**The Effect of Bias on the Timing of Information**

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**The Effect of Bias on the Timing of Information**

**Abstract:** We study the effect of bias on the timing of information in simultaneous versus sequential production. With simultaneous production, the signal about productivity is early and less accurate, while with sequential production the signal is produced between stages of production. Information externalities arise because the signal affects production, joint output, and payments. The principal prefers a late signal rather than an early signal when effort has a biased impact, because a more (conservatively or liberally) biased late signal enhances the signal's usefulness as a performance measure. With endogenous bias, the principal prefers either a perfectly conservative or liberal biased late signal, if the early signal's accuracy is sufficiently low. Further, the principal prefers the late signal rather than the early signal with the optimal bias when either joint output is not useful as a performance measure, or when the signal is inaccurate.

*Keywords: principal-agent theory, timing, accuracy*
*JEL D82, L20, L23, M41*

## 1. Introduction

The timing of information depends on whether production occurs sequentially or simultaneously, as with teams. While sequential production involves divided responsibilities and various externalities within an organization (Roberts, 2004; Milgrom and Roberts, 1992; Baron and Kreps, 1999), simultaneous production is lauded as superior in reducing costs and making more efficient use of information (Womack et al., 1990). What is largely unnoticed is that simultaneous production involves early information acquisition while sequential production allows for late information acquisition; clearly, the timing of when to collect, process, and report information significantly affects the possible uses of acquired information. While the FASB emphasizes timely information as most relevant (Statement of Financial Accounting Concepts No. 2) due to early information being useful for decision-making, late information can be relevant for performance evaluation (Demski and Feltham, 1976). In turn, early information is frequently regarded to be less accurate compared to late information, which can also be more biased, suggesting a tradeoff in terms of how to organize production and acquire information. By comparing simultaneous production with early reporting to sequential production with late reporting, this study considers the effect of bias on the timing of a signal about productivity in terms of both decision-making and stewardship value.

The effect of production on the timing of information is most obviously applicable to settings where firm owners choose the sequencing of multiple organizational units. Specifically, with a new product launch, firm owners can decide whether to launch the new product in all markets simultaneously based on early estimates about consumer demand or product quality, or can introduce the product sequentially, in which case more accurate, late information about demand or quality can be acquired. For example, in the film industry, it is common for a film to open in selected markets first, and then to open more generally in other markets (or alternatively, a film can go "straight to video" which implies simultaneous distribution). Electronic firms or durable good firms also can stagger the release of new products, e.g., first selling in the domestic market, and then distributing in foreign markets. A firm's internal innovation can also either be simultaneously or sequentially adopted throughout the organization.

In banking, a new method to check customer credit-worthiness may be implemented by all the branches at the same time or can be introduced sequentially. Similarly, in auditing, new, industry-specific procedures for auditing can be adopted simultaneously or sequentially.

With simultaneous production, early information increases the possibility of making the wrong production decisions because it is less precise. With sequential production, delayed estimates are less relevant for decision-making by the manager who is first to launch or to adopt an innovation but can provide more information about the performance of that manager. In addition, with sequential production, an important consequence of a more accurate estimate is the externality due to a downstream production manager's use of the estimate for decision-making. The usefulness of the information and therefore the effect of the timing of the information in terms of both decision-making and stewardship value will also depend on any bias inherent in the early or late signal. For example, information about product quality produced after an initial product launch can be more accurate relative to an early estimate about whether the product is of high or low quality. In this way, the information can exhibit a conservative or a liberal (i.e., aggressive) bias.

We consider a principal-multi-agent setting, where agents are risk neutral with limited liability. Joint output, which depends on the effort of both agents, is publicly observed at the end of production. In addition, there is a publically observed, imperfect signal about the underlying productivity state. The principal decides whether agents choose effort simultaneously, in which case the signal is observed prior to effort choice (i.e., early reporting) or whether production occurs sequentially, and the signal is observed after the upstream agent's effort choice (i.e., late reporting).[1] With sequential production and late reporting, the upstream agent's effort, besides being productive, also makes the signal more accurate

[1] Given our interest in the effect of production on the timing of information, we determine the principal's preference for either an early or late signal, but not both. First, the principal may not always be better off with both an early and late signal rather than only one signal because the signal is always pre-decision for the downstream agent (Demski and Sappington, 1986; Baiman and Sivaramakrishnan, 1991; Hofmann and Rothenberg, 2013). Second, if both early and late signals were produced, the question is how to design the agents' production choices, depending on the accuracy of the signals. For example, the principal must choose whether the upstream agent should use the early signal for decision-making, because the accuracy of the late signal increases in the upstream agent's effort. In addition, with the downstream agent, the principal must choose which signal the downstream agent should use for decision-making when the realizations of the signals differ. These questions go beyond the current study and could be addressed in future work.

about the underlying state of nature. With simultaneous production, both agents observe the signal prior to making effort choices, while with sequential production, the signal is observed prior to the downstream agent's effort choice. In this way, our setting captures the externalities arising from information acquisition.

With simultaneous production and early reporting, information is generated prior to both agents' effort choices, which can be useful for both agents in making productive decisions. Specifically, the principal prefers that the agents' choice of effort depends on whether the signal indicates the state is favorable or unfavorable. In contrast, with sequential production and late reporting, information is generated after the upstream agent's effort choice but before the downstream agent's effort choice. Because of the delay, late reporting generates less timely information for the upstream agent but more accurate information than early reporting. With late rather than early reporting, the upstream agent's effort is productively inefficient because of the inability to use the signal for decision-making, but the downstream agent's effort is more efficient. Moreover, besides the late signal being more useful for the downstream agent in making productive decisions, it is more useful as a performance measure because it is more informative about the upstream agent's effort. Hence, when the principal chooses late rather than early reporting, for the upstream agent the scope of the information shifts from decision-facilitating to decision-influencing (Demski and Feltham, 1976). In contrast, for the downstream agent, with both early and late reporting, the scope of the information remains decision-facilitating. Thus, the principal's tradeoff is also determined by the benefit of an additional performance measure for the upstream agent and the benefit or cost from the consequences of more accurate information for the incentives of the downstream agent.

The provision of incentives directly affected by the timing of information acquisition. With early reporting, the signal is produced before either agent chooses his effort (i.e., pre-decision), and agents must be given *ex post* incentives to communicate and work hard (Christensen, 1981). In contrast, with late reporting, the signal is produced after the upstream agent chooses his effort (i.e., post-decision), and the upstream agent must be given *ex ante* incentives to communicate and work hard (Dye, 1983). Because the information about the downstream agent's productivity is (publicly) produced before the downstream agent's choice of effort, the downstream agent must be given *ex post* incentives to work hard (Demski and Sappington, 1986).

We find that the principal's preference for simultaneous production and early reporting versus sequential production and late reporting can depend on the exogenous impact of the upstream agent's effort on the accuracy of the signal. Considering the compensation of the upstream agent, if the incentive problem to provide effort is not too significant, the principal always prefers an early signal. In this case, the decision-making aspect is more important because with a late signal the upstream agent's inefficient production is too costly. However, if the incentive problem is somewhat significant, we identify conditions where the principal will prefer the late signal when the accuracy of the late signal about the favorable state differs significantly from the accuracy of the late signal about the unfavorable state, that is, if the late signal is sufficiently biased, with either a conservative or a liberal bias.[2] A more accurate late signal enhances the signal's usefulness as a performance measure, but the specific effect depends on which combination of output and the signal are more informative about the upstream agent's effort. Overall, if the upstream agent's actions increase the accuracy of the signal about the state on which compensation is based, the principal refrains from providing information relevant for decision making to the upstream agent and rather releases a more accurate late signal that can only be used for performance evaluation.

Likewise, considering the compensation of the downstream agent, the principal's preference for a late signal reflects the information externalities due to the upstream agent's effect on the accuracy of the signal. Specifically, the principal prefers the late signal for the downstream agent when the late signal either has no bias, a liberal bias, or a moderately conservative bias and prefers the early signal only if the late signal has a significant conservative bias. This result is in sharp contrast to the result for the upstream agent, in that the principal prefers the late signal for the upstream agent when there is sufficient bias,

[2] Similar to Antle and Lambert (1988), a conservative (liberal) bias means that the signal is more accurate about the unfavorable (favorable) state. Also see Kwon et al. (2001), Gigler and Hemmer (2001) and Kwon (2005).

either liberal or conservative. For the downstream agent, the early and the late signal can be used for decision-making, which means that when comparing early with late reporting, the principal only considers the quality of information to be provided to the downstream agent for decision-making. Surprisingly, we identify conditions where the principal prefers to release a less accurate, early signal to the downstream agent, even though simply delaying the release would provide the agent with a more accurate, late signal (which is still timely enough for decision making). The key to our result is that the information is pre-decision to the downstream agent, and providing more (or higher quality) information can mean that the principal has to provide stronger incentives to the downstream agent (Demski and Sappington, 1986; Baiman and Sivaramakrishnan, 1991; Hofmann and Rothenberg, 2013).

We also consider the principal's preference for bias in the late signal with sequential production, which differs for each agent. For the upstream agent, if joint output is not a very good performance measure, the principal uses the signal as a performance measure and prefers a perfectly liberal bias, i.e., a signal that is backward-looking or more informative about the upstream agent's effort; otherwise, the principal prefers a perfectly conservative bias, i.e., a signal that is more forward-looking and complements joint output in measuring performance. In contrast, for the downstream agent, the signal is used for decision-making and performance measurement, and the principal always prefers a signal with a perfect liberal bias to facilitate decision-making and to dampen incentives.

We also consider the effect of the optimal bias on the tradeoff between simultaneous production with an early signal and sequential production with a late signal. For the upstream agent, if the accuracy of the early signal is sufficiently high, the usefulness of the late signal as a performance measure is dampened, and the principal more likely prefers the early signal. For the downstream agent, the principal always prefers the late signal because he can perfectly tailor the quality of the signal.

Despite the relevance of the effect of timing of information for accounting in general, there have been no studies we know of that explicitly address this topic in terms of both decision-making and stewardship value (Lambert, 2001). Related to our question about the timing of information, the tradeoff between timeliness and accuracy has been studied in various decision-making contexts: analysts' earnings forecasts (see for example Cooper et al., 2001 and Guttman, 2010), cost accounting systems (Feltham, 1968 and 1972; Hilton 1979; and Ijiri and Itami, 1973), forecasting macro-economic data (Mankiw and Shapiro, 1986), and the design of management information systems (Ballou, and Pazer, 1995). The primary focus of these studies is on what Demski and Feltham (1976) call the decision-facilitating role of information where no incentive problem exists, rather than on the decision-influencing role of information, which includes incentive problems. In contrast, in a dynamic agency model, Christensen et al. (2003) consider the relation among timeliness, accuracy, and relevance of the decision-influencing role of information. With contract renegotiation, a delayed report can have zero value. Demski and Sappington (1986) illustrate the effect of timing of the release of public information on incentives to privately acquire additional information, where a late signal is only useful for performance measurement. Our study considers the effect of varying the timing of accounting information, which has dual roles of decision-influencing and decision-facilitating and is inseparable from the productive incentives.

Our study is also related to prior work that focuses on the principal's preference for precision when designing manager's incentives. Liang and Nan (2012) study the design of incentives when the manager's effort increases the precision of the performance measure but decreases his ability to provide productive effort. Friedman (2013) studies the design incentives for a CFO, whose effort increases the precision of a performance measure, but who is pressured by a CEO to bias the performance measure in the CEO's favor. Demski and Dye (1999) consider linear contracting when the manager can choose a project with a particular variance, and where productive effort affects the project's mean output. Our work also involves the endogenous choice of the accuracy of a signal that is useful for performance measurement, but this is accomplished via the choice of timing of the information.

