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

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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 in which firms earn positive profits. The former equilibrium always exists, while the latter exists only when the marginal cost of capacity is sufficiently low. We also show that both truthful information sharing and pre-play 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 pre-play communication may be more effective at increasing profits than truthful information sharing. Finally, we document that "honesty is the best policy" when it comes to communicating private information.

Key words: Communication, Coordination, Supply Chains

1. Introduction

There is an extensive literature in operations management that studies coordination either 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, in this literature the main approach to addressing coordination has been aligning economic incentives. However, changing incentives within or between organizations 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. Alignment of decisions represents a more achievable goal within and across organizations given the behavioral realities. In practice, organizations do, among other things, 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 non-trivial 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 in order to meet demand. Sales are equal to the minimum of the two firms' capacities and realized demand. In this setup, if one firm plans for a given capacity to meet their perceived demand, the other firm would prefer not to invest in any more capacity, since 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, firms are engaged in a game with 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, meaning that 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) and Wang and Gerchak (2003), 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.

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) discuss 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, Lunsford (2007) notes that, "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 have outlined above: each supplier must choose its capacity without knowing the capacity choice of the other suppliers.

Another main assumption is that the firms may have private information about demand. While there are undoubtedly many small parts providers in the aerospace industry, there are very few engine suppliers (General Electric, Pratt & 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) 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 trepidation about increasing capacity was due, in part, to their 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 so-called "glitches" — cases where demand exceeds supply. Their analysis shows that when a reason for insufficient capacity to meet demand is cited, the most common reason is parts shortages (by a factor of 2 to 1). When the announcements explicitly assign responsibility to these glitches suppliers are the second most-named, after internal reasons. This evidence suggests that cases of mismatched capacities between firms and its suppliers may be commonplace in industry.

Our theoretical analysis shows us 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 sub-optimal 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, since firms receive independent signals, capacities are necessarily misaligned.

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. Since such institutions may be impossible or prohibitively costly, we also consider a game in which pre-play communication between players is allowed. Here we show a surprising result; namely, firms may be able to achieve the same benefits through pre-play communication only. 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. Thus, costly mechanisms to induce truthfulness may not be necessary.

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 pre-play 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, while 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 in order 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: while 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. While subjects under-adjust when it is high, they over-adjust 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, while 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 great misalignment.

The paper proceeds as follows. Section 2 reviews the relevant literature. Section 3 describes the model, Section 4 contains our theoretical results and Section 5 discusses our experimental design. Section 6 discusses the results of our CI and PI treatments, while Section 7 examines the results of our CI-2S and PI-MS treatments. Finally, Section 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) and 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 *intra*-firm 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 *inter*-firm 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. (2009) 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). The paper that is closest to our work is Özer et al. (2011). They study one-way communication in a standard newsvendor experiment, while 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 manufacturing, m, and to the other firm as sales, s. Manufacturing supplies sales with a product that sales 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 manufacturing and $\pi_s > 0$ for sales. 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 $[\theta_i - \eta, \theta_i + \eta]$, while firm i's 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 signals, then it believes that the other firm likely received a higher signal as well.

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

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

Recall that the two firms simultaneously choose capacity, $K_i \geq 0$ to maximize their expected profits. Define $s^* = \frac{\pi_s - \gamma}{\pi_s}$ and $m^* = \frac{\pi_m - \gamma}{\pi_m}$, where s^* and m^* are the traditional newsvendor critical fractiles for sales and manufacturing. Suppose, without loss of generality that $s^* \leq m^*$. Then we have:

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 $K_i(\theta) = F^{-1}(s^*|\theta)$ for $i \in \{m, s\}$.*

Proof See 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 since they reduce the perceived complexity of the game. Beyond that, monotone strategies are quite robust. For example, if firm j uses a monotone strategy, it will generally be a best response for firm i to play a monotone strategy as well. The intuition is straightforward. If firm i's signal increases slightly, then its expectation of demand increases, as does its belief about firm j's signal. Since 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 as well.

In general, the expected profit function of firm i is:

$$\bar{\Pi}_i(\theta_i, K_i, K_j(\cdot)) = \pi_i \int_{\theta_i-\eta}^{\theta_i+\eta} \left[\int_{x-\eta}^{x+\eta} \min\{x, K_i, K_j(\theta_j)\} g_i(\theta_j|x) d\theta_j \right] f(x|\theta_i) dx - \gamma K_i$$

$$= \frac{\pi_i}{4\eta^2} \int_{\theta_i-\eta}^{\theta_i+\eta} \int_{x-\eta}^{x+\eta} \min\{x, K_i, K_j(\theta_j)\} d\theta_j dx - \gamma K_i,$$

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 $g_i(\theta_j|x)$ and $f(x|\theta_i)$ 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 $K(\theta) = 0$ for all θ. If $\gamma > \bar{\gamma} \equiv \frac{\pi}{2}$, 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:*

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

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

Proof See 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 $\gamma > \frac{\pi}{2}$ is also not difficult. In equilibrium, each firm expects that the other firm will have a lower signal than them half of the time. Since 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 $\gamma > \frac{\pi}{2}$ since 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 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 that 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. Then we have:

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

Proof This follows from Proposition 0 upon updating the firms' beliefs about demand. □

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 pre-play (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.

While "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 Appendix. □

The intuition for this result is as follows. Since 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, since 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 possibly have received such a signal. Since the appropriate equilibrium concept for this game is Perfect Bayesian Equilibrium, we are required to specify beliefs for firm j; however, since 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 0), 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. For the reader who finds such beliefs unrealistic, as part of our proof, we show that any beliefs, combined with a consistent best response, also support the truth-telling equilibrium.

