Manufacturing & Service Operations Management

Publication details, including instructions for authors and subscription information:
http://pubsonline.informs.org

Aligning Capacity Decisions in Supply Chains When Demand Forecasts Are Private Information: Theory and Experiment

Kyle Hyndman, Santiago Kraiselburd, Noel Watson,

To cite this article:
Kyle Hyndman, Santiago Kraiselburd, Noel Watson, (2013) Aligning Capacity Decisions in Supply Chains When Demand Forecasts Are Private Information: Theory and Experiment. Manufacturing & Service Operations Management 15(1):102-117. http://dx.doi.org/10.1287/msom.1120.0400

MANUFACTURING & SERVICE OPERATIONS MANAGEMENT
Vol. 15, No. 1, Winter 2013, pp. 102–117
ISSN 1523-4614 (print) | ISSN 1526-5498 (online)
http://dx.doi.org/10.1287/msom.1120.0400

Aligning Capacity Decisions in Supply Chains When Demand Forecasts Are Private Information: Theory and Experiment

Kyle Hyndman
Maastricht University, 6211 LM Maastricht, The Netherlands; and Southern Methodist University, Dallas, Texas 75205, k.hyndman@maastrichtuniversity.nl

Santiago Kraiselburd
Universidad Torcuato Di Tella, Alte. Sáenz Valiente 1010, C1428BIJ Buenos Aires, Argentina; and INCAE Business School, Apartado Postal 960-4050, Alajuela, Costa Rica, skraiselburd@utdt.edu

Noel Watson
OPS MEND, Medford, Massachusetts 02155, nwatson@opsmend.com

We study the problem of a two-firm supply chain in which firms simultaneously choose a capacity before demand is realized. We focus on the role that private information about demand has on firms' ability to align their capacity decisions. When forecasts are private information, there are at most two equilibria: a complete coordination failure or a monotone equilibrium. The former equilibrium always exists, whereas the latter exists only when the marginal cost of capacity is sufficiently low. We also show that both truthful information sharing and preplay communication have an equilibrium with higher profits. We then test the model's predictions experimentally. Contrary to our theoretical predictions, we show that private demand forecasts do not have a consistently negative effect on firm profits, though capacities are more misaligned. We show that preplay communication may be more effective at increasing profits than truthful information sharing. Finally, we document that "honesty is the best policy" when communicating private information.

Key words: communication; coordination; supply chains; experiment
History: Received: March 1, 2011; accepted: May 4, 2012. Published online in *Articles in Advance* October 5, 2012.

1. Introduction

There is a large literature in operations management (OM) that studies coordination between firms, or across different functional units within a firm. In this literature, to achieve coordination, two conditions are necessary: (a) the players' decisions are aligned and (b) alignment occurs at a point that maximizes system profits. Furthermore, the main approach to addressing coordination has been aligning economic incentives. However, changing incentives can be difficult, with the potential for unintended consequences. In this paper, we focus on alignment of activities across multiple decision makers, without it necessarily maximizing joint profits. This represents a more achievable goal within and across organizations given the behavioral realities. In practice, organizations do pursue alignment in decisions both in collaborative programs across supply chain partners (e.g., collaborative planning, forecasting, and replenishment) and integration-based programs within the organization (e.g., sales and operations planning programs). Even the more modest goal of improving alignment has proven nontrivial to pursue, though in some cases performance improvements have been achieved without wholesale changes to the incentives (Oliva and Watson 2011).

In this paper, we define a game between two firms who simultaneously invest in capacity to meet demand, and sales are the minimum of the two firms' capacities and realized demand. In this setup, if one firm plans for a given capacity to meet its perceived demand, the other firm would prefer not to invest in any more capacity because the effective capacity is given by the constraining capacity. At the same time, so long as capacity is less than demand, both firms jointly choosing a higher capacity would lead to higher profits. That is, the game exhibits strategic complementarities.

Although, in some cases it may be natural to expect firms to try to jointly agree on the efficient capacity choice, our model focuses on the case in which contracts are not enforceable, i.e., each firm independently chooses its own capacity. Thus, we are in the *voluntary compliance* realm first discussed by Cachon and Lariviere (2001) and later by Tomlin (2003), Wang and Gerchak (2003), and Özer and Wei (2006), among others. Another important distinction of our paper from the existing literature is that we focus on the role of private information about demand on equilibrium behavior, as in Özer and Wei (2006) and Özer et al. (2011).

Assembly systems are one natural setting to which our model applies. Coordination problems among partners in assembly systems are well documented. For example, Cachon and Lariviere (2001) discussed several examples in which Boeing and General Motors were forced to delay production in the 1990s because of the limited capacity of one or more suppliers. Tomlin (2003) cites excerpts from Palm Inc.'s financial report that caution about potential inadequate capacity problems from third-party suppliers given uncertainties in demand for handhelds.

The production woes of the Boeing 787 exemplify our assumption that capacities are not fully contractible between Boeing and its suppliers, let alone between two or more suppliers. Rather than providing detailed plans for each part, Boeing gave a much shorter set of specifications and left much of the design and engineering work to the suppliers. Exacerbating this, as Lunsford (2007) notes, "many of [Boeing's] handpicked suppliers, instead of using their own engineers to do the design work, farmed out this key task to even-smaller companies.... The company says it never intended for its suppliers to outsource key tasks such as engineering." Faced with this situation, suppliers appear to be engaged in a game with each other similar to what we outlined earlier.

Another main assumption is that the firms may have private information about demand. Although there are undoubtedly many small-parts providers in the aerospace industry, there are very few engine suppliers (General Electric, Pratt and Whitney, and Rolls Royce). Each of these are large companies that can easily be expected to have their own sources of information regarding demand for aircraft and aircraft engines. For example, as Cachon and Lariviere (2001, p. 630) note about Boeing's attempts to have suppliers increase their capacity,

> Even suppliers who attempted to expand capacity did so with some trepidation. One supplier executive, commenting on a major expansion at his firm, observed "We're putting a lot of trust in the Boeing Co." (Cole 1997b). That trust was not necessarily well-deserved. Within a year the Asian financial crisis occurred.

It seems plausible that some of the trepidation about increasing capacity was due, in part, to suppliers' own private information about the state of the economy and the demand for aircraft.

Beyond these anecdotal examples, Hendricks and Singhal (2005) study announcements by companies about "glitches"—cases where demand exceeds supply. They show that when a reason for insufficient capacity is cited, the most common reason is parts shortages (by a factor of 2 to 1). When responsibility for the glitch is assigned, suppliers are the second-most named, after internal reasons. Thus, cases of mismatched capacities between firms and suppliers may be commonplace.

Our theoretical analysis shows that a crucial issue is whether firms have common or private information about demand. In the former case, there are multiple *Pareto rankable* equilibria of the game sketched above. Therefore, an important unanswered question is which equilibrium can we expect firms to play? Numerous experimental studies have shown that such games often lead to coordination failures (e.g., van Huyck et al. 1990). Our paper contributes to this by showing that the multiplicity of equilibria leads to coordination problems and suboptimal earnings.

In contrast to the continuum of equilibria in the common information model, when firms have private information about demand, we show that there are at most two equilibria. There is always the *complete coordination failure* equilibrium in which both firms always choose zero capacity. However, as long as the marginal cost of capacity is below a threshold, there is also a monotone equilibrium in which capacities are an increasing function of signals. In this equilibrium, capacities and profits are lower than in the Pareto efficient equilibrium of the common information game. Moreover, because firms receive independent signals, capacities are necessarily misaligned.

In the spirit of Özer et al. (2011), we next turn to a study of mechanisms that can lead to improved coordination. We first focus on truthful information sharing in which, say, firms have reached an agreement to share their demand forecasts with each other. In this setting, firms have more accurate information about demand (i.e., two signals). Not surprisingly, therefore, expected profits in the Pareto efficient equilibrium are higher, relative to both the common and private information games.

Of course, such a mechanism requires institutions to ensure that the information shared is in fact truthful. Because such institutions may be impossible or prohibitively costly, we also consider a game in which preplay communication between players is allowed. Here we show a surprising result; namely, costly mechanisms to induce truthfulness may not be necessary. That is, there exists an equilibrium in which (i) firms truthfully report their signals and (ii) firms coordinate on the Pareto efficient equilibrium of the game with truthful information sharing.

Having theoretically analyzed the role of private information and the beneficial effects of information sharing, we report the results of an experiment designed to test the theory. Our experiment was conducted with two questions in mind. First, how does private information about demand forecasts affect profits and alignment? Second, to what extent does information sharing increase profits and improve alignment, and is preplay communication enough to achieve these benefits?

To study these questions, our experiment has four information treatments: (i) the common information game (CI), (ii) the private information game (PI), (iii) the common information game with two signals (CI-2S), and (iv) the private information game with communication (PI-MS). The CI and PI treatments allow us to investigate the first question, and the CI-2S and PI-MS treatments allow us to investigate the second question. For each treatment, we conduct sessions with different sets of parameters to test the robustness of our experimental results.

Regarding the first question, we document the following results. First, although alignment is improved, profits are not consistently higher when subjects have common information. This suggests that the multiple equilibria in the CI game make coordination on the efficient equilibrium difficult. Second, subjects appear to be risk averse: although choices are below the theoretical prediction, the difference is increasing in the signal (where the potential to be undercut is greater). Third, *anchoring and insufficient adjustment* (Schweitzer and Cachon 2000) does not explain comparative statics on the newsvendor critical fractile. Although subjects underadjust when it is high, they overadjust when it is low. One striking inconsistency with our theory is that we do not observe the complete coordination failure in the PI game with high costs.

We then evaluate the two mechanisms that may improve coordination. Surprisingly, although only 25% of messages were truthful, the PI-MS treatment actually leads to *higher* average profits than the CI-2S treatment. This suggests that communication, even if untruthful, acts as a coordinating device for capacities in a way that simply having better, common information cannot. Finally, our experimental results show that honesty is the best policy when it comes to sending a message. That is, messages further from the truth lead to lower profits and greater misalignment.

The paper proceeds as follows. Section 2 reviews the relevant literature. Section 3 describes the model, §4 contains our theoretical results, and §5 discusses our experimental design. Section 6 discusses the results of our CI and PI treatments, and §7 examines the results of our CI-2S and PI-MS treatments. Finally, §8 provides some concluding remarks.