The rest of the paper is organized as follows. Section 2 describes the model. Section 3 analyzes the model and Section 4 concludes.

**2. Model**

The model consists of a risk neutral principal and two risk neutral agents, Agents A and B. The timeline is illustrated in Figure 1. The contract specifies whether production should occur simultaneously, or whether production should be sequential. With simultaneous production, the signal, $y$, is first publically observed and then both agents choose their effort. With sequential production, first Agent A chooses his effort, the signal is publically observed, and then Agent B chooses his effort. Finally, joint output, $x$, is produced and wages, $w$, are paid.

----- Insert Figure 1 around here. -----

Each agent contributes effort, $e^i \in \{0, 1\}$, $i$ =A, B, and each agent has the same cost of effort, $ce^i$. Agents' joint, observable output is $x_j$, $j \in \{g, b\}$, which depends on the effort of Agents A and B as well as a random state of nature. There are two unobservable states of nature, denoted by $\theta_k$, $k \in \{L, H\}$, with each state is equally likely. The probability of $x$ depending on both agents' effort and the state of nature is denoted $\varphi(x_j | \theta_k, e^A, e^B)$, $j \in \{g, b\}$, $k \in \{L, H\}$. Similar to Che and Yoo (2001), in the favorable state, $\theta_H$, agents' joint output is always $x_g$, regardless of effort, but in the unfavorable state $\theta_L$, joint output depends on agents' effort. There are many examples of this type of production function, including new product launches, where good news indicates the product will "sell itself" which implies that marketing managers do not have to supply high effort. Similarly in auditing, a signal indicating good news about the firm's financial statements means that it is efficient for auditors to not work hard, or in banking where information about a customer can indicate that the customer's credit worthiness is good, in which case the bank managers do not need to further investigate the customer.[3]

There is a public signal about $\theta$, $y_k^m$, $k \in \{L, H\}$, $m \in \{e, l\}$, the timing of which depends on whether production is simultaneous or sequential. If production is simultaneous, an early signal is produced prior to both agents' choosing effort ($y^e$), making it very timely. If production is sequential, a late signal is produced after Agent A chooses effort ($y^l$), but before Agent B chooses effort, making it timely for Agent B, but not for Agent A.

[3] We thank John Christensen for providing the banking and auditing examples.

With simultaneous production and an early signal, the accuracy of the signal is $s$, where $\varphi(y_k^e|\theta_k)$ $= s$, $k \in$ {L, H}, $s \in$ (0.5, 1), with $s$ = 1 a perfect signal about $\theta$. With sequential production and a late signal, the accuracy of the signal also depends on Agent A's effort, $\varphi(y_k|\theta_k, e^A)$, where $\varphi(y_k^l|\theta_k, e^A = 1)$ = $s + \delta_k$, $0 < \delta_k < 1 - s$, $k \in$ {L, H}, if Agent A works hard and $\varphi(y_k^l|\theta_k, e^A = 0) = s$ if Agent A does not work hard. Agent A's effort increases the accuracy of the signal, and the increase in accuracy can depend on whether the state is favorable or unfavorable. The *ex ante* probability of observing a late, high signal given Agent A works hard is $\varphi(y_k^l|e^A = 1) = 0.5(1 + \delta_H - \delta_L)$, and if Agent A does not work hard, $\varphi(y_H^l|e^A = 0) = 0.5$, the same as if the signal is early. Allowing for the increase in accuracy of the late signal to depend on whether the state is favorable or unfavorable has two consequences. First, the *ex ante* probability of observing the high late signal will differ from the *ex ante* probability of observing the low late signal. Second, the *ex ante* probability of observing the high signal will differ depending on whether the signal is early or late, and similarly for the low signal. In addition, we assume that the value of output is such that if the high signal is observed, the principal prefers agents do not work hard, but if low signal is observed, then the principal prefers agents work hard.

The relationship between agents' output and the productivity state, $\varphi(x_j|\theta_k, e^A, e^B)$, for all $j \in$ {$g$, $b$}, $k \in$ {L, H}, $e^A \in$ {0, 1} and $e^B \in$ {0, 1}, is as follows. By assumption, $\varphi(x_g|e^A = 1, e^B = 1, \theta_H) =$ $\varphi(x_g|e^A = 0, e^B = 1, \theta_H) = \varphi(x_g|e^A = 1, e^B = 0, \theta_H) = \varphi(x_g|e^A = 0, e^B = 0, \theta_H) = 1$, and for notational ease let $\varphi(x_g|e^A = 1, e^B = 1, \theta_L) = p_2$, $\varphi(x_g|e^A = 0, e^B = 1, \theta_L) = \varphi(x_g|e^A = 1, e^B = 0, \theta_L) = p_1$, and $\varphi(x_g|e^A = 0, e^B = 0, \theta_L) = p_0$. The probability distribution in the state $\theta_L$ is assumed to display first order stochastic dominance in the agents' efforts. This means that $p_2 > p_1 > p_0$, and we also assume that $p_2 - p_1 \geq p_1 - p_0$.

Regardless of whether production is simultaneous or sequential, the signal is not accurate about productivity, but rather includes error. Figure 2 illustrates the relationship between the early signal, $y^e$, and the agents' output $x$, for each productivity state, given accuracy $s$.

----- Insert Figure 2 around here. -----

Figure 3 illustrates the relationship between the late signal, $y^l$, and the agents' output $x$, for each productivity state, given accuracy $s$. Panel A of Figure 3 shows the probability of $x$ and $y^l$, assuming both Agent A and Agent B work hard, while Panel B shows the probability of $x$ and $y^l$, assuming Agent A does not work hard, but Agent B works hard.[4]

----- Insert Figure 3 around here. -----

If production is simultaneous and the signal is early, the joint probabilities are denoted $\varphi(x_j, y_k^e | e^A, e^B)$, $j \in \{g, b\}$, $k \in \{\text{L, H}\}$, $e^A \in \{0, 1\}$, $e^B \in \{0, 1\}$. If both agents work hard, the probability of good output and a high signal is $\varphi(x_g, y_H^e | 1,1) = 0.5s + 0.5(1 - s)p_2$, but if one agent shirks, $\varphi(x_g, y_H^e | 0,1) = \varphi(x_g, y_H^e | 1,0) = 0.5s + 0.5(1 - s)p_1$, and if both agents shirk, $\varphi(x_g, y_H^e | 0,0) = 0.5s + 0.5(1 - s)p_0$. Similarly for good output and a low signal, if both agents work hard, $\varphi(x_g, y_L^e | 1,1) = 0.5(1 - s) + 0.5sp_2$ but if one agent shirks, $\varphi(x_g, y_L^e | 0,1) = \varphi(x_g, y_L^e | 1,0) = 0.5(1 - s) + 0.5sp_1$ and if both agents shirk, $\varphi(x_g, y_L^e | 0,0) = 0.5(1 - s) + 0.5sp_0$.

If production is sequential and the signal is late, the joint probabilities are denoted $\varphi(x_j, y_k^l | e^A, e^B)$, $j \in \{g, b\}$; $k \in \{\text{L, H}\}$, $e^A \in \{0, 1\}$, $e^B \in \{0, 1\}$. The probability of good output and high signal if both agents work hard is $\varphi(x_g, y_H^l | 1,1) = 0.5(s + \delta_H) + 0.5(1 - s - \delta_L)p_2$, and if both agents shirk, $\varphi(x_g, y_H^l | 0,0) = 0.5s + 0.5(1 - s)p_0$. If Agent A works hard, but Agent B does not work hard, $\varphi(x_g, y_H^l | 1,0) = 0.5(s + \delta_H) + 0.5(1 - s - \delta_L)p_1$, and if Agent A does not work hard but Agent B works hard, $\varphi(x_g, y_H^l | 0,1)$

[4] If neither agent works hard, then $p_1$ in Panel B of Figure 3 is replaced by $p_0$.

$=0.5s + 0.5(1-s)p_1$. The probability of good output and an low signal if both agents work hard is $\varphi(x_g, y_L^l|1,1) = 0.5(1 - s - \delta_H) + 0.5(s + \delta_L)p_2$ and if both agents shirk, $\varphi(x_g, y_L^l|0,0) = 0.5(1 - s) + 0.5sp_0$. If Agent A works hard, but Agent B does not work hard, $\varphi(x_g, y_L^l|1,0) = 0.5(1 - s - \delta_H) + 0.5(s + \delta_L)p_1$ and if Agent A does not work hard but Agent B works hard, $\varphi(x_g, y_L^l|0,1) = 0.5(1 - s) + 0.5sp_1$.

Agents' payments, $w$, can depend on both output, $x$, and the signal, $y$. Agent $i$'s payment is denoted $w_j^i(y_k)$, $i \in \{A, B\}, j \in \{g, b\}$, and $k \in \{L, H\}$. Generally, the principal's problem is to minimize expected payments subject to both agents' participation constraints (or individual rationality constraints, IR), which ensure that each agent will at least earn his reservation wage, which we normalize to zero. Each agent has incentive constraints (IC-*A* and IC-*B*), which differ depending on the timing of the signal in relation to the agent's choice of effort.

In the following sections, we analyze both simultaneous and sequential production, varying the timing and accuracy of the signal.

**3. Analysis**

We first solve for each agent's payment with simultaneous production and an early signal and then we repeat the analysis for sequential production and a late signal. Given the bias in the late signal, we analyze the principal's preference for early versus the late signal. We also analyze the principal's choice of bias, and consider the tradeoff between and early and late signal with the optimal bias.

*3.1 Simultaneous Production and Early Signal*

In this section, we focus only on the setting where each agent chooses production simultaneously and the signal is produced before the agents choose their effort, which means that Agent A's effort does not affect the signal.

The principal's problem with simultaneous production and an early signal is as follows, in $P^{Early}$.

$$\underset{w\geq 0}{Min} = \sum_{j=g,b} \{\varphi(x_j, y_H^e|0,0)[w_j^A(y_H^e) + w_j^B(y_H^e)] + \varphi(x_j, y_L^e|1,1)[w_j^A(y_L^e) + w_j^B(y_L^e)]\}$$

s.t.

$$\sum_{j=g,b} \{\varphi(x_j, y_H^e \big| 0,0) w_j^i(y_H^e) + \varphi(x_j, y_L^e \big| 1,1)[w_j^i(y_L^e) - c)]\} \geq 0,\ i = \text{A, B} \qquad \text{(IR-}i\text{)}$$

$$\sum_{j=g,b} \varphi(x_j \big| y_L^e, 1,1) w_j^A(y_L^e) - c \geq \sum_{j=g,b} \varphi(x_j \big| y_L^e, 0,1) w_j^A(y_L^e)\,, \qquad (\text{IC-}A,\ y_L^e)$$

$$\sum_{j=g,b} \varphi(x_j \big| y_L^e, 1,1) w_j^B(y_L^e) - c \geq \sum_{j=g,b} \varphi(x_j \big| y_L^e, 1,0) w_j^B(y_L^e) \qquad (\text{IC-}B,\ y_L^e)$$

The principal's problem is to minimize expected payments to both agents. Because production is simultaneous and the signal is produced before either agent chooses effort, the incentive problem for both agents is identical. Also because the signal is early, before agents' choose their effort, the incentive constraint (IC $y_L^e$) ensures that both agents will work hard after observing the low signal.