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. Since $\hat{K}(\theta_i, \theta_j) < K^{\text{CI-2S}}(\theta_i, \theta_j)$, 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 $(\pi - \gamma)(\hat{K}(\theta_i + \Delta, \theta_j) - \hat{K}(\theta_i, \theta_j))$. 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 that the change in profits is approximately $(\pi - \gamma)\frac{\hat{K}(\theta_i, \theta_j)}{\partial \theta_i} > 0$. 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 contains 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 the more closely aligned are players' preferences, 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 Özer et al. (2011)'s result that all equilibria are uninformative in their model of one-way communication from a manufacturer to a supplier in a newsvendor setting.

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 to understand to what extent does information sharing improve profits and alignment, and is pre-play communication 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. $d^{\text{PI}} = |K_1(\theta_1) - K_2(\theta_2)| > |K_1(\theta) - K_2(\theta)| = d^{\text{CI}}$, *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, since 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 pre-play communication should lead to equivalent outcomes. That is,

Hypothesis 3. *Behaviour 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

264 subjects, recruited from undergraduate classes, participated in our experiments which were run at the experimental economics laboratory of a public university in the United States. In each session, after subjects read the instructions, they were read aloud by an experimental administrator. Sessions lasted for 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 in order to minimize any interpersonal influences.

The basic structure of each treatment was as follows. First, the prior distribution of demand was uniform with support $[\underline{x}, \overline{x}]$, where $\underline{x} > 0$. While 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 are 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 4 information treatments: (i) the common information game (CI), 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), and for each of these information treatments, we had 3 different sets of parameters, where $\underline{x}$, $\overline{x}$, 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 re-matched 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.

5.1. Details of Each Treatment

Table 1 summarizes the details of our experiment. A sample of the instructions used can be found in the supplemental notes. 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).

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

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, while 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 $[\underline{x} - \eta, \overline{x} + \eta]$, 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.

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.

Table 2 Summary statistics

(a) Distribution of Demand: $U(20,50)$; $\pi = 5$; $\gamma = 2$

Treatment	Payoff	Std. Dev.	Min	Max	Gap (%)†	t−test
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: $U(100,400)$; $\pi = 10$; $\gamma = 3$

Treatment	Payoff	Std. Dev.	Min	Max	Gap (%)†	t−test
CI	1649.4	104.0	1328.1	1818.1	3.0	$t_{46} = 1.60$
PI	1594.9	130.2	1331.6	1866.9	4.6	$p = 0.12$

(c) Distribution of Demand: $U(100,400)$; $\pi = 10$; $\gamma = 6$

Treatment	Payoff	Std. Dev.	Min	Max	Gap (%)†	t−test
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	$p = 0.08$

† Calculated as the percentage difference from the 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.

We highlight two results. First, the evidence in favor of Hypothesis 1 is mixed. In only one case (CI$(5,2)$ vs. 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 higher in the PI game, which is doubly surprising since 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, while 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 these data.

Table 3 The extent of misalignment ($\bar{d}$)

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

Standard deviations reported below, in parentheses.

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, behaviourally, there is more scope for misalignment in the former game where $K(\theta)=\theta+10$ for $\theta \in [125,375]$, while in the latter game, $K(\theta)=\theta-5$ for $\theta \in [125,375]$. Hence, there are "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 piece-wise continuous with kinks at $\underline{x}+\eta$ and $\overline{x}-\eta$. Furthermore, on the interval $[\underline{x}+\eta, \overline{x}-\eta]$, the slope of the capacity choice functions should be 1. We estimate the following equation via a random-effects Tobit procedure:

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

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 favour of a kink at $\theta=\underline{x}+\eta$ and $\theta=\overline{x}-\eta$, though the magnitude and significance is not consistent across treatments or parameter values. Thus, especially for high signals, subjects are more cautious than

Table 4 Random-effects Tobit regressions of choice on estimate

	Demand $\sim U[20,50]$ $\pi=5$; $\gamma=2$		Demand $\sim U[100,400]$ $\pi=10$; $\gamma=3$		Demand $\sim U[100,400]$ $\pi=10$; $\gamma=6$	
	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]
$[\theta>\overline{x}-\eta](\theta-(\overline{x}-\eta))$	-0.116	-0.470***	-0.279	-0.167	0.00269	-0.173
	[0.153]	[0.176]	[0.180]	[0.175]	[0.0948]	[0.123]
cons	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
LL	-1646	-1469	-4516	-4414	-3484	-3365

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

theory predicts. This could be due to risk aversion or, especially in the CI treatments, difficulty in coordinating on the efficient equilibrium due to 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 which 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 are affected by lagged variables in order 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 analyse subject behaviour 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 in Table 5 by reporting summary statistics on average earnings. 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.

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

(a) Distribution of Demand: $U(20, 50)$; $\pi = 5$; $\gamma = 2$

Treatment	Payoff	Std. Dev.	Min	Max	Gap (%)[†]	Hypothesis Test[‡] CI	PI
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: $U(100, 400)$; $\pi = 10$; $\gamma = 3$

Treatment	Payoff	Std. Dev.	Min	Max	Gap (%)[†]	Hypothesis Test[‡] CI	PI
CI-2S	1605.5	68.5	1451.0	1723.6	5.1	0.95[♯]	0.37
PI-MS	1668.5	107.2	1474.2	1853.6	1.4	0.27	0.02

(c) Distribution of Demand: $U(100, 400)$; $\pi = 10$; $\gamma = 6$

Treatment	Payoff	Std. Dev.	Min	Max	Gap (%)[†]	Hypothesis Test[‡] CI	PI
CI-2S	843.7	80.8	648.0	973.3	11.7	0.18	0.72[♯]
PI-MS	891.5	57.4	782.1	1001.3	6.7	$\ll 0.01$	0.03

[†] 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.
[‡] 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.
[♯] Profits are **lower** in the CI-2S treatment, significantly so for CI-2S$(10, 3)$,

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 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 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).