2. Literature Review

Many authors have studied coordination between firms in an OM context (see Cachon 2003 for a review). From a modeling perspective, the paper most closely related to ours is Tomlin (2003) (but see also Shapiro 1977, Lee and Whang 1999, Chao et al. 2008). Tomlin (2003) studies coordination when both firms have *identical* beliefs about demand. Instead, we focus on multiple equilibria, the role of private information, and experimentally testing our theoretical results.

In contrast to our approach, the OM literature has generally emphasized coordination instead of alignment. The *intrafirm* literature has either concentrated on approaches for managing the sales force (Chen 2005, Gonik 1978, Lal and Staelin 1986) or considered schemes for coordinating functions to achieve the benefits of centralized decision making (Porteus and Whang 1991, Celikbas et al. 1999, Li and Atkins 2002). The *interfirm* literature, which considers the interactions between manufacturers and retailers, generally concentrates on finding new incentive schemes to achieve the benefits of centralized decision making (Cachon 2003, Cachon and Lariviere 2001, Tomlin 2003).

Our paper also studies the role of information sharing in helping firms achieve a more profitable outcome (Cachon and Fisher 2000, Aviv 2001). Within the collaborative forecasting literature, Miyaoka (2003), Lariviere (2002), and Özer and Wei (2006) argue that whether the parties reveal truthful information depends on their incentives and go on to design truth-revealing mechanisms. In Kurtulus and Toktay (2007), parties must decide whether to invest to improve their forecasting before sharing it. Other papers, such as Li and Zhang (2008), Li (2002), and Jain et al. (2011), study information sharing in which several retailers can share their information with a single manufacturer. In contrast, we focus on two-sided information sharing.

Our paper also contributes to the growing literature on behavioral OM, which is summarized by Bendoly et al. (2006). We briefly touch upon some of the decision biases noted by Schweitzer and Cachon (2000). In terms of experimental methodology, the paper that is closest to our work is by Özer et al. (2011). They are concerned with trust and trustworthiness in a standard newsvendor experiment where there is one-way communication, whereas we examine the beneficial effects of *two-way* communication in an environment where both firms must invest in capacity.

3. The Model

Consider a two-firm supply chain. We will often refer to one firm as the manufacturer, m, and to the other firm as the supplier, s. The supplier provides the manufacturer with a product that the manufacturer converts into a final product. For demand to be met, each firm needs to invest in capacity. Denote by K_i, $i \in \{m, s\}$ the capacity of firm i. Assume that the unit cost of capacity is $\gamma > 0$ for each firm and that the *net revenue* per unit sold is $\pi_m > 0$ for the manufacturer and $\pi_s > 0$ for the supplier. One could view π_m and π_s as being derived from a simple transfer pricing scheme. All parameters are common knowledge.

The timing of events is as follows. First, firms m and s simultaneously choose their capacities, K_m and K_s. Second, demand, x, is realized and sales are given by $\min\{x, K_s, K_m\}$. Therefore, the profits of firm $i \in \{s, m\}$ can be written as

$$\Pi_i(x, K_s, K_m) = \pi_i \min\{x, K_s, K_m\} - \gamma K_i.$$

To make this analysis tractable, we assume that both firms have a diffuse prior about demand x over $\mathbb{R}$. Prior to choosing capacities, each firm receives a private signal, $\theta_i = x + \epsilon_i$, where $\epsilon_i \sim \mathcal{U}[-\eta, \eta]$ and $\eta > 0$ measures the noisiness of the signals. We consider two cases. First, we consider the case in which firms have *common information*; that is, $\epsilon_m = \epsilon_s$. In this case, the model is a special case of Tomlin (2003), where the distribution of demand, conditional on θ, is $\mathcal{U}[\theta - \eta, \theta + \eta]$.

Second, we consider the case in which firms have *private information*; that is, ϵ_s and ϵ_m are *independent* draws from the distribution $\mathcal{U}[-\eta, \eta]$. In this case, the firms do not have a commonly held demand forecast. For example, given a signal θ_i received by firm i, this firm believes that the true state is uniformly distributed on $[\theta_i - \eta, \theta_i + \eta]$, whereas firm i believes that firm j could have received a signal on $[\theta_i - 2\eta, \theta_i + 2\eta]$ with a triangular density function centered at θ_i. Note that *unconditional* on the state, signals are positively correlated. Therefore, if one firm receives a higher signal, then it believes that the other firm likely received a higher signal as well.

Before we proceed, more notation is in order. Let $F(x \mid \theta)$ denote the distribution over demand states conditional upon receiving a signal θ, and let $f(x \mid \theta)$ denote the corresponding density function. By assumption, F is uniformly distributed over $[\theta - \eta, \theta + \eta]$. Additionally, let $G_i(\theta_j \mid x)$ denote the distribution of player i's beliefs about the signal received by player j conditional on the true state. Given our setup, $G_i(\theta_j \mid x)$ is uniform over $[x - \eta, x + \eta]$.

Remark 1 (Priors and Signals). The assumption that the prior beliefs about demand are diffuse over $\mathbb{R}$ is unrealistic but is made for analytical convenience. If priors were diffuse over $\mathbb{R}_+$, then some technical issues (but no additional insights), which can be dealt with at the cost of added complexity, arise for signals in the interval $[-\eta, \eta)$.

One might also be concerned that the assumption that signals are uniformly distributed plays an important role in driving our results. In the supplemental notes (available at http://dx.doi.org/10.1287/msom.1120.0400), we show that qualitatively identical results go through if signals are normally distributed with mean 0 and variance σ^2.

4. Equilibrium Characterization

4.1. The Common Information Game

We can write the expected profits for firm $i \in \{m, s\}$, having received the common signal θ, as

$$\bar{\Pi}_i(\theta, K_i, K_j) = \pi_i \int_{\theta-\eta}^{\theta+\eta} \min\{x, K_i, K_j\} f(x \mid \theta)\, dx - \gamma K_s.$$

Recall that the two firms simultaneously choose capacity, $K_i \geq 0$ to maximize their expected profits. Define $s^* = (\pi_s - \gamma)/\pi_s$ and $m^* = (\pi_m - \gamma)/\pi_m$, where s^* and m^* are the traditional newsvendor critical fractiles for the supplier and manufacturer. Suppose without loss of generality that $s^* \leq m^*$. We then have the following:

Proposition 0. *For $\theta \leq \eta(1 - 2s^*)$, there is a unique equilibrium in which $K_i(\theta) = 0$ for $i \in \{m, s\}$. For $\theta > \eta(1 - 2s^*)$, there are multiple equilibria. In the Pareto efficient equilibrium outcome, both firms choose capacity $K_i(\theta) = F^{-1}(s^* \mid \theta)$ for $i \in \{m, s\}$.*

Proof. See the appendix. □

Notice that if both firms are symmetric, then the Pareto efficient equilibrium choice function corresponds to the single-player newsvendor solution.

4.2. The Private Information Game

We turn now to the case in which each firm receives a private signal $\theta_i = x + \epsilon_i$. This assumption is meant to capture the idea that different firms may have access to different information or methodologies in deriving their demand forecast.

We characterize an equilibrium in which both firms employ monotonic strategies, $K_i(\theta_i) < \theta_i + \eta$, where $K_i' > 0$ for all $\theta \geq \underline{\theta}$. It is quite natural to focus on such strategies because they reduce the perceived complexity of the game. Moreover, monotone strategies are quite robust in that if firm j uses a monotone strategy, it will generally be a best response for firm i to play a monotone strategy as well: If firm i's signal increases slightly, then its expectation of demand increases, as does its belief about firm j's signal. Because firm j is playing a monotone strategy, firm i therefore expects firm j's capacity choice to increase. Thus, it will be optimal for firm i to increase its capacity.

In general, the expected profit function of firm i is

$$\begin{aligned}\bar{\Pi}_i(\theta_i, K_i, K_j(\cdot)) &= \pi_i \int_{\theta_i-\eta}^{\theta_i+\eta} \left[\int_{x-\eta}^{x+\eta} \min\{x, K_i, K_j(\theta_j)\} g_i(\theta_j \mid x)\, d\theta_j \right] \cdot f(x \mid \theta_i)\, dx - \gamma K_i \\ &= \frac{\pi_i}{4\eta^2} \int_{\theta_i-\eta}^{\theta_i+\eta} \int_{x-\eta}^{x+\eta} \min\{x, K_i, K_j(\theta_j)\}\, d\theta_j\, dx - \gamma K_i,\end{aligned}$$

where $K_j(\theta_j)$ is the strategy of firm j as a function of its observed signal and x is the realization of demand over which we integrate. The second line follows because both $g_i(\theta_j \mid x)$ and $f(x \mid \theta_i)$ are uniform densities with a support of length 2η. In what follows, we assume that $\pi \equiv \pi_i = \pi_j$.

4.2.1. Main Characterization. We now provide a complete characterization of equilibrium behavior in the private information game.

Proposition 1. *For all $\gamma \in (0, \pi)$, there is an equilibrium such that $K_i(\theta_i) = 0$ for all θ_i and $i \in \{s, m\}$. If $\gamma > \bar{\gamma} \equiv \pi/2$, then this is the unique equilibrium. If $\gamma \leq \bar{\gamma}$, there is a symmetric equilibrium in monotone strategies. In this equilibrium, firms' capacity choices are given by*

$$K_i(\theta_i) = \begin{cases} 0 & \text{if } \theta_i \leq \eta - 2\eta\sqrt{1 - \dfrac{2\gamma}{\pi}}, \\ \theta_i - \eta + 2\eta\sqrt{1 - \dfrac{2\gamma}{\pi}} & \text{if } \theta_i > \eta - 2\eta\sqrt{1 - \dfrac{2\gamma}{\pi}}. \end{cases}$$

Furthermore, within the class of monotone strategies, the equilibrium is unique.

Proof. See the appendix. □

The intuition for the complete coordination failure is easy: $K_i(\theta) = 0$ is trivially a best response to the strategy $K_j(\theta_j) = 0$. That this is the unique equilibrium when $\gamma > \pi/2$ is also not difficult to intuit. In equilibrium, each firm expects that the other firm will have a lower signal than it does half of the time. Because the cost of capacity is high relative to the marginal revenue of sales, it is optimal for the firm to lower its capacity. However, both firms have the same incentives, which means that each firm's negative expectations are mutually reinforced until a complete coordination failure occurs.