The solution is based on the incentive constraint for the low signal, with payments to agent $i$ as follows:[5]

$$w_g^i(y_H^e) = w_b^i(y_H^e) = 0,\ w_g^i(y_L^e) = \frac{c}{s(p_2 - p_1)},\ w_b^i(y_L^e) = 0,\ i \in \{\text{A, B}\}.$$

The principal's expected payments are:

$$W^{Early} = \frac{[(1-s) + sp_2]c}{s(p_2 - p_1)}\,.$$

Each agent is paid a bonus only when output is good and the signal indicates the low productivity state, which is when agents work hard. When the signal indicates the high state, the principal prefers that agents do not work hard, and agents are not paid a bonus with a high signal. Because of the timing of the signal, incentives are *ex post* which means that the payment, $w_g^i(y_L^e)$, depends inversely on the marginal productivity in the low state, given one agent worked hard, $p_2 - p_1$. Thus, an increase in the marginal productivity in the low state lowers the payment, which is the usual case with risk neutral agents.

Both the payment and the likelihood of payment depend on the accuracy of the signal. The payment depends on the marginal productivity given the low signal, and involves the marginal productivity in the favorable state when it is mistakenly reported as the unfavorable state (which is zero)

[5] The detailed derivation of the optimal contract is found in Appendix A.

and the marginal productivity in the unfavorable state when the unfavorable state is reported accurately. As the signal becomes more accurate, more weight is put on the marginal productivity in the unfavorable state, which decreases the payment. In terms of the likelihood of payment, the accuracy of the signal has two effects. As the signal's accuracy increases, it is less likely that the signal mistakenly reports the favorable state as the unfavorable state, which decreases the cost of payment. However, increasing the signal's accuracy also increases the likelihood of correctly reporting good output when the state is unfavorable. Overall, because good output always occurs in the favorable state, the decrease in the probability of the signal mistakenly reporting the unfavorable state when the actual state is favorable has a greater impact on the joint probability of a good output and low signal than the increase in the likelihood of reporting good output in the unfavorable state.

*3.2 Sequential Production and Late Signal*

Next suppose that production is sequential and the signal is produced late, after Agent A chooses effort but before Agent B chooses effort.

The principal's problem with sequential production and a late signal is as follows, in $P^{Late}$.

$$\underset{w\geq 0}{Min} \quad \sum_{j=g,b} \{\varphi(x_j, y_H^l \,|\, 1,0)[w_j^A(y_H^l) + w_j^B(y_H^l)] + \varphi(x_j, y_L^l \,|\, 1,1)[w_j^A(y_L^l) + w_{jL}^B(y_L^l)]\}$$

s.t.

$$\sum_{j=g,b} [\varphi(x_j, y_H^l \,|\, 1,0)\, w_j^A(y_H^l) + \varphi(x_j, y_L^l \,|\, 1,1)\, w_j^A(y_L^l)] \text{ - } c \geq 0 \qquad \text{(IR-}A\text{)}$$

$$\sum_{j=g,b} \{\varphi(x_j, y_H^l \,|\, 1,0)\, w_j^B(y_H^l) + \varphi(x_j, y_L^l \,|\, 1,1)[w_j^B(y_L^l) - c)]\} \geq 0 \qquad \text{(IR-}B\text{)}$$

$$\sum_{j=g,b} [\varphi(x_j, y_H^l \,|\, 1,0)\, w_j^A(y_H^l) + \varphi(x_j, y_L^l \,|\, 1,1)\, w_j^A(y_L^l)] \text{ - } c \geq$$

$$\sum_{j=g,b} [\varphi(x_j, y_H^l \,|\, 0,0)\, w_j^A(y_H^l) + \varphi(x_j, y_L^l \,|\, 0,1)\, w_j^A(y_L^l)] \qquad \text{(IC-}A\text{)}$$

$$\sum_{j=g,b} \varphi(x_j \,|\, y_L^l, 1,1) w_j^B(y_L^l) \text{ - } c \geq \sum_{j=g,b} \varphi(x_j \,|\, y_L^l, 1,0) w_j^B(y_L^l) \qquad \text{(IC-}B, y_L^l\text{)}$$

Due to the timing of the signal, Agent A's incentive constraint (IC-*A*) differs from Agent B's incentive constraint (IC-*B*, $y_L^l$). Agent A's incentive constraint is *ex ante*, and motivates him to always work hard, while for Agent B the incentive constraint is *ex post*, and Agent B is motivated to work hard only given the signal $y_L^l$. In this case, the signal is still produced before Agent B's action, so Agent B's incentives are similar to above, when the signal was early and produced before both agents' action.

The solution for Agent A is as follows. For Agent A, the IC-*A* is binding, and there are three possible solutions, depending on which combination of the signal and output is most informative about Agent A's effort. (1) If $\delta_L \leq \bar{\delta}$ and $\delta_H \geq a_1\delta_L + K_1$, or if $\delta_L > \bar{\delta}$ and $\delta_H \geq a_2\delta_L + K_2$, with solution (1) Agent A's payments are:[6]

$$w_g^A(y_H^l) = \frac{2c}{\delta_H + (1-s)(p_1 - p_0) - \delta_L p_1}, w_b^A(y_H^l) = w_g^A(y_L^l) = w_b^A(y_L^l) = 0.$$

The principal's expected payment to Agent A is:

$$W_A^{Late} = \frac{[s + \delta_H + (1 - s - \delta_L)p_1]c}{\delta_H + (1-s)(p_1 - p_0) - \delta_L p_1}.$$

(2) If $\delta_L \leq \bar{\delta}$ and $\delta_H < a_1\delta_L + K_1$ or if $\delta_L > \bar{\delta}$ and $\delta_H < a_3\delta_L + K_3$, with solution (2) Agent A's payments are:

$$w_g^A(y_H^l) = w_b^A(y_H^l) = 0,\ w_g^A(y_L^l) = \frac{2c}{-\delta_H + s(p_2 - p_1) + \delta_L p_2},\ w_b^A(y_L^l) = 0.$$

The principal's expected payment to Agent A is:

$$W_A^{Late} = \frac{[(1 - s - \delta_H) + (s + \delta_L)p_2]c}{-\delta_H + s(p_2 - p_1) + \delta_L p_2}.$$

(3) Finally, if $\delta_L > \bar{\delta}$ and $a_3\delta_L + K_3 \leq \delta_H < a_2\delta_L + K_2$, with solution (3) Agent A's payments are:

$$w_g^A(y_H^l) = w_b^A(y_H^l) = w_g^A(y_L^l) = 0,\ w_b^A(y_L^l) = \frac{2c}{\delta_L(1 - p_2) - s(p_2 - p_1)}.$$

The principal's expected payment to Agent A is:

$$W_A^{Late} = \frac{(s + \delta_L)(1 - p_2)c}{\delta_L(1 - p_2) - s(p_2 - p_1)}.$$

[6] The function $\delta_H = a_1\delta_L + K_1$ is when the expected payments for solution (1) are the same as solution (2); the function $\delta_H = a_2\delta_L + K_2$ is when the expected payments for solution (1) are the same as solution (3); finally, the function $\delta_H = a_3\delta_L + K_3$ is when expected payments for solution (2) are the same as solution (3). The details of the conditions under which each solution is optimal are in Appendix A.

With sequential production, Agent A works hard in both states, unlike with simultaneous production. Because of the timing of the signal, Agent A's incentives are *ex ante*, which implies that Agent A's payment depends inversely on the expected marginal productivity of his effort, rather than being tied to the marginal productivity of the unfavorable state, as with the early signal. Whether the bonus is paid when the high signal is observed, $y_H$, or when the low signal is observed, $y_L$, and whether a bonus is paid for good or bad output depends on the effect of Agent A's effort on the outcome of the signal, i.e., $\delta_H$ and $\delta_L$. If the signal was perfectly accurate, i.e., if $s = 1$ which implies $\delta_H = \delta_L = 0$, the optimal contract involves a bonus for good output when the signal is low, because Agent A's effort has no effect on the outcome of the signal and no effect on output in the favorable state. Thus, the principal will pay a bonus for good output and the high signal, i.e., solution (1), as long as there is sufficient error and Agent A's effort has sufficiently significant impact in the favorable state relative to the impact in the unfavorable state. If Agent A's effort has a small impact in the favorable state, then the solution involves payment for good output when the signal is low, i.e., solution (2). Increasing Agent A's effect in the unfavorable state, $\delta_L$, makes the low signal more accurate and more informative about Agent A's effort.

Interestingly, when $\delta_H$ is in the intermediate range, the principal will pay a bonus for a bad output and low signal, i.e., solution (3). However, the principal never pays a bonus for bad output and high signal because it is impossible for bad output to be produced in the favorable state, which means that bad output and a high signal can never be more informative than bad output and a low signal. On the other hand, bad output and the low signal can be more informative about Agent A's effort than good output and the low signal if Agent A's impact in both states is sufficiently significant; the higher $\delta_L$ is, the more informative the low signal is, but the higher $\delta_H$ is, good output given the low signal is less informative.

With sequential production, the outcome of the signal is affected by Agent A's effort, i.e., $\delta_H$ and $\delta_L$, which can introduce more bias in the signal if $\delta_H \neq \delta_L$; for example, if $\delta_H > \delta_L$, Agent A's effort produces a more accurate signal in the favorable state than in the unfavorable state. The effect of the variations in $\delta_H$ or $\delta_L$ depends on the specific solution. When the principal makes a payment after observing good output and the high signal, i.e., solution (1), an increase of $\delta_H$ decreases the payment because it increases Agent A's expected marginal productivity, but increases the likelihood of observing the high signal and the likelihood of payment. However, overall the expected payment will decrease as $\delta_H$ increases. In addition, an increase of $\delta_L$ increases the payment because it decreases Agent A's expected marginal productivity, but decreases the likelihood of payment. Overall the expected payment will increase as $\delta_L$ increases. When the payment is based on the good output and the low signal, i.e., solution (2), an increase in $\delta_H$ and $\delta_L$ has the opposite effect from when the payment is based on the high signal. Thus, solutions (1) and (2) are similar in that $\delta_H$ and $\delta_L$ act as complements in terms of their effect on Agent A's expected payments. Finally, when the payment is based on bad output and the low signal, i.e., solution (3), $\delta_H$ has no effect on the expected payment, but increasing $\delta_L$ increases Agent A's expected marginal productivity based on the low signal which decreases the payment, and increases the likelihood of payment. Overall, the expected payment will decrease as $\delta_L$ increases.

Turning to Agent B, the incentive constraint, (IC-$B$, $y_L^l$) is binding and the solution as follows. The payment is:

$$w_g^B(y_H^l) = w_b^B(y_H^l) = 0,\; w_g^B(y_L^l) = \frac{(1-\delta_H+\delta_L)c}{(s+\delta_L)(p_2-p_1)},\; w_b^B(y_L^l) = 0.$$

The expected payment by the principal to Agent B is:

$$W_B^{Late} = \frac{0.5[(1-s-\delta_H)+(s+\delta_L)p_2](1-\delta_H+\delta_L)c}{(s+\delta_L)(p_2-p_1)}.$$

Agent B's contract with sequential production is very similar to the contract with simultaneous production because the timing of the signal with respect to Agent B's effort is the same in both settings. The only difference from the payment with simultaneous production is the effect of Agent A's effort on the signal, i.e., $\delta_H$ and $\delta_L$. Agent A's effort imposes externalities, in that Agent B's payment is directly affected by the quality of the signal, which depends on Agent A's effort. An increase in the effect of Agent A's effort in the favorable state, $\delta_H$, will cause Agent B's expected payment to decrease. If Agent

A's effort has a higher impact in the favorable state, the signal will more accurately report the favorable state, which lowers the likelihood of a low signal, because it is less likely that the low signal will be reported inaccurately in the favorable state. However, for a given $\delta_H$, an increase in Agent A's effect on the outcome of the signal in the low state, $\delta_L$, can cause Agent B's expected payment to increase or decrease, depending on productivity in the unfavorable state, i.e., $p_2$. If productivity in the unfavorable state is low, then the expected payment increases, and increasing $\delta_L$ will increase Agent B's expected payment, while for higher productivity, the payment is lower, and increasing $\delta_L$ will decrease Agent B's expected payment.