Table 6 **The extent of misalignment ($\bar{d}$)**

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 $\sim U[20,50]$; $\pi=5$; $\gamma=2$	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 $\sim U[100,400]$; $\pi=10$; $\gamma=3$	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 $\sim U[100,400]$; $\pi=10$; $\gamma=6$	19.61 (6.9)	18.79 (4.4)	13.77 (4.4)	23.46 (4.9)	$\ll 0.01^\sharp$	$\ll 0.01^\sharp$	0.04	0.01

Standard deviations reported below, in parentheses.
$^\sharp$ Observe that the yellow-shaded 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.

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 were greater than one's signal, while messages were truthful approximately 25% of the time. Somewhat puzzling is the fact 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.

Table 7 **The truthfulness of signals**

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

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, while 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 $M_i < \theta_i$ (resp. $M_i > \theta_i$) was 32.6% (resp. 42.9%), while over the last five periods the same frequency was 19.7% (resp. 54.4%). There is no detectable trend in the frequency of honest messages.

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/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, while 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 since 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).

Table 8 Random-effects Tobit regressions of capacity choice (pi-ms treatment)

	Demand $\sim U[20, 50]$ $\pi = 5$; $\gamma = 2$			Demand $\sim U[100, 400]$ $\pi = 10$; $\gamma = 3$			Demand $\sim U[100, 400]$ $\pi = 10$; $\gamma = 6$		
	(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 rec'd	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]
cons	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
LL	-1656	-1633	-1654	-4107	-4013	-4094	-3878	-3860	-3876

Standard errors (at subject level) in brackets. *** significant at 1%; ** significant at 5%; * significant at 10%.

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, one's own choice is 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. 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 a 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 pre-play 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% and (3) the frequency of truthful messages and the overall correlation between messages and signals increased (but neither were significant). Finally, and in support of our conjecture that communication allows subjects to signal their choice, when subjects are explicitly given the opportunity to recommend a capacity choice, the relationship between one's final capacity and the message that they sent declines substantially relative to the PI-MS treatment. 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 has on profits and on 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.

Table 9 The consequences of lying: Average profits & misalignment given the message received

(a) Average Profits

	CI-2S		PI-MS		PI-MS		PI-MS
			$\theta_j = M_j$		$\theta_j \neq M_j$ & $\lvert M_j - \theta_i \rvert \leq 2\eta$		$\theta_j \neq M_j$ & $\lvert M_j - \theta_i \rvert > 2\eta$
Dem. $\sim U[20,50]$; $\pi = 5$; $\gamma = 2$	90.2	$\underset{0.57}{=}$	91.6	$\underset{0.86}{=}$	92.1	$\underset{\ll 0.01}{>}$	73.0
Dem. $\sim U[100,400]$; $\pi = 10$; $\gamma = 3$	1605.5	$\underset{0.04}{<}$	1691.4	$\underset{0.82}{=}$	1681.2	$\underset{0.06}{>}$	1537.6
Dem. $\sim U[100,400]$; $\pi = 10$; $\gamma = 6$	843.7	$\underset{\ll 0.01}{<}$	947.3	$\underset{0.09}{>}$	890.3	$\underset{0.03}{>}$	746.4

(b) Average Misalignment

	CI-2S		PI-MS		PI-MS		PI-MS
			$\theta_j = M_j$		$\theta_j \neq M_j$ & $\lvert M_j - \theta_i \rvert \leq 2\eta$		$\theta_j \neq M_j$ & $\lvert M_j - \theta_i \rvert > 2\eta$
Dem. $\sim U[20,50]$; $\pi = 5$; $\gamma = 2$	3.29	$\underset{0.62}{=}$	3.08	$\underset{0.94}{=}$	3.11	$\underset{\ll 0.01}{<}$	5.99
Dem. $\sim U[100,400]$; $\pi = 10$; $\gamma = 3$	13.46	$\underset{0.29}{=}$	15.62	$\underset{0.59}{=}$	16.97	$\underset{\ll 0.01}{<}$	51.69
Dem. $\sim U[100,400]$; $\pi = 10$; $\gamma = 6$	19.61	$\underset{0.41}{=}$	17.19	$\underset{0.95}{=}$	17.36	$\underset{\ll 0.01}{<}$	37.01

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

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 behaviour vis-à-vis the CI and PI treatments, we omitted some results which 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, 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 subjects 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 which 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 pre-play 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 which guarantee truthful information sharing between firms.

Although our model was restricted to two symmetric firms, it is straight-forward 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 in order to highlight the practical role of information structure (*i.e.,* common vs. 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 pre-play 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 the fact 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 since 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 pre-play 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, 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, while 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.,* POS 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 which ensures truthful information sharing.

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Appendix. Omitted Proofs

Proof of Proposition 0. Consider first the sales firm. Ignoring for a moment the capacity choice of manufacturing, the derivative of sales' expected profit function is given by $\pi_s(1-F(K_s|\theta))-\gamma$. 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 $K_s^*(\theta)=F^{-1}(s^*|\theta)$. Of course, if $K_m<K_s^*(\theta)$, then sales prefers to choose capacity K_m. Hence, the best-response function for sales is $K_s^*(K_m)=\min\{K_m,F^{-1}(s^*|\theta)\}$.

A similar calculation holds for the manufacturing firm. Thus the result follows. Q.E.D.