This intuition also shows us that there cannot be an asymmetric equilibrium when $\gamma > \pi/2$ because then $K_i(\theta) \neq K_j(\theta)$. In this situation, for the firm choosing a higher capacity, it would be the case that *more than* half the time its opponent will choose a lower capacity, giving the firm a strong incentive to lower its capacity. The remainder of our analysis assumes that $\gamma \leq \bar{\gamma}$ so that we may be assured of a symmetric monotone equilibrium.

Observe that in the efficient equilibrium of the CI game as well as in the monotone equilibrium of the PI game, the capacity-choice function is affine in signal received, with a slope of 1. Furthermore, observe that the critical signal, above which firms choose a strictly positive capacity, is strictly higher in the PI game. That is, $\underline{\theta}^{\text{PI}} > \underline{\theta}^{\text{CI}}$. Taken together, these two observations imply that $K^{\text{PI}}(\theta) < K^{\text{CI}}(\theta)$. That is, the presence of private information means that firms' capacities will be necessarily misaligned, which causes them to be more cautious in their capacity choices than in the efficient equilibrium of the common information game. Therefore, we also have the following:

Corollary 1. *Expected profits in the private information game are strictly less than expected profits in the Pareto efficient equilibrium of the common information game.*

4.2.2. Information Sharing and Communication by Firms. Proposition 1 and Corollary 1 show us that the presence of private information about demand is more likely to lead to lower profits than if information was commonly held. Therefore, we turn our attention to some ways in which firms may be able to overcome the problems due to private information. We first focus on information sharing by firms. Suppose there is a mechanism in which firms receive each other's signal in addition to their own. This mechanism accomplishes two things. First, it makes the information that each firm has more precise (which should lead to higher profits). Second, it restores common information (which brings back multiple equilibria). We call this game the *common information game with two signals* (CI-2S).

More formally, let $\theta_\ell = \min\{\theta_s, \theta_m\}$ and $\theta_h = \max\{\theta_s, \theta_m\}$. Then the support of demand is $[\theta_h - \eta, \theta_\ell + \eta]$ and updated beliefs about demand are uniform on that support. We then have the following:

Proposition 2. *There are multiple equilibria of the CI-2S game. The Pareto efficient equilibrium is characterized by $K^{\text{CI-2S}}(\theta_\ell, \theta_h) = \max\{s^*(\theta_\ell + \eta) + (1 - s^*) \cdot (\theta_h - \eta), 0\}$. Moreover, expected profits in the Pareto efficient equilibrium are higher than without information sharing.*

Proof. See the appendix. □

Of course, it may be difficult or prohibitively costly for firms to set up such a mechanism to convey their private information. An alternative scenario is one in which, prior to setting capacities, firms engage in preplay (cheap-talk) communication. We briefly explore the potential of this mechanism to increase profits and improve alignment.

The *private information game with communication* (PI-MS) is identical to the PI game except that after receiving one's signal, but before choosing one's capacity, firms simultaneously send a message, $M_i \in \mathbb{R}$, to each other.

Although "babbling" equilibria always exist, we show that there is also a truthful equilibrium in which firms coordinate on the Pareto efficient equilibrium of the CI-2S game. Formally,

PROPOSITION 3. *There exists an equilibrium of the* PI-MS *game in which firm i sends message, $M_i = \theta_i$, $i \in \{m, s\}$, and both firms subsequently choose capacity $K^{\text{CI-2S}}(\theta_\ell, \theta_h)$.*

PROOF. See the appendix. □

The intuition for this result is as follows. Because firms expect to coordinate on the efficient equilibrium in the capacity-choice subgame, a firm can never strictly benefit from lying about its signal and may suffer. To see this more clearly, consider firm i's decision about whether to report $M_i \gtreqless \theta_i$. By truthfully reporting its signal, firm i ensures that in the capacity-choice subgame, the capacities of both firms will be set at their profit-maximizing level of $K^{\text{CI-2S}}(\theta_i, \theta_j)$.

If firm i reports $M_i \neq \theta_i$, then matters are more complicated; in particular, it matters whether $|M_i - \theta_j| \gtrless 2\eta$. If $|M_i - \theta_j| < 2\eta$, then this message is *on the equilibrium path*, which means that firm j will choose a capacity of $K_j^{\text{CI-2S}}(M_i, \theta_j) \neq K^{\text{CI-2S}}(\theta_i, \theta_j)$. If $M_i < \theta_i$, then $K_j^{\text{CI-2S}}(M_i, \theta_j) < K^{\text{CI-2S}}(\theta_i, \theta_j)$, and firm i is *strictly worse off* from misreporting its signal. On the other hand, if $M_i > \theta_i$, then $K_j^{\text{CI-2S}}(M_i, \theta_j) > K^{\text{CI-2S}}(\theta_i, \theta_j)$, *but firm i does not gain* from misreporting its signal because firm i will still choose $K^{\text{CI-2S}}(\theta_i, \theta_j)$. Thus, it is better for firm i to be truthful.

Now suppose that $|M_i - \theta_j| > 2\eta$. This message is *off the equilibrium path*; that is, firm j is certain that firm i could not have possibly received such a signal. Because the appropriate equilibrium concept for this game is perfect Bayesian equilibrium, we are required to specify beliefs for firm j; however, because this message is off the equilibrium path, we have complete freedom to specify *any* beliefs for firm j. In such cases, it is common to specify extremely pessimistic beliefs for firm j (so as to justify a capacity of zero), which is precisely what we do in the proof. Because of this, it is clear that firm i would be strictly better off sending a truthful message.

We conjecture that the equilibrium described in Proposition 3 is the *unique* truthful equilibrium (i.e., there may be other equilibria, but these involve firms lying about their signals). Unfortunately, we have been unable to formally prove this. To get some intuition, suppose that there was a truthful equilibrium in which firms set capacities $\hat{K}(\theta_i, \theta_j) < K^{\text{CI-2S}}(\theta_i, \theta_j)$, and observe that in a truthful equilibrium, capacities are increasing in the message received. Because $\hat{K}(\theta_i, \theta_j) < K^{\text{CI-2S}}(\theta_i, \theta_j)$, a firm would like to increase its capacity. The only way to accomplish this is to make the other firm think demand is higher (i.e., to report $M_i = \theta_i + \Delta > \theta_i$). By doing this, firm i's dishonesty will go undiscovered with probability $1 - \Delta^2/(8\eta^2)$, and so firm j will choose a higher capacity. This gives firm i the freedom to choose a higher capacity, which increases its profits by approximately $(\pi - \gamma) \cdot (\hat{K}(\theta_i + \Delta, \theta_j) - \hat{K}(\theta_i, \theta_j))$. With probability $\Delta^2/(8\eta^2)$, firm i will be found out to have lied, leading to a capacity choice of zero and a discrete drop in profits of $\mathbb{E}[\Pi(\theta_i, \theta_j)]$. Therefore, the total change in expected profits is, approximately,

$$(1 - \Delta^2/(8\eta^2))(\pi - \gamma)(\hat{K}(\theta_i + \Delta, \theta_j) - \hat{K}(\theta_i, \theta_j)) - (\Delta^2/(8\eta^2))\,\mathbb{E}[\Pi(\theta_i, \theta_j)].$$

Dividing by Δ and taking the limit as $\Delta \to 0$ gives us the change in profits as approximately $(\pi - \gamma) \cdot (\partial \hat{K}(\theta_i, \theta_j)/\partial \theta_i) > 0$. Thus, for Δ sufficiently small, firm i strictly prefers to inflate its signal by Δ, contradicting the assumption that we had a truthful equilibrium. The supplemental notes contain an example to provide further intuition for our conjecture.

REMARK 2. Crawford and Sobel (1982) provide the seminal work on cheap-talk games and establish that communication is easier when player's preferences are more closely aligned, but perfect communication can only occur if preferences are perfectly aligned. In our setting, if firms expect to coordinate on the efficient equilibrium, then their interests are actually perfectly aligned. Thus, as Proposition 3 shows, perfect communication can occur. However, if the firms do not expect to coordinate on the efficient equilibrium, then because of private information, firms' preferences are not perfectly aligned and Crawford and Sobel's (1982) logic suggests that full communication is impossible. Note that our result on truth telling with two-sided private information and two-way communication is in contrast to the Özer et al. (2011) result that all equilibria are uninformative in their model of one-way communication from a manufacturer to a supplier in a newsvendor setting.

REMARK 3. Some readers might not like the extremely "pessimistic" beliefs that we use in our proof. In the appendix, we show that any beliefs, combined with a consistent best response to those beliefs, also support the truth-telling equilibrium. Such pessimistic beliefs serve as a strong punishment to a subject for getting caught lying. There is an extensive literature in experimental economics showing that subjects will punish others for not behaving according to a particular norm, even when punishments are costly and do not directly benefit the punisher (Fehr and Gächter 2000, Andreoni et al.

2003). Our experimental results in §7 confirm that subjects do, in fact, punish their partner when the partner has been found to have lied, though the punishments are less extreme than assumed in the proof.

4.3. Discussion of Testable Hypotheses

As noted in the introduction, we have two goals: first, to understand the implications of private information on firms' ability to align their actions on a profitable outcome and, second, to understand to what extent information sharing improves profits and alignment and whether preplay communication is sufficient to achieve these benefits. Our theoretical results have shed some light on these questions; unfortunately, the presence of multiple equilibria complicates matters. Therefore, an experiment can help clarify these issues.

We generate our hypotheses under the best-case scenario of no coordination failures. That is, in the CI games, subjects play the efficient equilibrium and in the PI games, subjects play the monotone equilibrium (when it exists). In this case, our theoretical results give us the following:

Hypothesis 1. *Comparing the* CI *and* PI *games with respect to capacity choices, misalignment, and profits, the following should hold*:

1. $K^{\text{CI}}(\theta) > K^{\text{PI}}(\theta)$,
2. $d^{\text{PI}} = |K_1^{\text{PI}}(\theta_1) - K_2^{\text{PI}}(\theta_2)| > |K_1^{\text{CI}}(\theta) - K_2^{\text{CI}}(\theta)| = d^{\text{CI}}$, *and*
3. $\bar{\Pi}(\text{CI}) > \bar{\Pi}(\text{PI})$.

That is, for the same signal, subjects choose a higher capacity in the CI game. Also, because subjects receive independent signals in the PI games, their capacities should be more misaligned. Finally, both of these lead to lower average profits in the PI games.

We now turn to the implications of information sharing. First, because subjects receive *two* signals in the CI-2S game and only one in the CI game, they should earn more. Formally,

Hypothesis 2. $\bar{\Pi}(\text{CI-2S}) > \bar{\Pi}(\text{CI})$.