*3.3 Simultaneous versus Sequential Production*

In this section, we analyze the principal's preference for simultaneous versus sequential production separately for each agent. For Agent A the comparison between simultaneous and sequential production is much different than for Agent B. If production is sequential, the signal is late, and Agent A's incentives change significantly compared to when the signal is early with simultaneous production. In addition, the accuracy of the signal can increase with a late signal. For Agent B, the signal is still produced pre-decision, but the likelihood of the signal changes when it is produced after Agent A's productive choice.

We first consider the principal's preference for the timing of the signal for Agent A. The tradeoff between simultaneous production with an early signal and sequential production with a late signal depends on the marginal productivity in the unfavorable state and Agent A's impact on the outcome of the signal, or the accuracy of the late signal.

*Proposition 1: The principal prefers simultaneous production with an early signal to sequential production with a late signal with Agent A if* $p_2 - p_1 > \frac{0.5(1-s)}{s} + 0.5p_2$. *If* $p_2 - p_1 \leq \frac{0.5(1-s)}{s} + 0.5p_2$, *the principal's preference for simultaneous and sequential production with Agent A is as follows:*

*i. If* $\delta_L < \delta_L^*$*, there is an interval,* $X = [\delta_L p_2 + C_2, \delta_L p_1 + C_1]$*, such that when* $\delta_H$ *is outside the interval, i.e.,* $\delta_H \notin X$*, the principal prefers sequential production with a late signal; otherwise the principal prefers simultaneous production with an early signal.*

*ii. If* $\delta_L \geq \delta_L^*$*, the principal always prefers sequential production with a late signal.*

Proof: All proofs are in Appendix B.

From Proposition 1, there are two main effects: the first is the change in Agent A's incentives with regard to the timing of the signal, and the second is the informativeness of the signal with regard to Agent A's effort. In terms of the first effect, with simultaneous production, the signal is pre-decision, which means the incentives are *ex post*, while with sequential production, the signal is post-decision and incentives are *ex ante*. If the marginal productivity in the unfavorable state is very high, the principal prefers the early signal, regardless of Agent A's impact on the outcome of the signal, because the pre-decision incentives are never as strong as post-decision incentives. With a higher marginal productivity in the unfavorable state, the incentive problem with the early signal is insignificant and *ex post* incentives dominate the *ex ante* incentives, in which case the payment has to be high enough to induce Agent A to work hard in both states.

The second effect becomes important if the marginal productivity in the unfavorable state is low. If Agent A's effort has no effect on the outcome of the signal, i.e., $\delta_H = \delta_L = 0$, clearly the late signal is no more accurate than the early signal, and the principal prefers the early signal. Delaying the signal is costly because Agent A works hard in both states which leads to an increased payment. If Agent A's effort affects the signal, i.e., if $\delta_H$, $\delta_L \neq 0$, then the benefit of delaying the signal is that it is informative about Agent A's effort and can be useful as a performance measure.

Whether the benefit of the late signal as a performance measure is more than the benefit of an early signal for decision-making depends on the impact of Agent A's effort in the state on which the bonus is paid being high enough. If the principal pays a bonus to Agent A for good output and the high signal, i.e., solution (1), then an increase in Agent A's impact in the favorable state, $\delta_H$, reduces the expected payment, and an increase in Agent A's impact in the unfavorable state, $\delta_L$, increases the expected payment. The opposite occurs when the principal pays a bonus to Agent A for good output and the low signal, i.e., solution (2). Putting these together implies that there is an interval for $\delta_H$ such that the principal prefers the early signal to the late signal, when the bonus for the late signal involves a payment for good output given either the high or the low signal (i.e., *X*, Proposition 1, Case *i*). Note that on the boundaries of the interval, *X*, where the principal is indifferent between the early and late signal, there is a complementary relationship between $\delta_H$ and $\delta_L$ because both boundaries are increasing in $\delta_L$. This means that if there is sufficient bias (either conservative or liberal) in the late signal, i.e., when $\delta_H$ differs significantly from $\delta_L$, the principal prefers the late signal to the early signal for Agent A. Further, the slope of the lower boundary is less than the slope of the upper boundary (i.e., $p_1 < p_2$), which means that with a conservative (liberal) late signal, the principal more likely prefers the early (late) signal.

If the principal pays a bonus to Agent A for bad output and the low signal, i.e., solution (3), an increase in Agent A's impact in the unfavorable state, $\delta_L$, decreases the expected payment, while an increase in Agent A's impact in the favorable state, $\delta_H$, has no effect. Thus, there is a threshold for $\delta_L$ such that the principal prefers the late signal for higher levels of $\delta_L$ and prefers the early signal for lower levels of $\delta_L$ (Proposition 1, Case *ii*).

For Agent B, the tradeoff between simultaneous and sequential production is not so complex. The accuracy of the late signal with sequential production is greater than the early signal with simultaneous production due to the impact of Agent A's effort on the outcome of the signal, but it still provides pre-decision information to Agent B. The following proposition states the result concerning the principal's preference for the timing of the signal for Agent B.

*Proposition 2: The principal prefers sequential production with a late signal to simultaneous production with an early signal with Agent B if* $\delta_H \geq \delta_H^*(s, \delta_L, p_2)$.

The result in Proposition 2 shows that the principal's preference for an early or late signal depends on the effect of Agent A's effort on the likelihood of the signal, i.e., $\delta_H$ and $\delta_L$, and reflect the externalities of Agent A's effort. The threshold, $\delta_H^*$, depends on $\delta_L$, and is increasing in $\delta_L$.[7] This means that the more conservative the bias, the less likely the principal prefers sequential production and a late signal, which is in sharp contrast to Proposition 1, where the principal prefers sequential production and a late signal for Agent A if the late signal is sufficiently biased in either direction.

Agent B is only paid when the low signal is observed; with a late signal, increasing Agent A's impact in the favorable state decreases Agent B's expected payment while increasing Agent A's impact in the unfavorable state has the opposite effect. Thus, providing a more accurate signal can be more costly to the principal because the information is pre-decision for Agent B, and more information can mean that the principal has to provide stronger incentives to Agent B (Hofmann and Rothenberg, 2013).

We introduce a numerical example to illustrate the results. The numerical example in Figure 4 demonstrates that the total expected payments to Agent A and Agent B can be lower with simultaneous production with an early signal or sequential production with a late signal depending on Agent A's impact on the outcome of the signal.

----- Insert Figure 4 around here. -----

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[7] Technically, $\delta_H^* = \dfrac{s[(1-s)+(s+\delta_L)p_2]+(1+\delta_L)}{2s} + \dfrac{\sqrt{\{s[(1-s)+(s+\delta_L)p_2]+(1+\delta_L)\}^2 - 4s^2(1+\delta_L)\delta_L p_2}}{-2s}$, is increasing in $\delta_L$ if $\dfrac{\partial \delta_H^*}{\delta_L} > 0$, or if $(1 + sp_2) + \{2(1 + sp_2)[s(1 - s) + s(s + \delta_L)p_2 + (1 + \delta_L)] - 4s^2p_2(1 + 2\delta_L)\}\{[s(1 - s) + s(s + \delta_L)p_2 + (1 + \delta_L)]^2 - 4s^2(1 + \delta_L)\delta_L p_2\}^{-1/2} > 0$. Rearranging, $(1 + sp_2) + 2s\{sp_2[(1 - s) + (s + \delta_L)p_2 - 2\delta_L] + (1 - s) + (s + \delta_L)p_2 + 2(1 + \delta_L)]\}\{[s(1 - s) + s(s + \delta_L)p_2 + (1 + \delta_L)]^2 - 4s^2(1 + \delta_L)\delta_L p_2\}^{-1/2} > 0$, which is true.

From Proposition 1, if $p_2$ - $p_1$ is small enough, as in our example, the principal prefers sequential production with a late signal with Agent A if $\delta_H$ is very large and the optimal contract with the late signal involves a bonus based on good output and the high signal (solution 1). The bonus is based on good output and the low signal (solution 2), when $\delta_H$ is very small. Given the parameters of the example, the principal never prefers sequential production with a late signal for Agent A when the bonus is based on bad output and the low signal (solution 3), because $\delta_L^*$ is outside the feasible region.

Simultaneous production with an early signal is preferred to sequential production with a late signal if the performance measurement aspect of the late signal is diminished, which depends on the specific contract. This is demonstrated quite clearly in the numerical example. For Agent A, the bottom right area of the first graph is where the principal prefers sequential production with a late signal when the solution involves the bonus for good output and the low signal (solution 2), while the upper left region is where the principal prefers sequential production with a late signal when the optimal contract involves the bonus for good output and the high signal (solution 1). Summarizing, sequential production with a late signal is preferred if it is sufficiently biased. Further, as the example demonstrates, if the late signal has a conservative bias, the principal more likely prefers simultaneous production with an early signal than when the late signal has a liberal bias.

The externalities of Agent A's effort can be seen in the middle graph, in terms of the effect of the increased accuracy of the late signal on the principal's preference for the simultaneous versus sequential production for Agent B. From Proposition 2, the principal prefers simultaneous production with an early signal with Agent B if $\delta_H$ is very low or if $\delta_L$ very high, and this translates to the bottom right corner of the graph. What is striking is the magnitude of the difference between the principal's preference for simultaneous versus sequential production for Agent A and Agent B.

Further, the externalities are illustrated in the right-hand graph, which shows the principal's preference for simultaneous versus sequential production for both Agent A and Agent B. First, similar to the principal's preference for Agent A, there is still an interval outside of which the principal prefers sequential production with a late signal for both agents; however, the boundaries of this region are no longer linear due to the preference for Agent B. Second, there is a region where if only Agent A is considered, the principal prefers simultaneous production with an early signal, but with both agents, the principal prefers sequential production with a late signal. In this region, Agent A's contract is based on the bad outcome and the low signal (solution 3), which, when only considering Agent A, is never optimal.

The example demonstrates how exogenous bias of the late signal and the externalities of Agent A's effort influence the principal's preference for simultaneous versus sequential production. Specifically, the principal prefers sequential production with a late signal when it is sufficiently biased (either liberal or conservative) compared to the early signal. In addition, the example demonstrates the importance of considering the externalities of Agent A's effort on not only the principal's preference for the timing of the signal for Agent B, but also the principal's overall preference with both agents.

*3.4 Endogenous Bias*

In this section, we determine the principal's preference for bias in the late signal with sequential production. Given the optimal level and direction of the bias, we also consider the tradeoff between simultaneous production with an early signal and sequential production with a late signal.

With sequential production and the late signal, there are three different solutions to the principal's problem with Agent A, depending on the level of bias. As discussed previously, the effect of bias differs depending on the solution. In solution (1), the principal makes a payment to Agent A based on good output and the high signal, and prefers the highest $\delta_H$ and the lowest $\delta_L$, which is the opposite of the principal's preference for bias in solution (2), when the principal makes a payment based on good output and the low signal. In solution (3), the principal makes a payment based on bad output and the low signal and has no preference for $\delta_H$ because it does not impact the expected payment, but prefers the highest $\delta_L$. For Agent B, the principal makes a payment only for good output and the low signal, and prefers the highest $\delta_H$, but for a given $\delta_H$, the principal's preference for $\delta_L$ is ambiguous. The following lemma states the principal's overall preference for bias in the late signal for each agent.