Proof of Proposition 1. We focus on the characterisation 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 sales firm. Denote manufacturing's capacity choice rule by $K_m(\theta_m)$ and assume that it is strictly increasing. Fix the signal of sales 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 manufacturing, $\underline{\theta}(k)$, such that if $\theta_m>\underline{\theta}(k)$, then $K_m(\theta_m)>k$. Since manufacturing's capacity rule is strictly increasing, we know that $\underline{\theta}(k)=K_m^{-1}(k)$. Therefore, sales' 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 sales, given signal θ_s and contemplating a capacity choice of $k\in[0,\theta_s+\eta]$, is given by:

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

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:

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

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

We now solve for the equilibrium capacity choice functions for sales and manufacturing 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 $\gamma>\frac{\pi}{2}$, 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:

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

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 $\frac{\partial\bar{\Pi}_s}{\partial k}=\frac{1}{2}(\pi-2\gamma)$, which is negative for $\gamma>\frac{\pi}{2}$.

Therefore, if $\gamma>\frac{\pi}{2}$, 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 $\partial\bar{\Pi}_s/\partial k=\frac{1}{2}(\pi-2\gamma)<0$. Q.E.D.

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:

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

where $\underline{\theta}$ is sufficiently small such that the optimal capacity is to choose 0 (see Remark 3).

First, suppose that firm i has sent the message $M_i = \theta_i$ and received a message M_j such that $|\theta_j - M_i| \leq 2\eta$. 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 $|M_i - \theta_j| \leq 2\eta$, 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 $M_i = \theta_i$. Q.E.D.

Remark 3. 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 $M_i'' > \theta_i$.

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

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1. Alternative Assumptions on Noise

Recall that in Section 4 we assumed that demand, x, was uniformly distributed over $\mathbb{R}$ and that firms received a signal $\theta_i = x + \epsilon_i$, where ϵ_i was uniformly distributed over $[-\eta, \eta]$. In this section, we continue to assume that demand is uniformly distributed $\mathbb{R}$ but now assume that $\epsilon_i \sim N(0, \sigma^2)$. Then, given a signal θ_i, firm i believes that demand is normally distributed with mean θ_i and variance σ^2. Denote the distribution and density of firm beliefs given signal θ by $F_{x|\theta}$ and $f_{x|\theta}$, respectively.

We look for an equilibrium in monotone strategies. That is, each firm i's capacity choice is given by a function $K_i(\theta_i)$, which is strictly increasing in θ_i. Given this, we can write the expected profits of the sales firm who received a signal θ and is considering a capacity choice $k \geq 0$ as:

$$\Pi(\theta, k|K_m(\cdot)) = -\gamma k + \pi \int_{-\infty}^{\infty} \left[\int_{-\infty}^{\infty} \min\{K_m(\theta_m), k, x\} f_{\theta_m|x}(\theta_m|x) d\theta_m \right] f_{x|\theta}(x|\theta) dx,$$

where $f_{\theta_m|x}(\theta_m|x)$ is the density, conditional on demand, of possible signals of the manufacturing firm, and has a normal distribution with mean x and standard deviation σ.

We first show that there are signal realisations low enough such that it is a dominant strategy to choose a capacity of zero. To see this, suppose that $K_m(\theta_m) \geq 0$ for all $\theta_m \in \mathbb{R}$ and sales is contemplating a capacity of $k = 0$. This implies that for all possible signal realisations for the manufacturing firm, sales' choice of 0 will be at or below that of manufacturing. Therefore, it is not difficult to see that the derivative of sales' expected profit function evaluated at $k = 0$ is given by:

$$\frac{\partial \Pi_s}{\partial k}|_{k=0} < -\gamma + \pi \int_{0}^{\infty} f_{x|\theta}(x|\theta) dx,$$

which will be strictly less than zero for θ sufficiently small, since the integral goes to zero as $\theta \to -\infty$. Thus there exists $\underline{\theta}$, such that for all $\theta < \underline{\theta}$, it is a dominant strategy to choose a capacity of 0.

Therefore, we look for a symmetric equilibrium of the following form: Each firm has a capacity choice function given by $K(\theta)$, where, for some θ^*, $K(\theta) = 0$ for all $\theta \leq \theta^*$ and $K'(\theta) > 0$ for all $\theta > \theta^*$.

Let $K_m(\theta_m)$ denote the capacity choice function of manufacturing. We assume that it satisfies the two basic properties outlined above. In this case, the derivative of the expected profit function is given by:

$$\frac{\partial \Pi_s}{\partial k} = -\gamma + \pi \int_k^\infty \int_{\max\{\theta^*, K_m^{-1}(k)\}}^\infty f_{\theta_m|x}(\theta_m|x) f_{x|\theta}(x|\theta) d\theta_m dx.$$

Observe that in a symmetric equilibrium, it must be that $K_m(\theta) = K_s(\theta)$, which means that at the optimal solution to the above equation, we require that $K_m^{-1}(k) = \theta$.

We can actually characterise θ^* fairly easily. In particular, θ^* solves:

$$-\gamma + \pi \int_0^\infty (1 - F_{\theta|x}(\theta^*|\theta^*)) f_{x|\theta}(x|\theta^*) dx = 0.$$

Hence, for $\theta \leq \theta^*$, we have that $K(\theta) = 0$. On the other hand, for $\theta > \theta^*$, it can be shown that:

$$K(\theta) = \theta + \sqrt{2}\sigma \mathrm{Erfc}^{-1}\left(\frac{2\left(\pi - \sqrt{\pi^2 - 2\pi\gamma}\right)}{\pi}\right),$$

where $\mathrm{Erfc}(x) = 1 - \frac{2}{\sqrt{\pi}} \int_0^z e^{-t^2} dt$ and $\mathrm{Erfc}^{-1}(\cdot)$ is the inverse function. Notice that just as with the uniform case, if $\gamma > \frac{\pi}{2}$, then the term inside the square root is negative, which means that we don't have an equilibrium in monotone strategies. This result follows since one can show that: $\int_0^\infty (1 - F_{\theta|x}(\theta|x)) f_{x|\theta}(x|\theta) dx$ is increasing in θ and that the limit as $\theta \to \infty$ is $\frac{1}{2}$. Therefore, if $\gamma > \frac{\pi}{2}$, the derivative of the expected profit function is always negative. This actually shows that not only do we not have an equilibrium in monotone strategies, but also that the unique equilibrium is that of the complete coordination failure.