Second, under the best-case scenario, Proposition 3 tells us that truthful information sharing and preplay communication should lead to equivalent outcomes. That is,

Hypothesis 3. *Behavior should be indistinguishable in the* CI-2S *and* PI-MS *games. That is*,

1. $K^{\text{CI-2S}}(\theta_1, \theta_2) = K^{\text{PI-MS}}(\theta_i, M_j)$,
2. $d^{\text{CI-2S}} = d^{\text{PI-MS}}$, *and*
3. $\bar{\Pi}(\text{CI-2S}) = \bar{\Pi}(\text{PI-MS})$.

5. Experimental Design

A total of 264 subjects, recruited from undergraduate classes, participated in our experiments that were run at the experimental economics laboratory of a public university in the United States. In each session, after subjects read the instructions, the instructions were then read aloud by an experimental administrator. Sessions lasted between 45 and 90 minutes depending on the treatment, and each subject participated in only one session. A \$5.00 show-up fee and subsequent earnings, which averaged about \$18.00, were paid in private at the end of the session. Throughout the experiment, we ensured anonymity and effective isolation of subjects to minimize any interpersonal influences.

The basic structure of each treatment was as follows. First, the prior distribution of demand was uniform with support $[\underline{x}, \bar{x}]$, where $\underline{x} > 0$. Although our theoretical results were derived for the case of a diffuse prior, this is not implementable in the lab and was a necessary modification. None of the theoretical results is sensitive to this modification. Second, conditional on the state, x, subjects received a signal $\theta_i = x + \epsilon_i$, where $\epsilon_i \sim \mathcal{U}[-\eta, \eta]$. Third, the profit function was

$$\pi_i(K_i, K_j, x) = \pi \min\{K_i, K_j, x\} - \gamma K_i.$$

The experiment is a 4×3 design. Specifically, we have four information treatments: (i) the common information game (CI), (ii) the private information game (PI), (iii) the common information game with two signals game (CI-2S), and (iv) the private information game with communication (PI-MS); for each of these information treatments, we had three different sets of parameters, where $\underline{x}$, $\bar{x}$, η, π, and γ were varied. Our main interest is to contrast behavior and outcomes (e.g., profits and alignment) across information treatments. By varying the parameter values, we are able to see whether the comparative statics across information treatments are robust to changes in the exogenous parameters.

In all treatments, subjects were randomly rematched after each round and subjects played the game in their session for either 30 or 40 rounds. For each of the 12 experimental conditions, we conducted two sessions. Unless otherwise noted, the statistical tests reported in tables and the text assume that the unit of independent observation is the subject average.[1]

5.1. Details of Each Treatment

Table 1 summarizes the details of our experiment. A sample of the instructions used can be found at http://dx.doi.org/10.1287/msom.1120.0400.

[1] In the strictest sense, because subjects were randomly rematched each period, one may argue that the true unit of independent observation is the session average rather than the subject average as we assume. Independence at the subject level may not hold because all subjects in a session interact with each other one or more times. By taking the subject average as the unit of observation, we are implicitly assuming that this is not a major concern.

Table 1 **Summary of Experiments**

Treatment	π	γ	Prior on demand	Noisiness of signals (η)	Number of rounds	Number of subjects
CI	5	2	$U[20, 50]$	5	30	20
	10	3	$U[100, 400]$	25	40	24
	10	6	$U[100, 400]$	25	40	22
PI	5	2	$U[20, 50]$	5	30	18
	10	3	$U[100, 400]$	25	40	24
	10	6	$U[100, 400]$	25	40	20
CI-2S	5	2	$U[20, 50]$	5	30	22
	10	3	$U[100, 400]$	25	40	22
	10	6	$U[100, 400]$	25	40	24
PI-MS	5	2	$U[20, 50]$	5	30	22
	10	3	$U[100, 400]$	25	40	24
	10	6	$U[100, 400]$	25	40	22

The experiment was programmed using *z*-Tree (Fischbacher 2007). Note that it will often be convenient to refer to a specific game by the abbreviation CI(π, γ) or PI(π, γ).

5.1.1. Common Information Game (CI). For each pair, demand x was drawn from the appropriate distribution in Table 1 and *both* subjects received the *same* signal $\theta = x + \epsilon$.

5.1.2. Private Information Game (PI). For each pair, demand x was drawn from the appropriate distribution in Table 1 and each subject, i, received a signal $\theta_i = x + \epsilon_i$. In the games PI$(5, 2)$ and PI$(10, 3)$, the monotone equilibrium exists, whereas in the PI$(10, 6)$ game, only the complete coordination failure exists.

5.1.3. Common Information Game with Two Signals (CI-2S). This treatment was identical to the CI treatment, except that *both* subjects within a group received the *same* two signals $\theta_1 = x + \epsilon_1$ and $\theta_2 = x + \epsilon_2$. Thus, subjects have more accurate information than in the CI treatment.

5.1.4. Private Information Game with Communication (PI-MS). The information structure was the same as in the PI treatment, with the addition of a communication stage before capacities were chosen. Subjects sent messages of the form, "My estimate is: Z," where Z was restricted to the interval $[\underline{x} - \eta, \bar{x} + \eta]$, but did not have to match one's own signal. There was no cost of sending a message. After the communication stage, subjects again saw their estimate and the message sent by their match and made their capacity decisions.

Remark 4 (Notes on the Design). 1. Although some newsvendor and related experiments have used the normal distribution, by far most experiments implement the uniform distribution, and those that do use the normal distribution do so for very specific reasons that make the uniform distribution, despite its simplicity, less desirable (see, e.g., Szkup and Trevino 2011). Note also that the assumption that signals are uniformly distributed gives the CI-2s treatment the *best shot* at improving profits relative to the CI treatment. The reason is twofold. First, the beliefs about demand for a subject receiving two signals remains uniformly distributed, and this should be apparent to most subjects. In contrast, the distribution of beliefs when signals are more concentrated about the true demand are much more complicated to compute, which could be an additional source of mistakes for subjects. Second, the increase in information when going from the CI to the CI-2s treatment is actually highest when signals are uniformly distributed.

2. Our design allows us to make several interesting comparisons. First, for each of our three different sets of parameter values, we can compare the effects on private versus common information and also the effects of truthful information sharing versus cheap-talk communication. Second, within each treatment, the different parameter combinations lead to a ranking in terms of equilibrium capacity choice (in relation to mean demand), with the $(10, 6)$ treatment having the lowest capacity function and the $(10, 3)$ treatment having the highest equilibrium capacity function. Note also that by increasing the range of signals (η), we further increase the distance between capacity choice and mean demand in the $(10, 3)$ and $(10, 6)$ treatments relative to the $(5, 2)$ treatment. Although a full factorial design would be ideal, we believe that this design is sufficient to address our primary questions of interest.

6. Analysis: What Is the Role of Private Information?

In this section, we focus on our CI and PI games to gain insights into the role that private information about the state of demand has on alignment and profits. We focus our discussion on an analysis of Hypothesis 1.

6.1. Basic Results

6.1.1. Profits. We begin by presenting some basic summary statistics from each of the CI and PI sessions that we conducted. These results are on display in Table 2. The final column presents the gap between average profits in each game and the optimal expected profits if subjects played according to the efficient equilibrium for that treatment.

We highlight two results. First, the evidence in favor of Hypothesis 1 is mixed. In only one case (CI$(5, 2)$ versus PI$(5, 2)$) are average profits significantly higher in the CI treatment than in the corresponding PI treatment. Indeed, comparing CI$(10, 6)$ and PI$(10, 6)$ average profits are weakly significantly

Table 2 Summary Statistics

Treatment	Payoff	Std. dev.	Min	Max	Gap (%)[a]	t-test
	(a) Distribution of demand: $U(20, 50)$; $\pi = 5$; $\gamma = 2$					
CI	84.8	6.2	70.0	95.7	14.9	$t_{36} = 3.80$
PI	78.2	4.2	71.0	86.3	17.6	$p \ll 0.01$
	(b) Distribution of demand: $U(100, 400)$; $\pi = 10$; $\gamma = 3$					
CI	1,649.4	104.0	1,328.1	1,818.1	3.0	$t_{46} = 1.60$
PI	1,594.9	130.2	1,331.6	1,866.9	4.6	$p = 0.12$
	(c) Distribution of demand: $U(100, 400)$; $\pi = 10$; $\gamma = 6$					
CI	824.1	56.9	747.0	922.2	12.6	$t_{40} = 1.78$
PI	856.2	60.0	741.2	952.3	−114.1	$p = 0.08$

[a]Calculated as the percentage difference from either the efficient equilibrium of the CI game or from the monotone equilibrium of the PI game, depending on the treatment. The optimality gap was obtained via a Monte Carlo simulation consisting of 10,000 trials of 30 or 40 periods, depending on the treatment.

higher in the PI game, which is doubly surprising because the theoretical prediction is for the complete coordination failure! Second, in two of the CI games, subjects earn 12.6% and 14.9% less than in the Pareto efficient equilibrium, whereas in a third subjects come within 3.7%. This suggests that at least for some parameter values, the presence of multiple equilibria makes it difficult for subjects to coordinate on the efficient equilibrium.

6.1.2. What Is the Extent of Misalignment? Here we quantify the amount of misalignment in each group's choices and try to determine the role of information. Let d_t^j denote the absolute difference between the choices of the subjects in group j in round t, and let $\bar{d}$ denote the average over all groups and rounds. Table 3 reports the data.

With respect to misalignment, the evidence is much more supportive of Hypothesis 1. In particular, across all three parameter values $d^{\text{CI}} < d^{\text{PI}}$ and the difference is statistically significant in two cases. It is also interesting to note that subjects are significantly more misaligned in CI(10, 3) than in CI(10, 6) ($p = 0.014$). Although there is no theoretical reason for this to be the case, it is possible that, behaviorally, there is more scope for misalignment in the former game where $K(\theta) = \theta + 10$ for $\theta \in [125, 375]$, whereas in the latter game, $K(\theta) = \theta - 5$ for $\theta \in [125, 375]$. Hence, there are

Table 3 Extent of Misalignment ($\bar{d}$) in CI and PI Treatments

Parameters	CI	PI	t-test
Demand $\sim U[20, 50]$; $\pi = 5$; $\gamma = 2$	4.67	5.96	$t_{36} = 2.40$
	(2.03)	(1.03)	$p = 0.02$
Demand $\sim U[100, 400]$; $\pi = 10$; $\gamma = 3$	24.87	28.78	$t_{46} = 1.13$
	(11.1)	(12.8)	$p = 0.26$
Demand $\sim U[100, 400]$; $\pi = 10$; $\gamma = 6$	13.77	23.46	$t_{40} = 6.70$
	(4.4)	(4.9)	$p \ll 0.01$

Note. Standard deviations reported in parentheses.