*Lemma 1: The principal's preference for bias with sequential production is as follows. For Agent A if $p_2 \leq \frac{(1-p_0)+p_1(3+p_1)}{2(1+p_0)}$, and $s \leq s^*$, the principal prefers solution (1) with $\delta_H = 1 - s$ and $\delta_L = 0$. If $p_2 \leq \frac{(1-p_0)+p_1(3+p_1)}{2(1+p_0)}$ and $s > s^*$ or if $p_2 > \frac{(1-p_0)+p_1(3+p_1)}{2(1+p_0)}$, the principal prefers solution (2) with $\delta_H = 0$ and $\delta_L = 1 - s$. For Agent B, the principal prefers $\delta_H = 1 - s$ and $\delta_L = 0$.*

For Agent A, the late signal is *ex post* and the principal only uses the signal as a performance measure. Solution (1) is always less costly than solution (3), and there is a trade-off between solution (1) and solution (2). If $p_2$ is big enough, output given the low signal is very informative about Agent A's effort because Agent A's effort has a large impact in the unfavorable state, and with solution (2) the optimal bias indicates the unfavorable state perfectly. If $p_2$ is small, output is not that informative about Agent A's effort, and the principal relies on the signal to provide incentives to Agent A. With solution (1) Agent A's effort increases the accuracy of the high signal, and for a less accurate signal, i.e., $s \leq s^*$, the signal is more informative in the favorable state than in the unfavorable state. With solution (1), the high signal, $y_H$, is more backward-looking because the likelihood that the state is unfavorable given $y_H$ is very low, and Agent A's effort has no effect on output in the favorable state. With solution (2), the low signal, $y_L$, is more forward-looking, indicating that output is more informative, because the likelihood that the state is favorable given $y_L$ is very low and Agent A's effort increases the likelihood of good output in the unfavorable state.

For Agent B the signal is pre-decision, which is used for decision-making and as a performance measure. The principal prefers a perfect signal about the favorable state for decision-making and the least accurate signal about the unfavorable state for incentive purposes. With $\delta_H = 1 - s$ and $\delta_L = 0$, Agent B will undersupply effort but not oversupply effort because the favorable state will be identified correctly but the unfavorable state may not be identified correctly. Interestingly, if the principal were to choose a perfect signal about the unfavorable state, the incentive cost increases more than the decreased cost of efficient production (Baiman and Sivaramakrishnan, 1991).

Next, given the optimal bias, we determine the principal's preference for simultaneous production with an early signal versus sequential production with a late signal for each agent, as stated in the following proposition.

*Proposition 3: With the optimal bias, the principal prefers sequential production with a late signal for Agent A if* $p_2 \leq Min\{\frac{(1-p_0)+p_1(3+p_1)}{2(1+p_0)}, \frac{p_1(2+p_1)+0.5(1+p_1-p_0)}{0.5(3+p_1+p_0)}\}$ *and if* $s \leq Min\ \{s^*, s^{**}\}$ *or if* $s \leq \frac{p_2}{(2p_2-p_1)}$; *otherwise, the principal prefers simultaneous production with an early signal. With the optimal bias, the principal always prefers sequential production with a late signal to simultaneous production with an early signal for Agent B.*

For Agent A, even with the optimal bias, there is tradeoff between simultaneous production with an early signal and sequential production with a late signal that depends primarily on the signal's accuracy. With a more accurate signal, the benefit of the late signal as a performance measure is diminished and the principal prefers simultaneous production with an early signal because the decision-making aspect dominates the *ex post* performance measurement aspect of the signal. The first case of the proposition refers to solution (1) with the optimal bias, when the late signal is backward-looking; in this case, a more accurate signal means the signal is less backward-looking ($\delta_H$ is smaller), which means less benefit for delaying downstream production. In the second case, with solution (2) and the optimal bias, the late signal is more forward-looking and a more accurate signal diminishes the benefit of the late signal's forward-looking quality, making the early signal less costly.

For Agent B, the signal is always pre-decision, and the principal always prefers the late signal with the optimal bias rather than the early, less precise signal. Being able to tailor the quality of the signal makes sequential production with a late signal more beneficial to the principal. From Proposition 2, with exogenous bias, the principal prefers sequential production with the late signal with Agent B if Agent A's impact on the high signal is sufficiently large, or if the signal is not too conservatively biased. Being able to choose the optimal bias allows the principal to choose the most liberal biased signal, which is always less costly than the early signal with simultaneous production.

We extend the numerical example to illustrate the results with the optimal bias. The numerical example in Figure 5 demonstrates that the total expected payments to Agent A and Agent B can be lower with simultaneous production and an early signal or sequential production and a late signal depending on the accuracy of the signal *s*, and productivity in the unfavorable state, $p_2$.

----- Insert Figure 5 around here. -----

The first graph on the left demonstrates the results for Agent A from both Lemma 1 and Proposition 3, notably the tradeoff between solution (1) and (2) with the optimal bias, as well as the differences between simultaneous production with an early signal and sequential production with the late signal. The middle graph confirms that the principal always prefers the late signal with Agent B (Proposition 3). The graph on the right combines expected payments for both agents, and compares simultaneous production with an early signal to sequential production with the late signal. Note that when considering the expected payments to both agents, the principal never prefers solution (2) with Agent A because if the signal was accurate enough to use solution (2), the principal prefers to emphasize decision-making with simultaneous production and an early signal.

The results illustrated in Figure 5 provide directly testable empirical implications. The choice between the simultaneous production with the early signal and sequential production with late signal depends on whether joint output is useful as a performance measure in solving the incentive problem. When joint output is useful as a performance measure, i.e., when $p_2$ is very large, the emphasis of the signal shifts towards decision-making, i.e., simultaneous production with the early signal. In contrast, when joint output is not useful as a performance measure, i.e., when $p_2$ is very small, the emphasis is more on performance measurement, i.e., the late signal complements joint output. This suggests that the usefulness of the signal as a performance measure substitutes for the usefulness of joint output as a performance measure.

**4. Conclusion**

This paper considers how production affects the timing of a signal about productivity that is used for both decision-making and performance evaluation. Even when the signal is public, it is not always less costly to delay production and use a more accurate late signal. In the case of sequential production, for the upstream agent, the tradeoff involves not only the accuracy of the signal, but also the productive effect from the delay or the ability to use the signal as a performance measure and the inability to use the signal for decision-making. For the downstream agent, the tradeoff only involves the increase in accuracy from delaying production, which may or may not be beneficial due to stronger incentives.

Our study has implications for situations where there is demand for more timely information, rather than waiting for later, more accurate information on which to base decisions. Firm owners should carefully consider the tradeoffs when determining whether to produce more timely information as well as the impact on managers' incentives. Producing and disseminating information publically creates externalities in multi-divisional firms. These effects differ, depending on whether information is produced earlier and is less accurate or whether the information is produced later, with more accurate information.

## Appendix A

**1. Simultaneous production with early signal.** The principal's problem with an early signal, $P^{Early}$, is:

$$\underset{w\geq 0}{Min}\ 0.5\{[s + (1- s)p_0]\, w_g^i(y_H^e) + (1- s)(1 - p_0)\, w_b^i(y_H^e) + [(1 - s) + sp_2]\, w_g^i(y_L^e) + s(1 - p_2)\, w_b^i(y_L^e)\},\ i \in \{A, B\}$$

s.t.

$$0.5\{[s + (1- s)p_0]\, w_g^i(y_H^e) + (1- s)(1 - p_0)\, w_b^i(y_H^e) + [(1 - s) + sp_2][\, w_g^i(y_L^e) - c] + s(1 - p_2)[\, w_b^i(y_L^e) - c]\} \geq 0,\ i \in \{A, B\} \quad \text{(IR-}i\text{)}$$

$$[(1 - s) + sp_2]\, w_g^i(y_L^e) + s(1 - p_2)\, w_b^i(y_L^e) - c \geq [(1 - s) + sp_1]\, w_g^i(y_L^e) + s(1 - p_1)\, w_b^i(y_L^e),\ i \in \{A, B\} \quad \text{(IC-}i, y_L\text{)}$$

The incentive problem is the same for both agents, and the solution involves a binding incentive constraint. Clearly, the optimal contract is $w_g^i(y_L^e) = \dfrac{c}{s(p_2 - p_1)}$, $w_g^i(y_H^e) = w_b^i(y_H^e) = w_b^i(y_L^e) = 0$.

**2. Sequential production with late signal.** The principal's problem with a late signal, $P^{Late}$, is as follows:

$$\underset{w\geq 0}{Min} = 0.5\{[(s + \delta_H) + (1- s - \delta_L)p_1][\, w_g^A(y_H^l) + w_g^B(y_H^l)] + (1- s - \delta_L)(1 - p_1)[\, w_b^A(y_H^l) + w_b^B(y_H^l)] + [(1 - s - \delta_H) + (s + \delta_L)p_2][\, w_g^A(y_L^l) + w_g^B(y_L^l)] + (s + \delta_L)(1 - p_2)[\, w_b^A(y_L^l) + w_b^B(y_L^l)]\}$$

s.t.

$$0.5\{[(s + \delta_H) + (1- s - \delta_L)p_1]\, w_g^A(y_H^l) + (1- s - \delta_L)(1 - p_1)\, w_b^A(y_H^l) + [(1 - s - \delta_H) + (s + \delta_L)p_2]\, w_g^A(y_L^l) + (s + \delta_L)(1 - p_2)\, w_b^A(y_L^l)\} - c \geq 0 \quad \text{(IR-}A\text{)}$$

$$0.5\{[(s + \delta_H) + (1- s - \delta_L)p_1]\, w_g^B(y_H^l) + (1- s - \delta_L)(1 - p_1)\, w_b^B(y_H^l) + [(1 - s - \delta_H) + (s + \delta_L)p_2][\, w_g^B(y_L^l) - c] + (s + \delta_L)(1 - p_2)[\, w_b^B(y_L^l) - c] \geq 0 \quad \text{(IR-}B\text{)}$$

$$0.5\{[(s + \delta_H) + (1- s - \delta_L)p_1]\, w_g^A(y_H^l) + (1- s - \delta_L)(1 - p_1)\, w_b^A(y_H^l) + [(1 - s - \delta_H) + (s + \delta_L)p_2]\, w_g^A(y_L^l) + (s + \delta_L)(1 - p_2)\, w_b^A(y_L^l)\} - c \geq 0.5\{[s + (1- s)p_0]\, w_g^A(y_H^l) + (1- s)(1 - p_0)\, w_b^A(y_H^l) + [(1 - s) + sp_1]\, w_g^A(y_L^l) + s(1 - p_1)\, w_b^A(y_L^l)\} \quad \text{(IC-}A\text{)}$$

$$\frac{(1-s-\delta_H)+(s+\delta_L)p_2}{(1-s-\delta_H)+(s+\delta_L)}\ w_g^B(y_L^l)\ +\ \frac{(s+\delta_L)(1-p_2)}{(1-s-\delta_H)+(s+\delta_L)}\ w_b^B(y_L^l)\ -c \geq \frac{(1-s-\delta_H)+(s+\delta_L)p_1}{(1-s-\delta_H)+(s+\delta_L)}$$

$$w_g^B(y_L^l)\ +\ \frac{(s+\delta_L)(1-p_1)}{(1-s-\delta_H)+(s+\delta_L)}\ w_b^B(y_L^l) \qquad \text{(IC-}B,\ y_L\text{)}$$

For Agent A, IC-*A* is binding, which means that Agent A's incentive constraint can be rewritten as

$$[\delta_H + (1-s)(p_1 - p_0) - \delta_L p_1]\, w_g^A(y_H^l) + [(1-s-\delta_L)(p_0 - p_1) - \delta_L(1-p_1)]\, w_b^A(y_H^l) + [-\delta_H + s(p_2 - p_1) + \delta_L p_2]$$

$$w_g^A(y_L^l) + [s(p_1 - p_2) + \delta_L(1-p_2)]\, w_b^A(y_L^l) = 2c.$$

Clearly $w_b^A(y_H^l) = 0$, but $w_b^A(y_L^l)$ can be positive if $\delta_L > \frac{s(p_2-p_1)}{(1-p_2)}$ c. In addition, in order for $w_g^A(y_L^l) >$ 0, $\delta_H < s(p_2 - p_1) + \delta_L p_2$, and for $w_g^A(y_H^l) > 0$ $\delta_H > \delta_L p_1 - (1-s)(p_1 - p_0)$. The possible solutions are:

1) $w_g^A(y_H^l) = \dfrac{2c}{\delta_H + (1-s)(p_1 - p_0) - \delta_L p_1}$, and all other $w^A = 0$

2) $w_g^A(y_L^l) = \dfrac{2c}{-\delta_H + s(p_2 - p_1) + \delta_L p_2}$ , and all other $w^A = 0$.