1.1. Truthful Information Sharing With Normally Distributed Signals

Consider now the CI-2S game with normally distributed signals. Given two signals, θ_1 and θ_2, it is easy to see that the firms' common belief about demand is $N(0.5(\theta_1 + \theta_2), 0.5\sigma^2)$. Thus, the efficient equilibrium corresponds to firms choosing capacity $K^{\text{CI-2S}}(\theta_1, \theta_2) = F^{-1}_{\theta_1,\theta_2}((\pi - \gamma)/\pi)$. It is also not difficult to see that, at the efficient equilibrium, expected profits are given by:

$$\mathbb{E}[\pi^{\text{CI-2S}}(\theta_1, \theta_2)] = \pi \int_{-\infty}^{F^{-1}_{\theta_1,\theta_2}((\pi-\gamma)/\pi)} x f_{\theta_1,\theta_2}(x) dx.$$

On the other hand, the expected profits for firms in the CI game, upon receiving a signal $\hat{\theta} = 0.5(\theta_1 + \theta_2)$ (so that expected demand is identical) is similar:

$$\mathbb{E}[\pi^{\text{CI}}(\hat{\theta})] = \pi \int_{-\infty}^{F^{-1}_{\hat{\theta}}((\pi-\gamma)/\pi)} x f_{\hat{\theta}}(x) dx$$

which is the same expression as for the CI-2S game, but for the fact that the variance is twice as high. To complete the analogy for Proposition 2 from the text, one simply news to note that the above expressions are decreasing in the variance of beliefs. Thus, $\mathbb{E}[\pi^{\text{CI-2S}}(\theta_1, \theta_2)] > \mathbb{E}[\pi^{\text{CI}}(\hat{\theta})]$.

1.2. Cheap-Talk Communication With Normally Distributed Signals

We note here that Proposition 3 continues to hold under the assumption of normally distributed signals. The main difference is that because signals have infinite support, every message is *on the equilibrium path*. That is, upon receiving a message M_i, firm j can **never** know with certainty that firm i lied. However, this does not matter since, as we argued in the main text, so long as firms expect to coordinate on the efficient equilibrium of the post-communication subgame, the firms' interests are perfectly aligned. Moreover, as before, a firm never strictly benefits by inflating its signal and strictly suffer by deflating its signal.

2. Example: Truthful but Inefficient Equilibria May Not Exist

Suppose that there is a truthful equilibrium in which firms' capacity choices are given by $K_i(\theta_\ell, \theta_h) = 0.5[s^*(\theta_\ell + \eta) + (1 - s^*)(\theta_h - \eta)]$. That is, they only choose half of the efficient equilibrium quantities. To further simplify matters, let $\pi = 10$, $\gamma = 3$ and $\eta = 5$. Next suppose that firm 1 sends $M_1 = 20.1 > \theta_1 = 20$. To see whether this represents a profitable deviation, we calculate the expected profits of firm 1, taking into consideration capacities in the next stage, which are given by:

$$K = \begin{cases} 0, & \text{if } |\theta_2 - 20.1| > 10 \\ \frac{1}{2}[\frac{7}{10}(\min\{20.1, \theta_2\} + 5) + \frac{3}{10}(\max\{20.1, \theta_2\} - 5)], & \text{o.w.} \end{cases}.$$

Observe that firm 1 will choose a capacity of 0 if $|\theta_2 - 20.1| > 10$ because, in this case, it is common knowledge that firm 1 lied and that firm 2 will, therefore, choose a capacity of 0. Taking expectations over the set of states and the possible signals of firm 2, the expected profits of firm 1 from inflating its signal by 0.1 are: 74.8352. On the other hand, the expected profits from faithfully reporting its signal are: 74.6643. Therefore, firm 1's deviation is profitable, and so the equilibrium in this example cannot be truthful.

3. Supplemental Data Analysis

3.1. The CP and NCP Treatments

3.1.1. Learning We now discuss whether subjects are able to learn. We focus on two potentially different forms of learning: (i) does alignment improve over time and (ii) do profits increase over time?

Do subjects learn to align their choices? Recall that subjects played the game for 30 or 40 periods with random rematching in each round. In Table S.1 we show the results of a series of random-effects regressions where we regress d_t^j on the round and other control variables. Learning is indicated by a negative coefficient on round, which is generally what we see. Except for the PI(10, 6) game, the coefficient is negative, and is significant at the 1% level in four of five of these games, and at the 10% level in the fifth game. Next, note that learning appears to be stronger in the CI games than in the PI games. If we pool the data across the CI and PI treatments for each of the three parameter values, the coefficient on `round` is significantly smaller (meaning faster learning) in the CI game than the PI game for $(\pi, \gamma) \in \{(10, 3), (10, 6)\}$.

Although the evidence is not conclusive, Table S.1 also suggests that alignment may be more difficult to achieve when demand is higher. This seems intuitive because, when demand is high, there is more scope to be undercut. This could be due to heterogenous risk preferences among subjects. It is unclear to us what is driving the significantly negative coefficient in the PI(10, 3) game.

