(N)-(1-\pi_j)Q(j)}-\frac{(1-\pi_j)P(N)}{(1-\pi_j)P(N)-\pi_j Q(j)}\right) \\
= \; & \varepsilon\left[(1-\pi_j)P(N)-\pi_j Q(j)\right]\left(\frac{1}{1-\frac{1-\pi_j}{\pi_j}\frac{Q(j)}{P(N)}}-\frac{1}{1-\frac{\pi_j}{1-\pi_j}\frac{Q(j)}{P(N)}}\right)<0
\end{aligned}$$

where the last inequality follows from $\pi_j > 1/2$ and the assumed inequality $(1-\pi_j)P(N)-\pi_j Q(j) > 0$. Therefore, these changes preserve the agent's incentives and reduce the principal's expected payment. Again it contradicts the optimality of the original mechanism

Plugging $v_j^{ne,s} = v_j^{e,f} = v_j^{ne,f} = 0$ into (1) allows us to conclude that if the principal monitors agent j at level π_j, then the optimal compensation scheme is given by

$$\left(v_j^{e,s}, v_j^{ne,s}, v_j^{e,f}, v_j^{ne,f}\right)=\left(\frac{e_j}{\pi_j P(N)-(1-\pi_j)Q(j)},0,0,0\right).$$

[5]If $\pi_j(1-P(N))-(1-\pi_j)(1-Q(j)) = 0$, then these changes do not affect the principal's expected payment and hence the described contract is optimal, but not unique.

This completes the proof of the Lemma. ∎

Proof of Lemma 3. Note that the optimal payment scheme makes any agent indifferent between exerting effort and shirking given that the predecessors of that agent exerted effort. Moreover, if this agent exerts effort, all the later agents also exert effort and the project will succeed with probability $P(N)$, while if he doesn't, the project will succeed with probability $Q^q(j)$. Note that in the case of complementarity, any agent shirks if he observes shirking by at least one agent among his predecessors. Therefore, in any IIN mechanism

$$Q^q(j) = \sum_s P(A_{j-1} \cup S) \Pr_q(S)$$

where $\Pr_q(S)$ is the probability that the set S of later agents (after j) does not observe any shirking and hence in any IIN mechanism exerts effort if agent j shirks and A_{j-1} is the set of the first $j-1$ agents. Assume $j < n$ and denote by k the cardinality of set S, $k = |S|$, by $S(1)$ the first agent in set S, by $S(2)$ the second agent in set S, ..., and by $S(k)$ the last agent in set S. Since every agent after agent j exerts effort if and only if this agent does not observe any shirking, the probability that set S of agents exerts effort is

$$\begin{aligned}
\Pr_q(S) &= \prod_{m=j+1}^{S(1)-1} \left[1-(1-q)^{m-j}\right](1-q)^{S(1)-j} \times \\
&\times \prod_{m=S(1)+1}^{S(2)-1} \left[1-(1-q)^{m-j-1}\right](1-q)^{S(2)-S(1)-1+S(1)-j} \times \\
&\times \prod_{m=S(2)+1}^{S(3)-1} \left[1-(1-q)^{m-j-2}\right](1-q)^{S(3)-S(2)-1+S(2)-S(1)-1+S(1)-j} \times \cdots \times \\
&\times \prod_{m=S(k)+1}^{N} \left[1-(1-q)^{m-j-k}\right] \\
&= \prod_{m=j+1}^{N-k} \left[1-(1-q)^{m-j}\right](1-q)^{k(S(1)-j)+(k-1)(S(2)-S(1)-1)+\cdots+(S(k)-S(k-1)-1)} \\
&= \prod_{m=j+1}^{N-k} \left[1-(1-q)^{m-j}\right](1-q)^{\sum_{i=1}^{k} S(i)-kj-\frac{k(k-1)}{2}}.
\end{aligned}$$

Therefore, the derivative of $\Pr_q(S)$ with respect to q is

$$\begin{aligned}
\frac{\partial \Pr_q(S)}{\partial q} &= -\left(\sum_{i=1}^{k} S(i) - kj - \frac{k(k-1)}{2}\right) \prod_{m=j+1}^{N-k} \left[1-(1-q)^{m-j}\right](1-q)^{\sum_{i=1}^{k} S(i)-kj-\frac{k(k-1)}{2}-1} \\
&\quad + \sum_{m=j+1}^{N-k} (m-j)(1-q)^{m-j-1} \prod_{\substack{i=j+1 \\ i\neq m}}^{N-k} \left[1-(1-q)^{i-j}\right](1-q)^{\sum_{i=1}^{k} S(i)-kj-\frac{k(k-1)}{2}} \\
&= \prod_{m=j+1}^{N-k} \left[1-(1-q)^{m-j}\right](1-q)^{\sum_{i=1}^{k} S(i)-kj-\frac{k(k-1)}{2}} \times \\
&\quad \times \left[\sum_{m=j+1}^{N-k} (m-j)\frac{(1-q)^{m-j-1}}{1-(1-q)^{m-j-1}} - \frac{\sum_{i=1}^{k} S(i) - kj - \frac{k(k-1)}{2}}{1-q}\right] \\
&= \prod_{m=j+1}^{N-k} \left[1-(1-q)^{m-j}\right](1-q)^{\sum_{i=1}^{k} S(i)-kj-\frac{k(k-1)}{2}-1} \times \\
&\quad \times \left[\sum_{m=j+1}^{N-k} (m-j)\frac{(1-q)^{m-j}}{1-(1-q)^{m-j-1}} - \left(\sum_{i=1}^{k} S(i) - kj - \frac{k(k-1)}{2}\right)\right].
\end{aligned}$$