3) $w_b^A(y_L^l) = \dfrac{2c}{\delta_L(1-p_2) - s(p_2 - p_1)}$, and all other $w^A = 0$.

Comparing the possible solutions, solution (1) is less costly than (2) if $\dfrac{[(s+\delta_H)+(1-s-\delta_L)p_1]c}{\delta_H + (1-s)(p_1-p_0) - \delta_L p_1} \leq$

$\dfrac{[(1-s-\delta_H)+(s+\delta_L)p_2]c}{-\delta_H + s(p_2-p_1) + \delta_L p_2}$, or if $\delta_H \geq a_1\delta_L + K_1 =$

$\dfrac{\delta_L[s(p_2+p_1^2)+(1-s)(p_1+p_2p_0)]+s^2(p_2-p_1)+s(1-s)(p_2p_0-p_1^2)-(1-s)^2(p_1-p_0)}{(1+p_0)+s(p_1-p_0)}$. Solution (1) is

less costly than solution (3) if $\dfrac{[(s+\delta_H)+(1-s-I\delta_L)p_1]c}{\delta_H + (1-s)(p_1-p_0) - I\delta_L p_1} \leq \dfrac{(s+\delta_L)(1-p_2)c}{\delta_L(1-p_2) - s(p_2-p_1)}$, or if $\delta_H \geq a_2\delta_L + K_2$

$= \dfrac{\delta_L[sp_1(1-p_1)+s(1-p_2)+(1-s)p_0(1-p_2)] - s[s(p_2-p_1)+(1-s)p_1(p_2-p_1)+(1-s)(1-p_2)(p_1-p_0)]}{s(1-p_1)}$.

The optimality condition for solution (1) being preferred to solution (2) is equal to the optimality condition for solution (1) being preferred to solution (3) when $\delta_L = \bar{\delta} =$

$\frac{s\{(p_2 - p_1^2) - s[p_1(1-p_1) - (p_2 - p_1)] - (1-s)p_0(1-p_2)\}}{(1-p_2) + s[p_1(1-p_1) - (p_2 - p_1)] + (1-s)p_0(1-p_2)}$, which is greater than $\frac{s(p_2 - p_1)}{(1-p_2)}$. Thus, solution 1 is optimal if $\delta_L \leq \bar{\delta}$ and $\delta_H \geq a_1\delta_L + K_1$, or if $\delta_L > \bar{\delta}$ and $\delta_H \geq a_2\delta_L + K_2$.

Solution (2) is less costly than solution (3) if $\frac{[(1-s-\delta_H) + (s + I\delta_L)p_2]c}{-\delta_H + s(p_2 - p_1) + I\delta_L p_2} \leq \frac{(s+\delta_L)(1-p_2)c}{\delta_L(1-p_2) - s(p_2 - p_1)}$, or if

$\delta_H \leq \frac{\delta_L[s(p_2 - p_1) - (1-s)(1-p_2)] + s(p_2 - p_1)}{s(1-p_1)}$. Note that the optimality condition for solution (1) being preferred to solution (2) is equal to the optimality condition for solution (2) being preferred to solution (3) when $\delta_L = \bar{\delta}$, the same as above. Thus, by implication, the optimality condition for solution (1) being preferred to solution (3) is equal to the optimality condition for solution (2) being preferred to solution (3) when $\delta_L = \bar{\delta}$, also the same as above. Thus, solution (2) is optimal if $\delta_L \leq \bar{\delta}$ and $\delta_H < a_1\delta_L + K_1$, or if $\delta_L > \bar{\delta}$ and $\delta_H < a_3\delta_L + K_3 = \frac{\delta_L[s(p_2 - p_1) - (1-s)(1-p_2)] + s(p_2 - p_1)}{s(1-p_1)}$. Finally, solution (3) is optimal if $\delta_L > \bar{\delta}$ and $a_3\delta_L + K_3 \leq \delta_H < a_2\delta_L + K_2$.

For Agent B, the incentive constraint for the signal $y_L$ is binding, and the optimal contract is $w_g^B(y_L^I) =$

$\frac{(1-\delta_H + \delta_L)c}{(s+\delta_L)(p_2 - p_1)}$, all other $w^B(\cdot) = 0$.

## Appendix B

**Proof of Proposition 1**: If $0.5(1 - s) - 0.5sp_2 + sp_1 \leq 0$ or if $p_1 \leq 0.5[sp_2 - (1 - s)]/s$, the principal always prefers an early signal because the expected payment with an early signal is weakly less than one and the expected payment with a late signal is strictly greater than one. If $p_1 > 0.5[sp_2 - (1 - s)]/s$, there are three parts to rest of the proof.

1. If $\delta_L \leq \bar{\delta}$ and $\delta_H \geq a_1\delta_L + K_1$, or if $\delta_L > \bar{\delta}$ and $\delta_H \geq a_2\delta_L + K_2$, the principal will prefer a late signal to an early signal for Agent A if $\frac{0.5[(1-s)+sp_2]c}{s(p_2-p_1)} \geq \frac{[s+\delta_H+(1-s-\delta_L)p_1]c}{\delta_H+(1-s)(p_1-p_0)-\delta_L p_1}$, or $0.5[(1 - s) + sp_2][\delta_H + (1 - s)(p_1 - p_0) - \delta_L p_1] \geq s(p_2 - p_1)[s + \delta_H + (1 - s - \delta_L)p_1]$. If $0.5(1 - s) - 0.5sp_2 + sp_1 > 0$, this inequality is $\delta_H \geq \delta_L p_1 + \frac{s^2(p_2-p_1)+s(1-s)[p_1(p_2-p_1)-0.5p_2(p_1-p_0)]-0.5(1-s)^2(p_1-p_0)}{0.5(1-s)-0.5sp_2+sp_1}$, or $\delta_L p_1 + C_1$.

2. If $\delta_L \leq \bar{\delta}$ and $\delta_H < a_1\delta_L + K_1$ or if $\delta_L > \bar{\delta}$ and $\delta_H < a_3\delta_L + K_3$, the principal will prefer a late signal to an early signal for Agent A if $\frac{0.5[(1-s)+sp_2]c}{s(p_2-p_1)} \geq \frac{[(1-s-\delta_H)+(s+\delta_L)p_2]c}{-\delta_H+s(p_2-p_1)+\delta_L p_2}$, or $0.5[(1 - s) + sp_2][- \delta_H + s(p_2 - p_1) + \delta_L p_2] \geq s(p_2 - p_1)[(1 - s - \delta_H) + (s + \delta_L)p_2]$. This inequality is $(\delta_H - \delta_L p_2)[0.5(1 - s) - 0.5sp_2 + sp_1] \leq -0.5s(p_2 - p_1)[(1 - s) + sp_2]$. If $0.5(1 - s) - 0.5sp_2 + sp_1 > 0$ or if $p_1 > \frac{0.5[sp_2-(1-s)]}{s}$, this inequality will hold if $\delta_H \leq \delta_L p_2 - \frac{0.5s(p_2-p_1)[(1-s)+sp_2]}{0.5(1-s)-0.5sp_2+sp_1}$, or $\delta_L p_2 + C_2$.

3. If $\delta_L > \bar{\delta}$ and $a_3\delta_L + K_3 \leq \delta_H < a_2\delta_L + K_2$, the principal will prefer a late signal to an early signal for Agent A if $\frac{0.5[(1-s)+sp_2]c}{s(p_2-p_1)} \geq \frac{(s+\delta_L)(1-p_2)c}{\delta_L(1-p_2)-s(p_2-p_1)}$, or $0.5s(1 - s)(1 - p_2) - 0.5s^2(p_2 - p_1) + 0.5\delta_L[(1 - s)(1 - p_2) + sp_2(1 - p_2)] \geq s^2(p_2 - p_1)(1 - p_2) + \delta_L s(1 - p_2)(p_2 - p_1)$. This inequality will hold if $\delta_L \geq \delta_L^* = \frac{s(p_2-p_1)[s(1-0.5p_2)+0.5(1-s)]}{(1-p_2)[0.5(1-s)+s(p_1-0.5p_2)}$. Note that $\delta_L^* \geq \bar{\delta}$. If it were not, there exists a $\delta_H$ such that the expected payment under solution (1) is equal to the expected payment under solution (3) where $\delta_L = \delta_L^*$.

This is a contradiction because by assumption, $\delta_L^*$ is less than $\bar{\delta}$, which has already been shown to be the point where the expected payments for solution (1), solution (2) and solution (3) are the same. ■

**Proof of Proposition 2**: The principal will prefer a late signal to an early signal for Agent B if $\frac{0.5[(1-s)+sp_2]c}{s(p_2-p_1)} \geq \frac{0.5[(1-s-\delta_H)+(s+\delta_L)p_2](1-\delta_H+\delta_L)c}{(s+\delta_L)(p_2-p_1)}$ or $-s\delta_H^2 + \delta_H[s(1-s) + sp_2(s+\delta_L) + (1+\delta_L)] - s\delta_L p_2(1+\delta_L)] \geq 0$. At the boundary, where the principal is indifferent between the early and late signal, there are two roots for $\delta_H$, $\frac{s[(1-s)+(s+\delta_L)p_2]+(1+\delta_L)}{2s}$ +/- $\frac{\sqrt{\{s[(1-s)+(s+\delta_L)p_2]+(1+\delta_L)\}^2-4s^2(1+\delta_L)\delta_L p_2}}{-2s}$. Checking the roots for the restrictions on $\delta_H$, $\frac{s[(1-s)+(s+\delta_L)p_2]+(1+\delta_L)}{2s}$ +/- $\frac{\sqrt{\{s[(1-s)+(s+\delta_L)p_2]+(1+\delta_L)\}^2-4s^2(1+\delta_L)\delta_L p_2}}{-2s} \leq 1-s$, or +/- $\sqrt{\{s[(1-s)+(s+\delta_L)p_2]+(1+\delta_L)\}^2-4s^2(1+\delta_L)\delta_L p_2} \geq 3s(1-s) + s(s+\delta_L)p_2 + (1+\delta_L)$. The only root that satisfies this restriction is $\delta_H^* = \frac{s[(1-s)+(s+\delta_L)p_2]+(1+\delta_L)}{2s}$ + $\frac{\sqrt{\{s[(1-s)+(s+\delta_L)p_2]+(1+\delta_L)\}^2-4s^2(1+\delta_L)\delta_L p_2}}{-2s}$. Also, note that $\frac{s[(1-s)+(s+\delta_L)p_2]+(1+\delta_L)}{2s}$ + $\frac{\sqrt{\{s[(1-s)+(s+\delta_L)p_2]+(1+\delta_L)\}^2-4s^2(1+\delta_L)\delta_L p_2}}{-2s} \geq 0$, or rearranging, $-4s^2(1+\delta_L)\delta_L p_2 \leq 0$, which is true. Therefore, the principal will prefer the late signal with Agent B if $\delta_H \geq \delta_H^*$.