Table S.1 Random-effects regressions of d_t^j on round

	Demand $\sim U[20,50]$ $\pi=5;\ \gamma=2$		Demand $\sim U[100,400]$ $\pi=10;\ \gamma=3$		Demand $\sim U[100,400]$ $\pi=10;\ \gamma=6$	
	CI	PI	CI	PI	CI	PI
`round`	-0.159***	-0.136***	-0.823***	-0.283*	-0.287***	-0.0605
	[0.0217]	[0.0234]	[0.191]	[0.146]	[0.0727]	[0.0659]
`demand`	0.0840***	0.181***	-0.0228	-0.0192**	0.00955	0.0257**
	[0.0195]	[0.0250]	[0.0154]	[0.00836]	[0.00774]	[0.0117]
`cons`	4.168***	1.753**	47.61***	39.42***	17.34***	18.08***
	[0.857]	[0.851]	[7.438]	[5.320]	[3.129]	[2.596]
N	600	540	960	960	880	800
R^2	0.090	0.144	0.069	0.013	0.033	0.009

Standard errors in brackets, clustered at subject level. *** significant at 1%; ** significant at 5%; * significant at 10%

Do subjects earn more in later rounds? Table S.1 shows a tendency towards improved coordination in capacity choices as the experiment proceeds. We now analyze whether subject's earnings increased as the experiment proceeds. We regress profits on round and round^2, the (unknown) state of demand and also on the match's choice. The results are reported in Table S.2. We focus our attention on the coefficients involving `round`. As can be seen, the coefficient on `round` is positive and statistically significant in all games. Thus, at least for initial rounds, profits tend to increase. However, it is also true that the coefficient on `round`^{2} is negative and also always significant. Thus, at some point, learning reaches a maximum and profits begin to decline. What is generally true is the following: the decline in profits in late rounds is more pronounced in the PI games than in the CI games, especially in the PI(10, 6) game. This could be indicate that subjects were learning to play the equilibrium of the game (i.e., the complete coordination failure).

Table S.2 Random-effects regressions of profits on round

	Demand $\sim U[20,50]$ $\pi=5;\ \gamma=2$		Demand $\sim U[100,400]$ $\pi=10;\ \gamma=3$		Demand $\sim U[100,400]$ $\pi=10;\ \gamma=6$	
	CI	PI	CI	PI	CI	PI
`round`	0.953***	1.637***	12.700***	9.389***	4.818***	4.278***
	[0.250]	[0.284]	[3.312]	[2.450]	[1.308]	[1.477]
`round`^{2}	-0.016**	-0.040***	-0.209***	-0.202***	-0.074***	-0.090***
	[0.007]	[0.008]	[0.063]	[0.054]	[0.027]	[0.032]
`demand`	0.542***	-0.192*	3.881***	3.349***	0.262	-0.428
	[0.143]	[0.108]	[0.450]	[0.394]	[0.524]	[0.615]
`m.c.`†	2.104***	2.699***	2.990***	3.555***	3.673***	4.339***
	[0.183]	[0.174]	[0.454]	[0.394]	[0.531]	[0.623]
`cons`	-12.142***	-11.890***	-269.282***	-228.062***	-120.973***	-134.606***
	[1.749]	[2.973]	[38.503]	[31.553]	[18.315]	[19.911]
N	600	540	960	960	880	800
R^2	0.774	0.752	0.929	0.935	0.929	0.882

Clustered standard errors (at subject level) in brackets. *** significant at 1%; ** significant at 5%; * significant at 10%.
† `m.c.` denotes one's match's choice.

3.1.2. Autocorrelation in choices To examine whether subjects use history-dependent strategies, we estimate the capacity choice function as a function of the current signal and other lagged variables. We include the lagged choice and lagged demand as well as the lagged difference between a subject's choice and her opponent's choice. We have no *a priori* prediction about the relationship between current choice and lagged choice. On the other hand, because the demand was i.i.d. across rounds we might expect a negative correlation between current choice and lagged demand. Concerning the lagged difference between own choice and opponent's choice, we do not have a clear prediction. On one hand, because subjects were randomly matched each period, the previous choice by one's opponent need not be informative about the current choice. On the other hand, one might expect a negative relationship. If $c \neq m.c.$ then it is very likely that the subject suffered from lost earnings, either because she was undercut by her opponent or because she lost out on potential earnings by choosing too conservatively. In the former case, this negative feedback causes subjects to lower their capacity choice, while in the latter case she chooses a higher capacity, all else equal, in the next period — hence the negative relationship. The results of this exercise are on display in Table S.3.

Table S.3 Random-effects Tobit regressions of choice on estimate and lagged variables

	Demand $\sim U[20,50]$ $\pi=5;\ \gamma=2$		Demand $\sim U[100,400]$ $\pi=10;\ \gamma=3$		Demand $\sim U[100,400]$ $\pi=10;\ \gamma=6$	
	CI	PI	CI	PI	CI	PI
θ	0.821***	0.841***	0.945***	0.958***	0.968***	0.964***
	[0.0199]	[0.0213]	[0.0116]	[0.0103]	[0.00593]	[0.00732]
`lagged choice`	0.118**	0.111**	0.0994**	0.0149	0.104***	0.0744*
	[0.0485]	[0.0547]	[0.0405]	[0.0417]	[0.0300]	[0.0387]
`lagged demand`	-0.0662	-0.0649	-0.0936**	-0.0226	-0.108***	-0.0765**
	[0.0425]	[0.0448]	[0.0390]	[0.0406]	[0.0291]	[0.0376]
`lagged c − m.c.`	-0.0704**	-0.131***	-0.0114	-0.0248	-0.0272	-0.0681**
	[0.0345]	[0.0345]	[0.0297]	[0.0289]	[0.0275]	[0.0265]
`cons`	1.583	0.648	13.48***	12.92***	-7.366***	-2.37
	[1.209]	[1.278]	[4.754]	[4.479]	[2.702]	[3.559]
`N`	580	522	936	936	858	780
`LL`	-1568	-1387	-4390	-4279	-3391	-3272

Standard errors in brackets. *** significant at 1%; ** significant at 5%; * significant at 10%.
The variable `lagged c − m.c.` denotes the lagged difference between the subjects choice and his/her match's choice.