"more" equilibria in CI(10, 3), making it more difficult for players to coordinate on any one of them.

6.2. Estimated Capacity-Choice Functions

We now turn our attention to the capacity-choice functions used by subjects in our experiments. According to our theoretical results, for both the CI and PI treatments, the capacity-choice functions should be piecewise continuous with kinks at $\underline{x} + \eta$ and $\bar{x} - \eta$. Furthermore, on the interval $[\underline{x} + \eta, \bar{x} - \eta]$, the slope of the capacity-choice functions should be 1. We estimate the following equation via a random-effects Tobit procedure:

$$\texttt{choice}_{it} = \alpha + \beta_1 \theta_{it} + \beta_2(\theta_{it} - (\underline{x} + \eta)) \cdot [\theta_{it} < \underline{x} + \eta] + \beta_3(\theta_{it} - (\bar{x} - \eta)) \cdot [\theta_{it} > (\bar{x} - \eta)] + \mu_i + \nu_{it},$$

where $[A]$ is an indicator variable which takes value 1 if A is true.

The results are on display in Table 4. As can be seen, the coefficient on θ is positive and highly significant, though always less than one. Furthermore, there is some statistical evidence in favor of a kink at $\theta = \underline{x} + \eta$ and $\theta = \bar{x} - \eta$, though the magnitude and significance is not consistent across treatments or parameter values. Thus, especially for high signals, subjects are more cautious than theory predicts. This could be due to risk aversion or, especially in the CI treatments, difficulty in coordinating on the efficient equilibrium because of the multiplicity of equilibria.

Finally, note that Hypothesis 1 is not supported with respect to the capacity-choice functions. In particular, for each set of parameters, we pooled across the CI and PI treatments and estimated the model above (interacting all of the independent variables with treatment dummies). We were unable to reject the hypothesis that these treatment interactions were jointly zero (in all cases, $p > 0.21$). Thus, from a practical perspective, it appears that subjects do not fully appreciate that the presence of private information should lead to lower capacities. This is most apparent in the PI(10, 6) treatment where the complete coordination failure is predicted.

6.3. Further Data Analysis

In the interest of parsimony, we have chosen to relegate to a set of supplemental notes some results that may be of interest to some readers. We provide a brief summary. First, learning occurs: With one exception, both alignment and profits improve as the experiment progresses. With respect to profits, most learning occurs in early rounds, with the effect dying out in later rounds. Indeed, particularly in the PI treatments, profits actually appear to decline over the final periods. Second, we investigate whether current choices

Table 4 Random-Effects Tobit Regressions of Choice on Estimate

	Demand ~ $U[20,50]$; $\pi=5$; $\gamma=2$		Demand ~ $U[100,400]$; $\pi=10$; $\gamma=3$		Demand ~ $U[100,400]$; $\pi=10$; $\gamma=6$	
	CI	PI	CI	PI	CI	PI
θ	0.837***	0.882***	0.961***	0.968***	0.981***	0.978***
	[0.0321]	[0.0333]	[0.0141]	[0.0125]	[0.00697]	[0.00870]
$[\theta < \underline{x}+\eta](\theta-(\underline{x}+\eta))$	−0.0898	−0.158	−0.299	−0.337*	−0.66***	−0.524***
	[0.163]	[0.174]	[0.215]	[0.190]	[0.108]	[0.167]
$[\theta > \bar{x}-\eta](\theta-(\bar{x}-\eta))$	−0.116	−0.470***	−0.279	−0.167	0.00269	−0.173
	[0.153]	[0.176]	[0.180]	[0.175]	[0.0948]	[0.123]
Constant	2.486*	0.438	10.90**	8.797**	−14.02***	−7.423**
	[1.312]	[1.342]	[4.283]	[4.017]	[2.496]	[3.254]
N	600	540	960	960	880	800
Log-likelihood	−1,646	−1,469	−4,516	−4,414	−3,484	−3,365

Note. Standard errors in brackets.
***Significant at 1%; **significant at 5%; *significant at 10%.

are affected by lagged variables to see whether subjects follow an adaptive process. We show that there is a positive correlation between current and lagged choice, indicating some inertia in choices. We also show a negative relationship between current choice and the lagged difference between the subject's own choice and her opponent's choice, though the effect is only significant in three of six games.

7. Analysis: Mechanisms to Improve Coordination

We now analyze subject behavior in our CI-2S and PI-MS treatments. Our goal is to determine whether, as predicted, profits and alignment improve relative to the CI and PI games.

7.1. Basic Results

We begin by reporting summary statistics on average earnings in Table 5. The table also reports the efficiency gap, relative to the efficient equilibrium in CI-2S. It also reports the results of hypothesis tests comparing average profits in each game with the corresponding CI and PI game.

First, and somewhat surprisingly, the evidence in favor of Hypothesis 2 is mixed. In particular, average profits are significantly higher in CI-2S(5, 2) than in CI(5, 2). However, average profits are actually significantly *lower* in the CI-2S(10, 3) game than in the CI(10, 3) game, and the difference is not significant between CI-2S(10, 6) and CI(10, 6).

Turn now to Hypothesis 3, which stated that the CI-2S and PI-MS treatments should be indistinguishable. As can be seen from Table 5, there is strong evidence *against* this hypothesis with respect to average profits. In particular, for two of the three games, average profits are actually higher in PI-MS than in CI-2S. Furthermore, average profits in the PI-MS games are always significantly higher than in the corresponding PI games and are significantly higher in two of three CI games. Thus, despite the potential for lying, communication seems to have strong welfare-improving effects.

Continue with Hypothesis 3 but focus now on alignment. Here the evidence, reported in Table 6, is more supportive. That is, in two of the three games we cannot reject the hypothesis that subjects are equally well aligned in CI-2S and PI-MS. Furthermore, in the game where we do find a difference in alignment, it goes in the direction of the most sensible alternative hypothesis, namely, that subjects are better aligned in the CI-2S treatment. Observe also that both information sharing and communication generally lead to better alignment than in either of the CI

Table 5 Summary Statistics for the CP-2S and MS Treatments

						Hypothesis test[b]	
Treatment	Payoff	Std. dev.	Min	Max	Gap (%)[a]	CI	PI
(a) Distribution of demand: $U(20,50)$; $\pi=5$; $\gamma=2$							
CI-2S	90.2	4.1	77.1	100.8	10.4	$\ll 0.01$	$\ll 0.01$
PI-MS	90.8	5.9	75.7	99.1	9.8	$\ll 0.01$	$\ll 0.01$
(b) Distribution of demand: $U(100,400)$; $\pi=10$; $\gamma=3$							
CI-2S	**1,605.5**	68.5	1,451.0	1,723.6	5.1	0.95[c]	0.37
PI-MS	**1,668.5**	107.2	1,474.2	1,853.6	1.4	0.27	0.02
(c) Distribution of demand: $U(100,400)$; $\pi=10$; $\gamma=6$							
CI-2S	**843.7**	80.8	648.0	973.3	11.7	0.18	0.72[c]
PI-MS	**891.5**	57.4	782.1	1,001.3	6.7	$\ll 0.01$	0.03

Note. The cells in bold indicate a statistically significant difference between CI-2S and PI-MS.
[a]Calculated as the percentage difference from the efficient equilibrium of the CI-2S game. The optimality gap was obtained via a Monte Carlo simulation consisting of 10,000 trials of 30 or 40 periods, depending on the treatment.
[b]Reports the p-value of the *one-sided* hypothesis test that average profits in PI-MS or CI-2S are equal to average profits in the CI and PI treatments.
[c]Profits are *lower* in the CI-2S treatment, significantly so for CI-2S(10, 3).

Table 6 Extent of Misalignment ($\bar{d}$) in CI-2S and PI-MS Treatments

Parameters	CI-2S	PI-MS	CI	PI	Test CI vs. CI-2S	Test CI vs. PI-MS	Test PI vs. CI-2S	Test PI vs. PI-MS
Demand ~ $U[20, 50]$; $\pi = 5$; $\gamma = 2$	3.29 (1.39)	3.27 (0.77)	4.67 (2.03)	5.96 (1.03)	0.01	$\ll$0.01	$\ll$0.01	$\ll$0.01
Demand ~ $U[100, 400]$; $\pi = 10$; $\gamma = 3$	**13.46** (**4.3**)	**19.41** (**8.3**)	24.87 (11.1)	28.78 (12.8)	$\ll$0.01	0.06	$\ll$0.01	$\ll$0.01
Demand ~ $U[100, 400]$; $\pi = 10$; $\gamma = 6$	19.61 (6.9)	18.79 (4.4)	13.77 (4.4)	23.46 (4.9)	$\ll$0.00[a]	$\ll$0.01[a]	0.04	0.01

Notes. Standard deviations reported in parentheses. The cells in bold indicate a statistically significant difference between CI-2S and PI-MS.

[a]Observe that these cells indicate that alignment is actually significantly better in the CI game than in *both* CI-2S and PI-MS, contrary to the theoretical prediction.

and PI treatments. The one exception to this is that subjects are significantly better aligned in CI(10, 6) than in either CI-2S(10, 6) or PI-MS(10, 6).

7.2. How Truthful Are Subjects?

The results of the previous subsection indicate that (cheap-talk) communication appears to be beneficial. Of course, we do not know whether subjects are playing the truthful equilibrium of Proposition 3. We turn our attention to this now. In Table 7, we categorize the messages that were sent. Consistent with our intuition, the plurality of messages was greater than one's signal, and messages were truthful approximately 25% of the time. Somewhat puzzling is that subjects sent messages that were strictly less than their estimate between 16% and 23% of the time. To the extent that messages are believed, this can only lead to lower subsequent capacities and profits.