$(s+\delta_L)[(1-s)+sp_2] \geq s[(1-s-\delta_H)+(s+\delta_L)p_2](1-\delta_H+\delta_L)$. Rearranging, this inequality is $\frac{\delta_H}{\delta_L} \geq \frac{sp_2(s-\delta_H+\delta_L)-(1-s)^2}{s[(1-s)+sp_2+(1-\delta_H+\delta_L)]}$. ■

**Proof of Lemma 1:** There are two parts to the proof.

1. For Agent A, we first determine the optimal bias for each solution, and then compare the solutions to determine the overall optimal bias. For solution (1), the partial derivative of the expected payment with respect to $\delta_H$, $\partial W_A^{Late} / \partial \delta_H$, is negative if $[(1 - s)(p_1 - p_0) + \delta_H - \delta_L p_1] - [s + (1 - s)p_1 + \delta_H - \delta_L p_1] < 0$, or if $-(1 - s)p_0 - s < 0$, which is true. Therefore, for solution (1) the optimal $\delta_H$ is $1 - s$. The partial derivative of the expected payment with respect to $\delta_L$, $\partial W_A^{Late} / \partial \delta_L$, is positive if $- p_1[(1 - s)(p_1 - p_0) + \delta_H - \delta_L p_1] + p_1[s + (1 - s)p_1 + \delta_H - \delta_L p_1] > 0$, or $(2s -1) > 0$, which is true. Therefore, for solution (1) the optimal $\delta_L$ is 0. For solution (2), the partial derivative of the expected payment with respect to $\delta_H$, $\partial W_A^{Late} / \partial \delta_H$, is positive if $-[s(p_2 - p_1) - \delta_H + \delta_L p_2] + [(1 - s) + sp_2 - \delta_H + \delta_L p_2] > 0$, or if $(1 - s) + sp_1 > 0$, which is true. Therefore, for solution (2) the optimal $\delta_H$ is 0. The partial derivative of the expected payment with respect to $\delta_L$, $\partial W_A^{Late} / \partial \delta_L$, is negative if $p_2[s(p_2 - p_1) - \delta_H + \delta_L p_2] - p_2[(1 - s) + sp_2 - \delta_H + \delta_L p_2] < 0$, of if $- sp_1 - (1 - s) < 0$, which is true. Therefore, for solution (2), the optimal $\delta_L$ is $1 - s$. With solution (3), the expected payment does not depend on $\delta_H$. The partial derivative of the expected payment with respect to $\delta_L$, $\partial W_A^{Late} / \partial \delta_L$, is negative if $(1 - p_2)[\delta_L(1 - p_2) - s(p_2 - p_1)] - (1 - p_2)^2(s + \delta_L) < 0$, or if $- s(p_2 - p_1) - s(1 - p_2) < 0$, which is true. Therefore, for solution (3) the optimal $\delta_L$ is $1 - s$.

Next, we compare the expected payments under the three solutions with the optimal bias. The principal will prefer solution (1) to solution (3) if $\dfrac{s+(1-s)(1+p_1)}{(1-s)(1+p_1-p_0)} \leq \dfrac{(1-p_2)}{(1-s)(1-p_2)-s(p_2-p_1)}$, or rearranging, $s(1 - s)p_1(1 - p_1) + s(p_2 - p_1) - (1 - s)p_0(1 - p_2) > 0$. This inequality holds strictly because $s \geq (1 - s)$ and $(p_2 - p_1) > p_0(1 - p_2)$. The principal will prefer solution (1) to solution (2) if $\dfrac{s+(1-s)(1+p_1)}{(1-s)(1+p_1-p_0)} \leq \dfrac{(1-s)+p_2}{s(p_2-p_1)+(1-s)p_2}$, which rearranging is $- s^2[(1 + p_1 - p_0) - p_1^2] + s[(2 + p_2)(1 - p_0) + p_1(1 - p_1)] + [p_2p_0 - (1 + p_1 - p_0)] \leq 0$. At the boundary, where principal is indifferent between solution (1) and (2), there are two roots, $\frac{-[(2+p_2)(1-p_0)+p_1(1-p_1)]}{-2[(1+p_1-p_0)-p_1^2]}$ +/-

$\frac{\sqrt{[(2+p_2)(1-p_0)+p_1(1-p_1)]^2-4[(1+p_1-p_0)-p_1^2][(1+p_1-p_0)-p_2p_0]}}{-2[(1+p_1-p_0)-p_1^2]}$. Note that

$[(2+p_2)(1-p_0)+p_1(1-p_1)]^2-4[(1+p_1-p_0)-p_1^2][(1+p_1-p_0)-p_2p_0] > 0$, because the inequality can be reduced to $(1 - p_0)[4(p_2 - p_1) + p_2^2(1 - p_0)] + p_1(1 - p_1)[2p_2(5 - p_0) - p_1(3 + p_1)]$, which is positive.

Checking that the roots satisfy the restrictions on $s$, $\frac{-[(2+p_2)(1-p_0)+p_1(1-p_1)]}{-2[(1+p_1-p_0)-p_1^2]}$ +/-

$\frac{\sqrt{[(2+p_2)(1-p_0)+p_1(1-p_1)]^2-4[(1+p_1-p_0)-p_1^2][(1+p_1-p_0)-p_2p_0]}}{-2[(1+p_1-p_0)-p_1^2]} \leq 1$, or rearranging,

+/- $\sqrt{[(2+p_2)(1-p_0)+p_1(1-p_1)]^2-4[(1+p_1-p_0)-p_1^2][(1+p_1-p_0)-p_2p_0]} \geq p_2(1 - p_0) - p_1(1 - p_1)$

This holds only if the left-hand side is positive. Therefore, the root, $s^* = \frac{[(2+p_2)(1-p_0)+p_1(1-p_1)]}{2[(1+p_1-p_0)-p_1^2]}$ -

$\frac{\sqrt{[(2+p_2)(1-p_0)+p_1(1-p_1)]^2-4[(1+p_1-p_0)-p_1^2][(1+p_1-p_0)-p_2p_0]}}{2[(1+p_1-p_0)-p_1^2]}$, satisfies the restriction, $s \leq 1$.

Checking that $\frac{[(2+p_2)(1-p_0)+p_1(1-p_1)]}{2[(1+p_1-p_0)-p_1^2]}$ -

$\frac{\sqrt{[(2+p_2)(1-p_0)+p_1(1-p_1)]^2-4[(1+p_1-p_0)-p_1^2][(1+p_1-p_0)-p_2p_0]}}{2[(1+p_1-p_0)-p_1^2]} \geq 0.5$, which rearranging is

$\sqrt{[(2+p_2)(1-p_0)+p_1(1-p_1)]^2-4[(1+p_1-p_0)-p_1^2][(1+p_1-p_0)-p_2p_0]} \leq (1 + p_2)(1 - p_0)$, or $(1 - p_0)[4(p_2 - p_1) + p_2^2(1 - p_0)] + p_1(1 - p_1)[2p_2(5 - p_0) - p_1(3 + p_1)] \leq (1 + p_2)^2(1 - p_0)^2$. This inequality holds if $p_2 \leq \frac{(1-p_0)+p_1(3+p_1)}{2(1+p_0)}$. Therefore, if $p_2 \leq \frac{(1-p_0)+p_1(3+p_1)}{2(1+p_0)}$, there is a threshold, $s^*$, such that for 0.5

$\leq s \leq s^*$ the principal prefers solution (1), and for $s^* \leq s \leq 1$, the principal prefers solution (2). If $p_2 >$

$\frac{(1-p_0)+p_1(3+p_1)}{2(1+p_0)}$, the principal prefers solution (2).

2. For Agent B, the partial derivative of the expected payment with respect to $\delta_H$, $\partial W_B^{Late}/\partial\delta_H$, is negative if $-0.5[(1 - s - \delta_H) + (s + \delta_L)p_2] - 0.5(1 - \delta_H + \delta_L) < 0$, which is true. Therefore the optimal $\delta_H$ is $1 - s$. The partial derivative of the expected payment with respect to $\delta_L$, $\partial W_B^{Late}/\partial\delta_L$, is positive if $0.5\{[(1 - s - \delta_H) + (s + \delta_L)p_2] + p_2(1 - \delta_H + \delta_L)\}(s + \delta_L)(p_2 - p_1) - 0.5(1 - \delta_H + \delta_L)[(1 - s - \delta_H) + (s + \delta_L)p_2](p_2 - p_1) > 0$. This inequality can be rearranged as $(s + \delta_L)^2 p_2 - (1- s - \delta_H)^2 > 0$, which is true with $\delta_H = 1 - s$. Therefore the optimal $\delta_L$ is 0. ■

**Proof of Proposition 3:**

1. If $p_2 \leq \frac{(1-p_0)+p_1(3+p_1)}{2(1+p_0)}$ and $s \leq s^*$, with the optimal bias and solution (1), the principal will prefer the late signal to the early signal with Agent A if $\frac{[s+(1-s)(1+p_1)]c}{(1-s)(1+p_1-p_0)} \leq \frac{0.5[(1-s)+sp_2]c}{s(p_2-p_1)}$, or $-s^2[p_1(p_2 - p_1) + 0.5(1 - p_2)(1 + p_1 - p_0)] + s[(1 + p_1)(p_2 - p_1) + 0.5(2 - p_2)(1 + p_1 - p_0)] - 0.5(1 + p_1 - p_0) \leq 0$.