As can be seen, for all games there is a positive relationship between the current and previous capacity choice, and the effect is significant (at the 5% level or better) in four of the six games. Moreover, when significant, the effect seems to be fairly large in magnitude at more than 10% of the effect on one's signal. This positive correlation indicates that subjects are prone to some inertia in their decision making. For lagged demand, the coefficient is always negative (as expected), but is only significant for three of the games. Finally, as expected, we also see a negative relationship between current choice and the lagged difference between c and $m.c.$; however, the effect is only significant in 3 games. Thus, it would seem that there is some evidence that players adopt an adaptive learning strategy and react to lagged variables.

3.2. The CP-2S and MS Treatments

3.2.1. Do subjects learn to align their choices? In Table S.4 we replicate Table S.1, which looks at the question of whether subjects become better-aligned as the experiment progressed. As can be seen, in all games we find a negative and significant coefficient on `round`, which indicates that alignment is improving over time. Consistent with the results from the main text, the coefficients on `round` appear to be smaller in magnitude for the $(\pi,\gamma)=(10,6)$ games than for the $(\pi,\gamma)=(10,3)$ games.

Table S.4 Random-effects regressions of d_t^j on round

	Demand $\sim U[20,50]$ $\pi=5;\ \gamma=2$		Demand $\sim U[100,400]$ $\pi=10;\ \gamma=3$		Demand $\sim U[100,400]$ $\pi=10;\ \gamma=6$	
	CI-2S	PI-MS	CI-2S	PI-MS	CI-2S	PI-MS
`round`	-0.0496*	-0.108***	-0.341***	-0.412***	-0.314***	-0.505***
	[0.0265]	[0.0197]	[0.091]	[0.0968]	[0.087]	[0.109]
`demand`	0.100***	-0.0119	-0.003	-0.029	0.037**	0.01
	[0.0285]	[0.0115]	[0.006]	[0.0211]	[0.017]	[0.009]
`cons`	0.568	5.359***	21.192***	34.87***	17.054***	26.536***
	[0.703]	[0.644]	[3.774]	[7.823]	[3.999]	[3.976]
N	660	660	880	914	960	880
R^2	0.077	0.0777	0.0377	0.0284	0.0263	0.0686

Standard errors in brackets, clustered at subject level. *** significant at 1%; ** significant at 5%; * significant at 10%

3.2.2. Do subjects earn more in later rounds? Table S.5 replicates Table S.2, examining the relationship between profits and `round` in the CI-2S and PI-MS treatments. The only difference from our previous results is that we fail to find a learning effect in the CI-2S(5, 2) game and that in the CI-2S(10, 3) game, the learning effect is positive over all rounds.

Table S.5 Random-effects regressions of profits on round

	Demand $\sim U[20,50]$ $\pi=5;\ \gamma=2$		Demand $\sim U[100,400]$ $\pi=10;\ \gamma=3$		Demand $\sim U[100,400]$ $\pi=10;\ \gamma=6$	
	CI-2S	PI-MS	CI-2S	PI-MS	CI-2S	PI-MS
`round`	0.191	0.881***	7.319***	10.416***	3.935**	9.259***
	[0.158]	[0.197]	[1.513]	[1.707]	[1.887]	[2.542]
`round`^{2}	-0.002	-0.020***	-0.133***	-0.215***	-0.058	-0.176***
	[0.006]	[0.005]	[0.030]	[0.037]	[0.038]	[0.052]
`demand`	-0.085	0.617***	2.701**	4.832***	-0.668	-0.607
	[0.262]	[0.161]	[1.119]	[0.490]	[1.108]	[0.455]
`m.c.`†	2.917***	2.397***	4.264***	2.135***	4.605***	4.640***
	[0.281]	[0.176]	[1.141]	[0.498]	[1.116]	[0.473]
`cons`	-6.348**	-18.011***	-162.733***	-206.923***	-145.149***	-207.364***
	[2.535]	[1.847]	[21.491]	[32.002]	[20.581]	[32.647]
N	660	660	880	914	960	880
R^2	0.865	0.904	0.972	0.959	0.835	0.91

Clustered standard errors (at subject level) in brackets. *** significant at 1%; ** significant at 5%; * significant at 10%.
† `m.c.` denotes one's match's choice.

3.2.3. The Consequences of Lying We briefly take a deeper look on the consequences of lying. Table S.6, reports the results of a series of random-effects regression of profits on variables related to messages. Specifically, we include two dummy variables, one for sending a dishonest message and one for receiving a dishonest message. We also include variables which capture the extent to which one sent (or received) an inflated message, and variables which indicate whether one sent (or received) a deflated message.

Table S.6 Random-effects regressions of profits on round and the misrepresentation of signals