Two remarks are in order. First, the averages in Table 7 mask the issue of subject heterogeneity. We note here that there is some evidence for "types" in that 17.6% of subjects send $M_i > \theta_i$ more than 90% of the time, whereas 11.8% of subjects are honest more than 90% of the time, and only 1.5% of the subjects send $M_i < \theta_i$ more than 90% of the time. Second, note that over time the tendency to deflate one's signal declines and the tendency to inflate one's signal increases. Specifically, over the first five periods, the average frequency of sending a message $M_i < \theta_i$ (respectively, $M_i > \theta_i$) was 32.6% (respectively, 42.9%), whereas over the last five periods the same frequency was 19.7% (respectively, 54.4%). There is no detectable trend in the frequency of honest messages.

Table 7 Truthfulness of Signals

Parameters	$\theta_i < M_i$ (%)	$\theta_i = M_i$ (%)	$\theta_i > M_i$ (%)
Demand ~ $U[20, 50]$; $\pi = 5$; $\gamma = 2$	23.03	27.88	49.09
Demand ~ $U[100, 400]$; $\pi = 10$; $\gamma = 3$	16.08	23.19	60.72
Demand ~ $U[100, 400]$; $\pi = 10$; $\gamma = 6$	27.61	20.11	52.27

Table 7 shows that subjects are generally not truthful; however, this does not mean that they are not informative. For each subject we look at the correlation between his or her message and estimate. Indeed, the correlation is high in all treatments. Specifically, the average correlation is 0.870, 0.949, and 0.961 in the PI-MS(5, 2), PI-MS(10, 3), and PI-MS(10, 6) treatments, respectively. For all three treatments, the median correlation is 0.978 or higher. Thus, messages, although not completely honest, conveyed a great deal of information for the vast majority of subjects.

We next turn to the question of what affects capacity choices in the PI-MS treatment. Recall that if subjects are playing the truthful equilibrium of Proposition 3, then because messages are truthful, one should give equal weight to their own estimate and the message received, as in the CI-2S treatment. Consistent with our findings that subjects are not truthful, the columns labeled (1) in Table 8 show that subjects give significantly less weight to the message received than to their own signal. This is in contrast to the CI-2S treatment where we are never able to reject the null hypothesis that subjects give equal weight to their two signals (results available upon request).

We have seen that subjects frequently lie about their signals and that subjects recognize this and consequently place less weight on the message received than on their own signal. Yet as we saw in Table 5, the ability to communicate leads to higher profits. The question, therefore, is why? We believe that there are at least three reasons for this. First, as noted above, messages are highly correlated with signals, with the median correlation being at least 0.978. Therefore, messages are highly informative. Second, as columns labeled (2) of Table 8 indicate, subjects' own choices are positively correlated with the message that *they* send to their match. This provides subjects with an opportunity to make inferences about their match's eventual choice. These two reasons suggest that communication may serve as a coordination device that allows subjects to come close to the efficient outcome.

Table 8 Random-Effects Tobit Regressions of Capacity Choice (PI-MS Treatment)

	Demand ~ $U[20, 50]$; $\pi = 5$; $\gamma = 2$			Demand ~ $U[100, 400]$; $\pi = 10$; $\gamma = 3$			Demand ~ $U[100, 400]$; $\pi = 10$; $\gamma = 6$		
	(1)	(2)	(3)	(1)	(2)	(3)	(1)	(2)	(3)
Estimate	0.739***	0.595***	0.730***	0.716***	0.328***	0.658***	0.665***	0.516***	0.658***
	[0.023]	[0.030]	[0.023]	[0.024]	[0.034]	[0.026]	[0.022]	[0.033]	[0.022]
Message received	0.193***	0.180***	0.202***	0.245***	0.259***	0.302***	0.303***	0.297***	0.309***
	[0.022]	[0.021]	[0.022]	[0.023]	[0.021]	[0.025]	[0.022]	[0.021]	[0.022]
Message sent		0.178***			0.390***			0.162***	
		[0.026]			[0.027]			[0.027]	
$\lvert M_j - \theta_i \rvert > 2\eta$			−0.930*			−17.83***			−4.633*
			[0.534]			[3.356]			[2.654]
Constant	0.756	−0.173	0.803	10.40***	1.921	11.50***	−0.282	−3.005	0.108
	[0.597]	[0.603]	[0.598]	[3.448]	[3.075]	[3.414]	[2.502]	[2.526]	[2.504]
N	660	660	660	914	914	914	880	880	880
Log-likelihood	−1,656	−1,633	−1,654	−4,107	−4,013	−4,094	−3,878	−3,860	−3,876

Note. Standard errors (at subject level) in brackets.
***Significant at 1%; *significant at 10%.

In contrast, in the CI-2s treatment, the fact that each player receives the same two signals about demand does not give them the opportunity to signal their intended action. Of course, all would be for naught if subjects lied "too much," which brings us to our third reason. Namely, although we showed in the proof of Proposition 3 that punishments are not required to sustain the truthful equilibrium, it appears that subjects punish off-the-equilibrium path messages. That is, if $|M_j - \theta_i| > 2\eta$, then subject j is known to have lied and may be subject to punishment. Indeed, as the columns labeled (3) of Table 8 show, the coefficient on the dummy variable for this event is negative and significant. This would appear to provide some discipline to ensure that people are not "too dishonest."

To examine further our conjecture that preplay communication allows subjects to use messages to signal their eventual capacity choice, we ran another experiment in which subjects first sent a message as in the PI-MS treatment but were then able to send a recommended capacity choice. Being able to send both a message and a recommendation had the following effects: (1) average profits increased (but not significantly so); (2) misalignment declined by a statistically significant 57%; (3) the frequency of truthful messages increased and, conditional on lying, subjects lied less (the latter is marginally significant); and (4) the relationship between subjects' final capacity and the message that they sent declines substantially relative to the PI-MS treatment. Thus, allowing recommendations means that subjects do not need to use messages to signal both their private information and their intended action. Instead, they can use messages to more accurately signal their private information and recommendations to signal their intended action, which seems to have a modest positive impact on profits. More details are available in the supplemental notes.

7.3. Are There Consequences from Lying?

Finally, we examine the impact of sending and receiving messages on profits and misalignment. In panels (a) and (b) of Table 9 we report the average profits and average misalignment of subjects in the PI-MS treatment conditional on (i) receiving an honest message; (ii) unknowingly receiving a dishonest message (i.e., $0 < |\theta_i - M_j| \leq 2\eta$); and (iii) knowingly receiving a dishonest message (i.e., $|\theta_i - M_j| > 2\eta$). We also report the average profits from the CI-2s treatment. There are two interesting features. First, average profits are higher in the PI-MS treatment when the subject receives an honest message than in the CI-2s treatment. Thus, communication, as suggested by Proposition 3, may serve as a coordination device and allow subjects to reach the efficient equilibrium. In contrast, the continuum of equilibria in the CI-2s treatment may make coordination on any equilibrium, let alone the efficient one, difficult to achieve. Second, with one exception, we see that average profits are decreasing as messages become more dishonest.

The same general pattern is at play when we look at the relationship between misalignment and the message received. In all cases, average misalignment increases as messages become more dishonest. The main punchline from this analysis, however, is that honesty appears to be the best policy when it comes to sending messages.

7.4. Further Data Analysis

Because of our choice to focus on how information sharing and communication affect behavior vis-à-vis the CI and PI treatments, we omitted some results that may be of interest to readers. In particular, we show that both alignment and profits improve in both the CI-2s and PI-MS treatments. Additionally,

Table 9 Consequences of Lying: Average Profits and Misalignment Given the Message Received

	CI-2S		PI-MS $\theta_j = M_j$		PI-MS $\theta_j \neq M_j$ and $\lvert M_j - \theta_i \rvert \leq 2\eta$		PI-MS $\theta_j \neq M_j$ and $\lvert M_j - \theta_i \rvert > 2\eta$
(a) Average profits							
Demand $\sim U[20, 50]$; $\pi = 5$; $\gamma = 2$	90.2	$=_{0.57}$	91.6	$=_{0.86}$	92.1	$>_{\ll 0.01}$	73.0
Demand $\sim U[100, 400]$; $\pi = 10$; $\gamma = 3$	1,605.5	$<_{0.04}$	1,691.4	$=_{0.82}$	1,681.2	$>_{0.06}$	1,537.6
Demand $\sim U[100, 400]$; $\pi = 10$; $\gamma = 6$	843.7	$<_{\ll 0.01}$	947.3	$>_{0.09}$	890.3	$>_{0.03}$	746.4
(b) Average misalignment							
Demand $\sim U[20, 50]$; $\pi = 5$; $\gamma = 2$	3.29	$=_{0.62}$	3.08	$=_{0.94}$	3.11	$<_{\ll 0.01}$	5.99
Demand $\sim U[100, 400]$; $\pi = 10$; $\gamma = 3$	13.46	$=_{0.29}$	15.62	$=_{0.59}$	16.97	$<_{\ll 0.01}$	51.69
Demand $\sim U[100, 400]$; $\pi = 10$; $\gamma = 6$	19.61	$=_{0.41}$	17.19	$=_{0.95}$	17.36	$<_{\ll 0.01}$	37.01

Note. The p-value of the two-sided hypothesis test of equality is given below each equality/inequality.

we provide greater detail about the consequences for lying. Specifically, taking a regression based approach, we show that profits decline as the message sent or received is further away from the truth. We also find that it is worse to send a message *below* one's own signal than it is to send a message *above* one's signal, and similarly for receiving messages. These findings further reinforce our claim that honesty is the best policy. Finally, we provide a more thorough discussion of our follow-up experiment in which subjects first sent messages and then sent recommendations about the appropriate capacity choice.

8. Conclusions

In this paper, we set out to formulate a tractable framework for studying the subtle role that information plays in the coordination problem of firms operating in a supply chain and then to test the predictions in a series of human subject experiments. Our theoretical model had four main results. First, when demand forecasts are common information, there are multiple Pareto rankable equilibria. Second, when demand forecasts are private information, if the marginal cost of capacity is below a certain threshold, there is a unique monotone equilibrium. In this equilibrium, capacity choices are lower and necessarily misaligned, both of which lead to profits that are lower than in the efficient equilibrium of the common information game. Third, we showed that information sharing leads to improved forecast accuracy, which consequently leads to higher expected profits in the efficient equilibrium. Finally, and most surprisingly, we showed that a game with preplay communication, despite being cheap talk, has an equilibrium that delivers the same expected profits as the efficient equilibrium of the game with truthful information sharing. Thus, from a business perspective, our results suggest that it may not be necessary to go through the costly process of implementing systems that guarantee truthful information sharing between firms.