We will now show that if for some S we have $\frac{\partial \Pr_q(S)}{\partial q} < 0$, then for any $S' \supset S$ we also have $\frac{\partial \Pr_q(S')}{\partial q} < 0$. The previous expression implies that if $\frac{\partial \Pr_q(S)}{\partial q} < 0$, then

$$\sum_{m=j+1}^{N-k} (m-j)\frac{(1-q)^{m-j}}{1-(1-q)^{m-j-1}} - \left(\sum_{i=1}^{k} S(i) - kj - \frac{k(k-1)}{2}\right) < 0.$$

Consider now set $S' \supset S$. Moreover, assume without loss of generality that $|S'| = k+1$. Note that

$$\begin{aligned}
&\sum_{i=1}^{k} S(i) - kj - \frac{k(k-1)}{2} - \left(\sum_{i=1}^{k+1} S'(i) - (k+1)j - \frac{k(k+1)}{2}\right) \\
&= -S'(k+1) + j + k < 0.
\end{aligned}$$

Since

$$\begin{aligned}
&\sum_{m=j+1}^{N-k} (m-j)\frac{(1-q)^{m-j}}{1-(1-q)^{m-j-1}} - \sum_{m=j+1}^{N-k-1} (m-j)\frac{(1-q)^{m-j}}{1-(1-q)^{m-j-1}} \\
&= (N-k-j)\frac{(1-q)^{N-k-j}}{1-(1-q)^{N-k-j-1}} > 0.
\end{aligned}$$

Therefore, if for some S we have $\frac{\partial \Pr_q(S)}{\partial q} < 0$, then for any $S' \supset S$ we also have $\frac{\partial \Pr_q(S')}{\partial q} < 0$. Since $\sum_S \Pr_{q_1}(S) = \sum_S \Pr_{q_2}(S) = 1$ there exists a set S such that for any $S' \supset S$ we also have $\frac{\partial \Pr_q(S')}{\partial q} < 0$. Assume that $q_1 > q_2$. Since $P(\cdot)$ is a monotone function, we get that

$$Q^{q_1}(j) = \sum_s P(A_{j-1} \cup S) \Pr_{q_1}(S) < \sum_s P(A_{j-1} \cup S) \Pr_{q_2}(S) = Q^{q_2}(j).$$

■

References

[1] Alchian, Armen A. and Harold Demsetz (1972) "Production, Information Costs, and Economic Organization," *American Economic Review*, 62(4), 777-795.

[2] Bag, Parimal and Nona Pepito (2012) "Peer Transparency in Teams: Does it Help or Hinder Incentives," *International Economic Review*, 53(4), 1257-1286.

[3] Baliga, Sandeep (2002) "The Not-so-Secret Agent: Professional Monitors, Hierarchies and Implementation," *Review of Economic Design*, 7(1), 17-26.

[4] Deb, Joyee, Li, Jin and Arijit Mukherjee (2013) "Relational Contracts with Subjective Peer Evaluations," *Working paper*

[5] Holmstrom, Bengt (1982) "Moral Hazard in Teams," *Bell Journal of Economics*, 13, 324-340.

[6] Ichino, Andrea and Gerd Muehlheusser (2008) "How Often Should You Open the Door? Optimal Monitoring to Screen Heterogeneous Agents," *Journal of Economic Behavior and Organizations*, 67, 820-831.

[7] McAfee, Preston and John McMillan (1991) "Optimal Contracts for Teams," *International Economic Review*, 32(3), 561-577.

[8] Miller, Nolan (1997) "Efficiency in Partnerships with Joint Monitoring," *Journal of Economic Theory*, 77, 285-299.

[9] Osterman, Paul (1995) "How Common is Workplace Transformation and Who Adapts It?," *Industrial and Labor Relations Review*, 47(2), 173-87.

[10] Rahman, David (2012) "But Who Will Monitor the Monitor?" *American Economic Review*, 102(6), 2267-2297.

[11] Strausz, Roland (1997) "Delegation of Monitoring in a Principal Agent Relationship," *Review of Economic Studies*, 64, 337-357.

[12] Strausz, Roland (1999) "Efficiency in Sequential Partnerships," *Journal of Economic Theory*, 85, 140-156.

[13] Varian, Hal (1990) "Monitoring Agents with Other Agents," *Journal of Institutional and Theoretical Economics*, 146, 153-174

[14] Winter, Eyal (2009) "Incentive Reversal," *American Economic Journal: Microeconomics*, 1(2), 133-147.

[15] Winter, Eyal (2010) "Transparency among Peers and Incentives," *Rand Journal of Economics*, 41, 504-523.