		Dem. $\sim U[20,50]$ $\pi=5;\ \gamma=2$		Dem. $\sim U[100,400]$ $\pi=10;\ \gamma=3$		Dem. $\sim U[100,400]$ $\pi=10;\ \gamma=6$	
	round		0.176***		1.238***		1.426**
			[0.0370]		[0.273]		[0.597]
	demand	0.757***	0.763***	4.289***	4.274***	-0.253	-0.226
		[0.169]	[0.163]	[0.373]	[0.366]	[0.583]	[0.558]
	m.c.	2.273***	2.258***	2.650***	2.669***	4.279***	4.248***
		[0.175]	[0.171]	[0.372]	[0.364]	[0.592]	[0.567]
message sent	$(M_i-\theta_i)1_{(M_i>\theta_i)}$	-0.338*	-0.333**	-2.034***	-2.022***	-0.811***	-0.756***
		[0.174]	[0.167]	[0.332]	[0.315]	[0.205]	[0.222]
	$(M_i-\theta_i)1_{(M_i<\theta_i)}$	0.845*	0.747	3.457**	3.343**	1.646***	1.475***
		[0.451]	[0.457]	[1.520]	[1.535]	[0.363]	[0.392]
	$1_{(M_i\neq\theta_i)}$	0.26	0.268	25.69	21.11	34.56	36.87
		[0.820]	[0.718]	[15.68]	[15.46]	[35.77]	[33.98]
message rec'ed	$(M_j-\theta_j)1_{(M_j>\theta_j)}$	-0.291***	-0.288***	-1.792***	-1.802***	-1.177***	-1.127***
		[0.099]	[0.092]	[0.341]	[0.339]	[0.294]	[0.300]
	$(M_j-\theta_j)1_{(M_j<\theta_j)}$	0.759***	0.664***	3.288**	3.180**	1.432***	1.264***
		[0.227]	[0.223]	[1.468]	[1.491]	[0.301]	[0.287]
	$1_{(M_j\neq\theta_j)}$	0.262	0.27	22.36***	20.55***	15.01	15.26
		[0.763]	[0.713]	[7.023]	[7.478]	[13.58]	[13.90]
	cons	-9.052***	-11.74***	-84.91***	-105.7***	-118.7***	-151.90*
		[1.183]	[1.385]	[16.09]	[18.13]	[45.05]	[53.68]
	N	660	660	914	914	880	880
	R^2	0.911	0.914	0.973	0.974	0.914	0.916

Clustered standard errors (at subject level) in brackets. *** significant at 1%; ** significant at 5%; * significant at 10%.
† m.c. denotes one's match's choice.

If inflated messages lead to lower profits, then, because $M_k-\theta_k>0$, the coefficient on $(M_k-\theta_k)1_{(M_k>\theta_k)}$ will be negative. Similarly, if sending a deflated message leads to lower profits, then because $M_k-\theta_k<0$, the coefficient on $(M_k-\theta_k)1_{(M_k<\theta_k)}$ will be positive. Indeed, this is precisely the pattern that we see. Across all games and specifications, the coefficients on $(M_k-\theta_k)1_{(M_k>\theta_k)}$, $k=1,2$, are negative and significant, indicating that it is not profitable to lie by inflating messages. In the game PI-MS$(10,3)$, this effect is partially mitigated by the positive and significant coefficient on $1_{(M_j\neq\theta_j)}$. Therefore, for this game, small lies may be profitable, but big lies are counterproductive. We also see that the coefficient on $(M_k-\theta_k)1_{(M_k<\theta_k)}$ is positive across all games and specifications, though it loses significance in PI-MS$(5,2)$ once we account for learning. Therefore, as with inflating messages, it is unprofitable to send or receive a deflated message. Finally, notice that the coefficients on $(M_k-\theta_k)1_{(M_k<\theta_k)}$ are generally larger in magnitude than are the coefficients on

$(M_k - \theta_k)1_{(M_k > \theta_k)}$. This suggests that it is *worse* to send a deflated message, which is intuitive because doing so can only cause one's opponent to choose a lower capacity, which can only lower profits.

3.3. Further Enhancements to Communication

In the text, we conjectured that one of the reasons why the PI-MS treatments worked so well, indeed, better than the CI-2S treatments, was because the ability to communicate allowed subjects to signal not just their private information but also their intended action. To further investigate this conjecture, we ran another experiment in which (i) subjects received private signals, (ii) subjects simultaneously sent messages to each other, (iii) subjects observed the messages and then sent a recommended capacity choice to each other, and (iv) subjects simultaneously choose capacities. We call this the PI-RP treatment, and we conducted two sessions (20 subjects in total) with prior demand support $[100, 400]$, $\eta = 25$ and $(\pi, \gamma) = (10, 3)$.

In the PI-RP$(10, 3)$ treatment, average profits are 1699.5, which is greater than the average profits of 1668.5 in the PI-MS$(10, 3)$ treatment, though the difference is not statistically significant ($t_{42} = 1.06$, $p = 0.294$). On the other hand, misalignment declines by more than half from 19.4 to 8.4 ($t_{42} = 5.76$, $p \ll 0.01$).

If, in the PI-MS treatments messages were being used, in part, to signal intended actions, then we might expect greater honesty by subjects in the communication phase of the PI-RP treatment. The frequency of honest messages does increase slightly (from 23.2% to 28.5%) as does the average correlation between messages and signals; however, in neither case is the difference significant.

In Table S.7 we look at the relationship between the recommendation and the message sent and also between the capacity choice and the both the messages and recommendations (sent and received). We also include the results for the PI-MS$(10, 3)$ treatment for the sake of comparison. As can be seen, both the message sent and the message received have a positive effect on the recommendation. Thus, higher messages lead to higher recommendations. As can also be seen, recommendations also have a positive effect on final capacity choices. Notice now, however, that the effect on the message sent becomes small and negative (though still significant). This is in sharp contrast to the PI-MS$(10, 3)$ game where the message sent had a strong positive effect on one's own capacity choice. Thus, while the effect of the message sent has an *indirect* positive effect on capacity choice (working via the relationship between recommendation and message sent), the direct effect is severely diminished, even changing signs.

Table S.7 Messages and Recommendations in ms-rp

	PI-RP(10, 3)		PI-MS(10, 3)
Ind. Vars. / Dep. Var.	recommendation	capacity	capacity
estimate	0.538***	0.650***	0.328***
	[0.030]	[0.024]	[0.034]
message sent	0.276***	-0.05***	0.390***
	[0.023]	[0.018]	[0.027]
message received	0.178***	0.048***	0.259***
	[0.019]	[0.015]	[0.021]
recommendation sent		0.152***	
		[0.023]	
recommendation received		0.196***	
		[0.022]	
cons	-2.960	-2.620*	1.921
	[2.391]	[1.444]	[3.075]
N	800	800	914
LL	-3334.9	-3014.8	-4013

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