Although our model was restricted to two symmetric firms, it is straightforward to extend the PI game to N symmetric firms. Indeed, it is possible to show that (1) as N increases, capacities in the monotone equilibrium are decreasing and (2) the monotone equilibrium exists only when $\gamma < \pi/N$. Thus, as the number of firms increases, coordination becomes more difficult and the possibility of the complete coordination failure becomes more likely. Matters are substantially more difficult if firms are asymmetric. A natural conjecture is that the complete coordination failure will be more likely; however, our numerical results suggest that this need not be so. In particular, there are cases in which $\gamma_i > \pi_i/2$ for one player, but a monotone equilibrium still exists. Analytically characterizing equilibrium behavior has proven to be quite difficult.

Our experiment set out to test the main predictions of our model to highlight the practical role of information structure (i.e., common versus private information) and communication. Somewhat surprisingly, we found that average profits were not consistently higher in our CI games than in our PI games and were sometimes worse. This suggests two things. First, it suggests that the continuum of equilibria inherent in the CI games makes coordination on any equilibrium, let alone the efficient one, a challenge. Second, subjects in our PI games may not have fully appreciated exactly how different their information could be from their match's, which may explain why we did not observe the complete coordination failure in the PI(10, 6) game. Although average profits were not consistently higher in our CI games, subjects were always better aligned in the CI games, which is consistent with our theoretical prediction.

Our results also showed the beneficial effects of both truthful information sharing and preplay communication. Indeed, average profits were between 1%

and 16% higher in the PI-MS treatment than in the CI and PI treatments overall and were even more so when receiving a truthful message. Along with the increase in profits, alignment was generally improved in the CI-2S and PI-MS treatments relative to the CI and PI treatments. Similarly, alignment was best in the PI-MS treatment when subjects received truthful messages from their match.

A surprise to us was that the PI-MS treatment outperformed the CI-2S treatment in terms of average profits. We believe that this is because the act of communicating—not necessarily truthful—information can also be an opportunity to signal possible plans. In other words, when one player sends a message about his or her forecast of demand to the other player, this message has information about his or her plans as well. In contrast, in the CI-2S treatment, even though information is more precise, subjects cannot tell whether they are "on the same page" with their match, making it more difficult to coordinate on the optimal capacity choice.

There are a number of promising avenues for future research. First, there are many environments in which it may be natural that one firm chooses its capacity first and the other firm observes this before making its capacity choice. One advantage of this is that it may eliminate the complete coordination failure when γ is high. However, this is by no means guaranteed. The sequential game is a signaling game with two-sided incomplete information in which the first mover can send a *costly* signal (i.e., its capacity) about its private information to the second mover. Such games are quite difficult to analyze, but we can be sure that any equilibrium will be inefficient for two reasons: First, information transmission is only one way and, second, to ensure that the first mover does not deviate from the equilibrium, the first mover must choose a higher than optimal capacity.

From an experimental perspective, there is also more that could be done. We did not look for specific biases in decision making that have been noted in the existing literature on experimental newsvendor games. Such an analysis may be fruitful because our experimental methodology differs from the existing literature. It would also be interesting to play the PI-MS game where the distribution of signals has infinite support. Although the truthful equilibrium still exists, there may be behavioral differences because now subjects can never be sure that they received a false message. The results of our follow-up experiment, in which subjects could send messages about their signals as well as a recommended capacity, suggest that recommendations improve profits modestly and alignment substantially. A deeper analysis of mechanisms for enhanced communication may yield further insights.

One also wonders whether repeated interactions could improve coordination to the point where the perfect information setting outperforms the setting with preplay communication. If so, then this would suggest that long term relations would be better at achieving coordination than imperfect information sharing. In a follow-up study (Hyndman et al. 2012), we actually show that repeated interaction is a two-edged sword: for some groups profits improve substantially relative to the one-shot setting we analyze here, whereas other groups get stuck choosing too-low capacities.

One important insight from this study is the following. Not surprisingly, information sharing leads to better alignment and higher profits. What is surprising is that this is true whether there is truthful information sharing or cheap-talk communication in which firms may lie about their private information. Thus, our results suggest that instead of sharing actual sales and other information that could be used to come up with a common forecast (e.g., point-of-sale data), companies should directly share their own forecasts. Moreover, despite the fact that complaints about "exaggerated" forecasts can be common among practitioners, companies should not be too concerned about people not being perfectly honest in these shared forecasts (within certain limits). What our experiment teaches us is that communication, despite the potential for lying, may be more valuable than information. In our view, this is because communication gives players the opportunity to implicitly signal their intended course of action, which has value above and beyond any information about demand contained in the message. Moreover, communication is a much less costly institution to introduce than one that ensures truthful information sharing.

Electronic Companion

An electronic companion and general instructions to this paper are available as part of the online version at http://dx.doi.org/10.1287/msom.1120.0400.

Acknowledgments

The authors thank editor Steve Graves, an associate editor, and two anonymous referees for their valuable comments, which led to a substantially improved final draft. They also thank Elizabeth Pickett, Eric McLester, Drew Goin, Ravi Hanumara, and Robert Reeves for their help running the experiments. The authors also thank participants at the 4th Annual Behavioral Operations Conference and the 2010 POMS Annual Meeting, as well as seminar participants at the University of Texas at Austin and MIT for their valuable comments. Finally, the authors are grateful to Rachel Croson, Karen Donohue, Dorothée Honhon, Özalp Özer, and Sridhar Seshadri for their valuable comments. Financial support for this project was provided by the National Science Foundation [SES-1025044], the Southern Methodist

University, the Zaragoza Logistics Center, and the Harvard Business School.

Appendix. Omitted Proofs

Proof of Proposition 0. Consider first the supplier. Ignoring for a moment the capacity choice of the manufacturer, the derivative of the supplier's expected profit function is given by $\pi_s(1 - F(K_s \mid \theta)) - \gamma$. Notice that if $\theta < \eta(1-2s^*)$, then the derivative is strictly negative for all $K_s \geq 0$. Therefore, for this range of θ, there is a unique best response in which $K_s(\theta) = 0$. On the other hand, for $\theta > \eta(1-2s^*)$, the solution to the first order condition is easily seen to be $K_s^*(\theta) = F^{-1}(s^* \mid \theta)$. Of course, if $K_m < K_s^*(\theta)$, then the supplier prefers to choose capacity K_m. Hence, the best-response function for the supplier is $K_s^*(K_m) = \min\{K_m, F^{-1}(s^* \mid \theta)\}$.

A similar calculation holds for the manufacturer. Thus, the result follows. $\square$

Proof of Proposition 1. We focus on the characterization of the monotone equilibrium. The other results in the proposition are easy to prove and are already discussed in the text.

Consider the problem of the supplier. Denote the manufacturer's capacity-choice rule by $K_m(\theta_m)$ and assume that it is strictly increasing. Fix the signal of the supplier at θ_s and suppose that it contemplates a capacity of k. We know that there exists a critical value of the signal received by the manufacturer, $\underline{\theta}(k)$, such that if $\theta_m > \underline{\theta}(k)$, then $K_m(\theta_m) > k$. Because the manufacturer's capacity rule is strictly increasing, we know that $\underline{\theta}(k) = K_m^{-1}(k)$. Therefore, the supplier's capacity choice k will determine total capacity whenever $x \geq k$ *and* $\theta_m \geq K_m^{-1}(k)$.

It can be shown that the derivative of the profit function for the supplier, given signal θ_s and contemplating a capacity choice of $k \in [0, \theta_s + \eta]$, is given by

$$\frac{\partial \bar{\Pi}_s}{\partial k} = \frac{\pi}{4\eta^2} \int_{\max\{\theta_s - \eta,\, k\}}^{\theta_s + \eta} \int_{\max\{x-\eta,\, K_m^{-1}(k)\}}^{x+\eta} dy\, dx - \gamma. \tag{1}$$

We may now impose the symmetric equilibrium condition $K_m(\theta) = K_s(\theta) \equiv K(\theta)$. This implies that we may replace $K_m^{-1}(k)$ with θ_s in the lower limit of the inner integral. Furthermore, it is apparent that $\theta_s \geq x - \eta$ for all $x \in [\theta_s - \eta, \theta_s + \eta]$. Therefore, the lower limit of the inner integral must, in fact, be θ_s.

We first show that there exists $\underline{\theta}$ such that for $\theta_s \leq \underline{\theta}$, $K_s(\theta_s) = 0$. Indeed, $\underline{\theta}$ is the solution to

$$\frac{\pi}{4\eta^2} \int_0^{\underline{\theta}+\eta} \int_{\underline{\theta}}^{x+\eta} dy\, dx - \gamma = 0,$$

which, upon solving, yields $\underline{\theta} = \eta - 2\eta\sqrt{1 - 2\gamma/\pi}$.

We now solve for the equilibrium capacity-choice functions for the supplier and manufacturer for $\theta > \underline{\theta}$. This amounts to setting (1) equal to zero and solving for k. Upon doing so, we find that

$$K(\theta) = \theta - \eta + 2\eta\sqrt{1 - \frac{2\gamma}{\pi}}.$$

Observe, however, that if $\gamma > \pi/2$, then the term inside the square root will be negative. In fact, this gives the condition, under which a symmetric equilibrium in monotone strategies can be said to exist. To see this more clearly, observe that (1) evaluates to

$$\frac{\partial \bar{\Pi}_s}{\partial k} = -\gamma + \frac{\pi}{8\eta^2}[k^2 - 3\eta^2 + 2k(\eta - \theta) - 2\eta\theta + \theta^2].$$

Upon noting that the derivative of (1) with respect to k over the interval $[\theta - \eta, \theta + \eta]$ is negative (i.e., the profit function is concave) and evaluating the above expression at $k = \theta - \eta$, we see that $\partial \bar{\Pi}_s / \partial k = (1/2)(\pi - 2\gamma)$, which is negative for $\gamma > \pi/2$.

Therefore, if $\gamma > \pi/2$, the firms will lower their capacities to at least $\theta - \eta$. In fact, they will set $K(\theta) = 0$. To see this, observe that if $k < \theta - \eta$, then (1) also simplifies to $\partial \bar{\Pi}_s / \partial k = (1/2)(\pi - 2\gamma) < 0$. $\square$

Proof of Proposition 2. The first part follows from Proposition 0 upon updating the firms' beliefs about demand. To prove that expected profits are higher, it suffices to show that the expected profits of the CI-2S game are higher than the CI game. To that end, we study the profits of a firm in the CI game that has received a signal, θ_1 and then consider the effect of adding a second signal, θ_2 (where we take expectations over the possible realizations of θ_2, given θ_1). For ease of notation, let $s = (\pi - \gamma)/\pi$.