At the boundary, there are two roots, $\frac{-[(1+p_1)(p_2-p_1)+(1-0.5p_2)(1+p_1-p_0)]}{-2[p_1(p_2-p_1)+0.5(1-p_2)(1+p_1-p_0)]}$ +/- $\frac{\sqrt{[(1+p_1)(p_2-p_1)+0.5(2-p_2)(1+p_1-p_0)]^2-2[p_1(p_2-p_1)+0.5(1-p_2)(1+p_1-p_0)](1+p_1-p_0)}}{-2[p_1(p_2-p_1)+0.5(1-p_2)(1+p_1-p_0)]}$. Note that $[(1+p_1)(p_2-p_1)+0.5(2-p_2)(1+p_1-p_0)]^2-2[p_1(p_2-p_1)+0.5(1-p_2)(1+p_1-p_0)](1+p_1-p_0) > 0$, or rearranging, $(1 + p_1)^2(p_2 - p_1)^2 + (p_2 - p_1)(1 + p_1 - p_0)(2 - p_2 - p_2p_1) + 0.25p_2^2(1 + p_1 - p_0)^2 > 0$, which is true. Checking the roots satisfy the restrictions on $s$, $\frac{-[(1+p_1)(p_2-p_1)+(1-0.5p_2)(1+p_1-p_0)]}{-2[p_1(p_2-p_1)+0.5(1-p_2)(1+p_1-p_0)]}$ +/- $\frac{\sqrt{[(1+p_1)(p_2-p_1)+(1-0.5p_2)(1+p_1-p_0)]^2-2[p_1(p_2-p_1)+0.5(1-p_2)(1+p_1-p_0)](1+p_1-p_0)}}{-2[p_1(p_2-p_1)+0.5(1-p_2)(1+p_1-p_0)]} \leq 1$, or rearranging, +/-

$\sqrt{[(1+p_1)(p_2-p_1)+(1-0.5p_2)(1+p_1-p_0)]^2-2[p_1(p_2-p_1)+0.5(1-p_2)(1+p_1-p_0)](1+p_1-p_0)} \leq (1-p_1)(p_2-p_1)+0.5p_2(1+p_1-p_0)$. The right hand side of this inequality is positive and only the real root, $s^{**}$

$= \frac{[(1+p_1)(p_2-p_1)+(1-0.5p_2)(1+p_1-p_0)]}{2[p_1(p_2-p_1)+0.5(1-p_2)(1+p_1-p_0)]}$ -

$$\frac{\sqrt{[(1+p_1)(p_2-p_1)+(1-0.5p_2)(1+p_1-p_0)]^2-2[p_1(p_2-p_1)+0.5(1-p_2)(1+p_1-p_0)](1+p_1-p_0)}}{2[p_1(p_2-p_1)+0.5(1-p_2)(1+p_1-p_0)]}$$

satisfies the restriction, $s \leq 1$. Checking that $\frac{[(1+p_1)(p_2-p_1)+(1-0.5p_2)(1+p_1-p_0)]}{2[p_1(p_2-p_1)+0.5(1-p_2)(1+p_1-p_0)]}$ -

$$\frac{\sqrt{[(1+p_1)(p_2-p_1)+(1-0.5p_2)(1+p_1-p_0)]^2-2[p_1(p_2-p_1)+0.5(1-p_2)(1+p_1-p_0)](1+p_1-p_0)}}{2[p_1(p_2-p_1)+0.5(1-p_2)(1+p_1-p_0)]} \geq 0.5,$$

which rearranging is

$\sqrt{[(1+p_1)(p_2-p_1)+(1-0.5p_2)(1+p_1-p_0)]^2-2[p_1(p_2-p_1)+0.5(1-p_2)(1+p_1-p_0)](1+p_1-p_0)} \leq (p_2-p_1)+0.5(1+p_1-p_0)$. This inequality holds if $p_2 \leq \frac{p_1(2+p_1)+0.5(1+p_1-p_0)}{0.5(3+p_1+p_0)}$. Therefore, if $p_2 \leq$ Min $\{\frac{(1-p_0)+p_1(3+p_1)}{2(1+p_0)}, \frac{p_1(2+p_1)+0.5(1+p_1-p_0)}{0.5(3+p_1+p_0)}\}$ and if $s \leq$ Min $\{s^*, s^{**}\}$, with solution (1), the principal prefers the late signal to the early signal.

With the optimal bias and solution (2), the principal will prefer the late signal to the early signal with Agent A if $\frac{[(1-s)+p_2]c}{s(p_2-p_1)+(1-s)p_2} \leq \frac{0.5[(1-s)+sp_2]c}{s(p_2-p_1)}$, or $s \leq \frac{p_2}{(2p_2-p_1)}$.

2. With the optimal bias, the principal prefers the late signal to the early signal with Agent B if $\frac{0.5sp_2c}{(p_2-p_1)} < \frac{0.5[(1-s)+sp_2]c}{s(p_2-p_1)}$. Rearranging, this inequality is $(1-s)(1+sp_2) > 0$, which is true. ■

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**Figure 1 Timeline**

| Date 0 | Date 1 | Date 2 | Date 3 | Date 4 | Date 5 |
| --- | --- | --- | --- | --- | --- |
| Principal and agents contract, which specifies simultaneous or sequential production and wages. | If signal is early, signal is publically observed. | Agent A chooses effort. | If signal is late, signal is publically observed. | Agent B chooses effort. | Joint output is observed, wages paid. |

**Figure 2**
**Early signal (simultaneous production), Probability of $x$ and $y$ Given $\theta$ and $e^A = e^B = 1$**

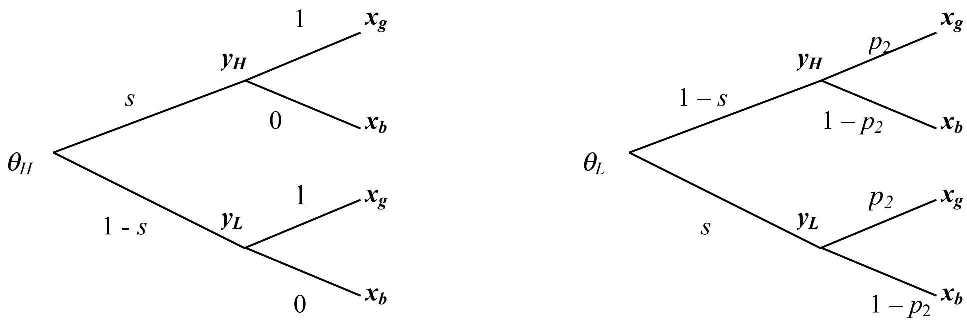
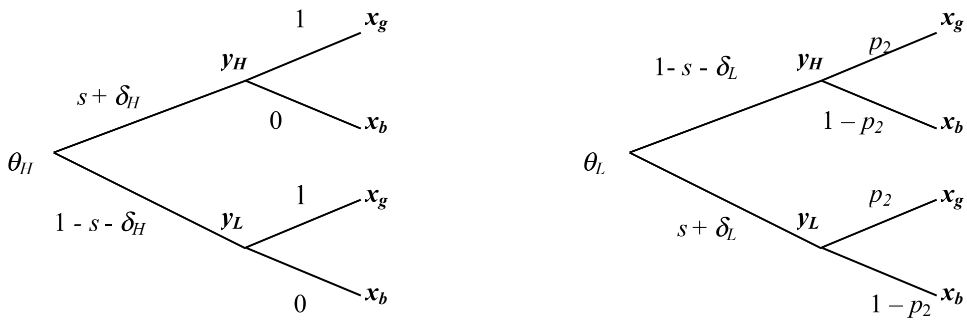


**Figure 3**
**Late signal (sequential production), Probability of $x$ and $y$ Given $\theta$**

**Panel A $e^A = e^B = 1$**




**Panel B $e^A = 0$, $e^B = 1$**

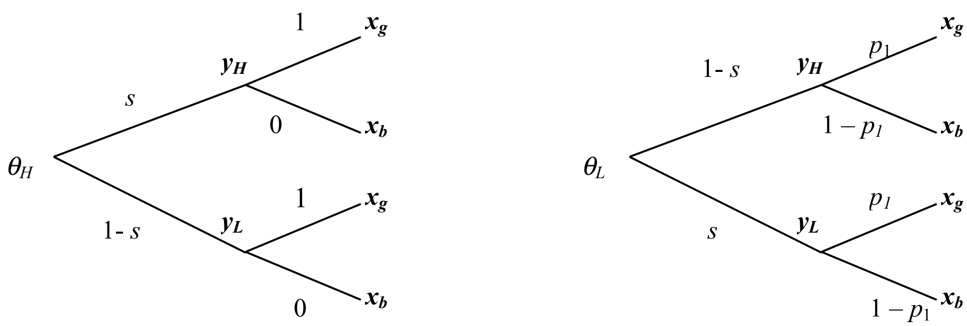
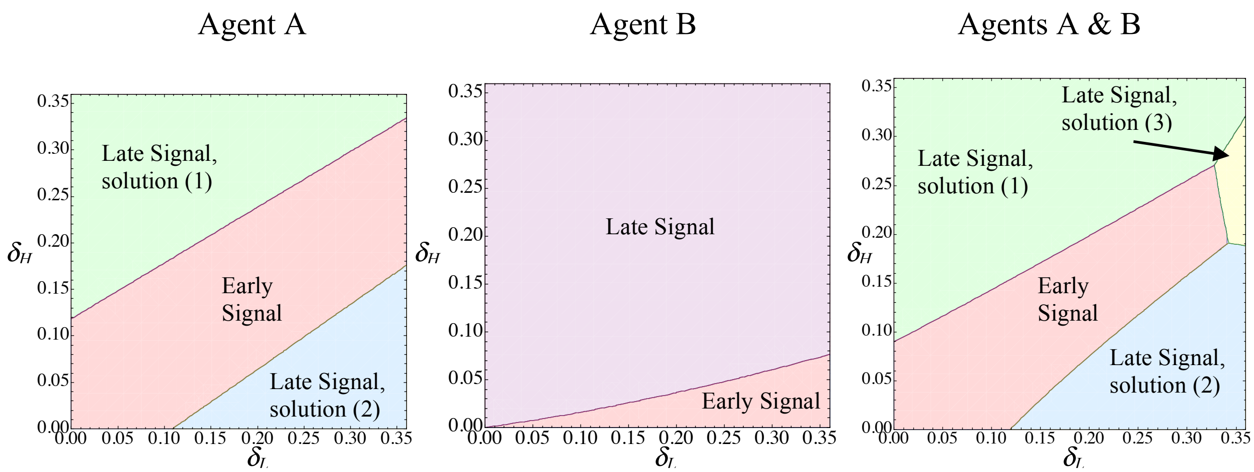
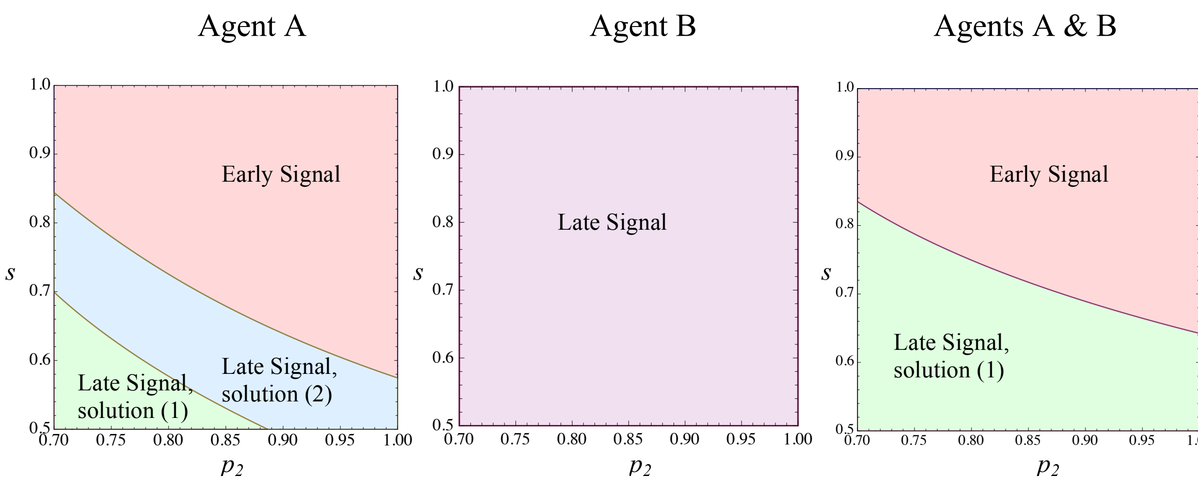


**Figure 4**
**Numerical Example of Principal's Preference for an Early or Late Signal with Exogenous Bias**
(with $c = 1$, $p_2 = 0.7$, $p_1 = 0.6$, $p_0 = 0.5$, $s = 0.64$)[8]




[8] In the figure for Agents A & B, solutions (1), (2) and (3) refer to the different solutions for Agent A. With Agent B, there is only one solution.

**Figure 5**
**Numerical Example of Principal's Preference for an Early or Late Signal with Endogenous Bias**
(with $c = 1$, $p_1 = 0.6$, $p_0 = 0.5$)[9]




[9] In the figure for Agents A & B, solutions (1) and (2) refer to the different solutions for Agent A. With Agent B, there is only one solution.