If demand is distributed uniformly on $[a, b]$ $(0 < a < b < \infty)$, then expected profits in the Pareto efficient equilibrium are given by $0.5(\pi - \gamma)[sb + (1-s)a + a]$. Therefore, given a signal of θ_1, expected profits are

$$\mathbb{E}(\pi^{\text{CI}} \mid \theta_1) = 0.5(\pi - \gamma)[s(\theta_1 + \eta) + (1-s)(\theta_1 - \eta) + \theta_1 - \eta].$$

On the other hand, expected profits from adding another signal are

$$\mathbb{E}(\pi^{\text{CI-2S}} \mid \theta_1) = \frac{\pi - \gamma}{8\eta^2} \int_{\theta_1 - \eta}^{\theta_1 + \eta} \int_{x-\eta}^{x+\eta} [s(\min\{\theta_1, \theta_2\} + \eta) + (1-s) \cdot (\max\{\theta_1, \theta_2\} - \eta) + \max\{\theta_1, \theta_2\} - \eta]\, d\theta_2\, dx.$$

With a little algebra, one can see that

$$\mathbb{E}(\pi^{\text{CI-2S}} \mid \theta_1) - \mathbb{E}(\pi^{\text{CI}} \mid \theta_1) = \frac{\pi - \gamma}{8\eta^2} \int_{\theta_1 - \eta}^{\theta_1 + \eta} \int_{x-\eta}^{x+\eta} [2(\max\{\theta_1, \theta_2\} - \theta_1) + s(\min\{\theta_1, \theta_2\} - \max\{\theta_1, \theta_2\})]\, d\theta_2\, dx.$$

By symmetry and because $s < 1$, one can see that this difference is strictly positive. $\square$

Proof of Proposition 3. This is a dynamic game of two-sided incomplete information; therefore, the appropriate equilibrium concept is that of perfect Bayesian equilibrium (PBE). A PBE must specify a strategy for each player as well as a set of beliefs about the "type" of their opponent (i.e., the signal received). Moreover, the prescribed actions must be optimal given one's beliefs and, where possible, beliefs should be updated according to Bayes rule. Off the equilibrium path, beliefs are unrestricted. Let M_i denote firm i's message. Define the beliefs of firm j, upon receiving message M_i as follows:

$$\hat{\theta}_i = \begin{cases} M_i & \text{if } |\theta_j - M_i| \leq 2\eta, \\ \underline{\theta} & \text{otherwise.} \end{cases}$$

where $\underline{\theta}$ is sufficiently small such that the optimal capacity is to choose 0 (see Remark 5).

First, suppose that firm i has sent the message $M_i = \theta_i$ and received a message M_j such that $|\theta_j - M_i| \le 2\eta$. Given i's beliefs about the message from firm j and also the capacity-choice rule by j, clearly it is optimal for firm i to choose $K_i = K^{\text{CI-2s}}(\theta_i, M_j)$. Next suppose that firm i has sent the message $M_i = \theta_i$ and received a message M_j such that $|\theta_j - M_i| > 2\eta$. Given the beliefs that we defined above, it is clearly optimal for firm i to choose a capacity of 0 in this *off the equilibrium path* event.

Now suppose that firm i reports $M_i > \theta_i$. Then one of two things will happen. First, it may be that $|M_i - \theta_j| \le 2\eta$, in which case firm j will choose $K_j > K^{\text{CI-2s}}(\theta_i, \theta_j)$; however, firm i will still find it optimal to choose $K_i = K^{\text{CI-2s}}(\theta_i, M_j)$. Second, it may be that $|M_i - \theta_j| > 2\eta$, in which $K_j = 0$. Firm i, upon receiving firm j's message, will be able to deduce that $|M_i - \theta_j| > 2\eta$ and so will also choose $K_i = 0$, which means that firm i will earn a payoff of 0. Therefore, it is better for firm i to report $M_i = \theta_i$.

Finally, suppose that firm i reports $M_i < \theta_i$. Then, with probability 1, player j will choose capacity strictly less that $K^{\text{CI-2s}}(\theta_i, \theta_j)$, in which case firm i will earn profits strictly less than the Pareto optimal equilibrium payoff. Therefore, it is better for firm i to report $M_i = \theta_i$. □

Remark 5. Note that observing a message, M_i, such that $|\theta_j - M_i| > 2\eta$ is a probability 0 event in the prescribed equilibrium. Therefore, we have complete freedom to specify the beliefs of player j. We chose the most pessimistic beliefs because it makes things especially stark. Other beliefs would generate the same result. The reason is that even if firm i can get firm j to choose $K_j > K^{\text{CI-2s}}(\theta_i, \theta_j)$, firm i will still produce exactly $K^{\text{CI-2s}}(\theta_i, \theta_j)$; therefore, firm i never benefits from lying. Moreover, the same result would hold even if signals had an infinite support. In this case, one could never know with certainty that a message is untruthful and so any message is on the equilibrium path. Even if player j believes that $\hat{\theta}_i = M_i$ with certainty, then i strictly prefers to report $M_i = \theta_i$ rather than $M_i' < \theta_i$ and is indifferent between $M_i = \theta_i$ and $M_i'' > \theta_i$.

References

Andreoni J, Harbaugh W, Vesterlund L (2003) The carrot or the stick: Rewards, punishments and cooperation. *Amer. Econom. Rev.* 93(3):893–902.

Aviv Y (2001) The effect of collaborative forecasting on supply chain performance. *Management Sci.* 47(10):1326–1343.

Bendoly E, Donohue K, Schultz KL (2006) Behavior in operations management: Assessing recent findings and revisiting old assumptions. *J. Oper. Management* 24(6):737–752.

Cachon GP (2003) Supply chain coordnation with contracts. Graves SC, de Kok AG, eds. *Supply Chain Management: Design, Coordination and Operation*, Handbooks in Operations Research and Management Science, Vol. 11 (Elsevier, Amsterdam), 227–339.

Cachon GP, Fisher M (2000) Supply chain inventory management and the value of shared information. *Management Sci.* 46(8):1032–1048.

Cachon GP, Lariviere M (2001) Contracting to assure supply: How to share demand forecasts in a supply chain. *Management Sci.* 47(5):629–646.

Celikbas M, Shanthikumar JG, Swaminathan JM (1999) Coordinating production quantities and demand forecasts through penalty schemes. *IEE Trans.* 31(3):851–864.

Chao X, Seshadri S, Pinedo M (2008) Optimal capacity in a coordinated supply chain. *Naval Res. Logist.* 55(2):130–141.

Chen F (2005) Salesforce incentives, market information and production/inventory planning. *Management Sci.* 51(1):60–75.

Crawford VP, Sobel J (1982) Strategic information transmission. *Econometrica* 50(6):1431–1451.

Fehr E, Gächter S (2000) Cooperation and punishment in public goods experiments. *Amer. Econom. Rev.* 90(4):980–994.

Fischbacher U (2007) z-tree: Zurich toolbox for ready-made economic experiments. *Experiment. Econom.* 10(2):171–178.

Gonik J (1978) Tie salesmen's bonuses to their forecasts. *Harvard Bus. Rev.* 56(3):116–123.

Hendricks KB, Singhal VR (2005) Association between supply chain glitches and operating performance. *Management Sci.* 51(5):695–711.

Hyndman K, Kraiselburd S, Watson N (2012) Coordination in games with complementarities: An experiment on fixed vs. random matching. *Production Oper. Management*. Available at http://onlinelibrary.wiley.com/doi/10.1111/j.1937-5956.2012.01384.x/abstract.

Jain A, Seshadri S, Sohoni M (2011) Differential pricing for information sharing under competition. *Production Oper. Management* 20(2):235–252.

Kurtulus M, Toktay B (2007) Investing in forecast collaboration. Working paper, Vanderbilt University, Nashville, TN.

Lal R, Staelin R (1986) Salesforce compensation plans in environments with asymmetric information. *Marketing Sci.* 5(3):179–198.

Lariviere M (2002) Inducing forecast revelation through restricted returns. Working paper, Northwestern University, Evanston, IL.

Lee HL, Whang S (1999) Decentralized multi-echelon supply chains: Incentives and information. *Management Sci.* 45(5):633–640.

Li L (2002) Information sharing in a supply chain with horizontal competition. *Management Sci.* 48(9):1196–1212.

Li L, Zhang H (2008) Confidentiality and information sharing in supply chain coordination. *Management Sci.* 54(8):1759–1773.

Li Q, Atkins D (2002) Coordinating replenishment and pricing in a firm. *Manufacturing Service Oper. Management* 4(4):241–257.

Lunsford JL (2007) Boeing scrambles to repair problems with new plane. *Wall Street Journal* (December 7), http://online.wsj.com/article/SB119698754167616531.html.

Miyaoka J (2003) Implementing collaborative forecasting through buyback contracts. Working paper, Stanford University, Stanford, CA.

Oliva R, Watson N (2011) Cross-functional alignment in supply chain planning: A case study of sales and operations planning. *J. Oper. Management* 29(5):434–448.

Özer Ö, Wei W (2006) Strategic commitment for optimal capacity decision under asymmetric forecast information. *Management Sci.* 52(8):1238–1257.

Özer Ö, Zheng Y, Chen K-Y (2011) Trust in forecast information sharing. *Management Sci.* 57(6):1111–1137.

Porteus EL, Whang S (1991) On manufacturing marketing incentives. *Management Sci.* 37(9):1166–1181.

Schweitzer ME, Cachon GP (2000) Decision bias in the newsvendor problem with a known demand distribution: Experimental evidence. *Management Sci.* 46(3):404–420.

Shapiro BP (1977) Can marketing and manufacturing co-exist? *Harvard Bus. Rev.* 55(5):104–114.

Szkup M, Trevino I (2011) Costly information acquisition in a speculative attack: Theory and experiments. Working paper, New York University, New York.

Tomlin B (2003) Capacity investments in supply chains: Sharing the gain rather than sharing the pain. *Manufacturing Service Oper. Management* 5(4):317–333.

van Huyck J, Battalio R, Beil R (1990) Tacit coordination games, strategic uncertainty and coordination failure. *Amer. Econom. Rev.* 80(1):234–248.

Wang Y, Gerchak Y (2003) Capacity games in assembly systems with uncertain demand. *Manufacturing Service Oper. Management* 5(3):252–267.