

# Private Information and Dynamic Bargaining in Supply Chains: An Experimental Study

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**Problem Definition:** We conduct a controlled human-subjects experiment in a two-tier supply chain where a supplier's per unit production cost may be private information while bargaining with a buyer.

**Academic/Practical Relevance:** Academically, supply chain studies often assume full information or highly structured bargaining. We consider private information with dynamic, unstructured, bargaining. In practice, a buyer may not know their supplier's cost exactly and interact with its supplier in a back-and-forth bargaining environment. Thus, understanding how a supplier's private cost information affects both supply chain outcomes and bargaining is new to the literature and relevant to practice.

**Methodology:** We employ insights from mechanism design to generate restrictions on the space of agreements and solve for a specific bargaining solution under private information to generate precise predictions. These predictions are then tested through a human-subjects experiment.

**Results:** In our experiment, theory predicts that all supplier types should earn at least 50% of total profits when their cost information is private. However, we find that high-cost suppliers earn a disproportionately low share of total profits under private information, 20.16%. We show that this is because buyers, under private information, act as if they are bargaining with the lowest-cost supplier and suppliers do not appear to blame buyers for behaving this way. Based on these findings, we conduct an additional experiment where suppliers have the ability to communicate their private costs to buyers and observe that verifiable disclosure significantly increases profits for high-cost suppliers.

**Managerial Implications:** High-cost suppliers actually suffer from having their costs as private information, which runs counter to theory. However, if high-cost suppliers can credibly disclose their costs to buyers, they can significantly increase profits. Lastly, while private information does not lead to more disagreements, negotiations do take longer, which can be costly to firms.

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## 1. Introduction

Private information is ubiquitous in many supply chain settings where a buyer wishes to contract with one or more suppliers to procure a product. For example, the buyer and supplier may have different beliefs or forecasts about demand. Even more commonly, the buyer may not know the supplier's cost structure. Indeed, an executive for a large durable goods manufacturer recently told us, when discussing his company's procurement practices, "I usually don't know my supplier's cost

structure exactly, but I have a rough estimate of what it might be.”

Understanding how private information affects supply chains is important from both an academic and practical perspective. In an environment in which there are many potential suppliers, the use of auctions as a procurement strategy for dealing with private information is well-studied in operations management (for a survey of the experimental literature, see Elmaghraby and Katok 2019). In this paper, our interest lies in those situations in which the set of suppliers is small. In particular, we focus on the case of a single buyer and supplier who meet to negotiate a contract and study how private information affects the outcome of such an interaction.

In studying buyer-supplier dyads, the supply chain literature often considers a highly structured form of bargaining, such as a powerful proposer making an ultimatum offer to the responder. In the presence of private information, this proposal is often extended to include a menu of contracts from which the responder chooses which contract, if any, to accept (as in, e.g., Corbett et al. 2004). Using the tools of mechanism design, these menus of contracts are carefully designed to screen the supplier types with private information in an incentive compatible manner so that each supplier accepts the contract that was specifically intended for that type. These approaches are not without merit. First, from a practical perspective, there are business-to-business (B2B) relationships where one party has considerable bargaining power. Second, at a more abstract level, such frameworks often yield clean, testable, theoretical predictions. However, not all negotiations take this form in practice. Instead, two companies may have relatively equal bargaining power and partake in a more dynamic, unstructured, back-and-forth negotiation. Such situations are the focus of our paper.

We investigate supply chain contracting in a dynamic unstructured bargaining environment where supplier costs may be private or full information. Because negotiations are conducted by human managers, we employ a combination of theory and human-subjects experiments to address the following questions: (1) What is the effect of private supplier cost information on supply chain outcomes (e.g., profits, efficiency, and contract terms)? (2) How does private supplier cost information affect the bargaining dynamics (e.g., agreements, duration, opening offers, and concessions)?

We operationalize more natural bargaining (between players with equal bargaining power) by allowing both parties to make unlimited contract offers and send limited feedback over a fixed amount of time. One advantage of this setting is that, in our experiment, we can observe more than simply outcomes. For instance, we can track each offer made by either party while negotiating, along with any feedback, over time. We focus exclusively on wholesale price contracts such that the two parties negotiate a wholesale price and stocking quantity simultaneously. We also assume that

the supplier incurs the cost of any unsold inventory. This closely matches a drop-shipping, vendor-managed inventory, or e-commerce environment. Randall et al. (2006) estimate that between 23% and 33% of e-retailers use drop-shipping, and the United States Census estimates that sales by e-retailers totaled \$389.1 billion in 2016 (United States Census Bureau 2016).

We begin by deriving theoretical predictions under full and private information regarding the supplier's cost. We refer to any buying firm in a B2B relationship (e.g., manufacturers, retailers, distributors, etc) as retailers for simplicity. In order to provide heterogeneity amongst suppliers we assume that "higher quality" suppliers have lower per-unit production costs (i.e., low cost does not imply low quality). To generate predictions under full information we rely on the Nash bargaining solution (Nash 1950), which has been used in past studies. Under private information, we first use insights from mechanism design to see how incentive compatibility restricts the set of possible contracts. From the set of incentive compatible contracts we go further and use Myerson's (1984) private information generalization to generate more precise predictions.

Under full and private information we generate point predictions including distribution of profits, supply chain efficiency, wholesale prices, and quantities. Interestingly, we show that incentive compatibility need not generate inefficiencies. That is, there exist incentive compatible mechanisms in which suppliers would truthfully reveal their private information and, in which the supply chain is coordinated for all supplier cost types. This stands in contrast to the typical mechanism design results in which inefficiency is a necessary consequence of providing incentives for truthful revelation of information. However, when we focus on the Myerson bargaining solution, for the parameters of our experiment, the supply chain is only coordinated for the lowest-cost supplier.

Another important theoretical insight from the Myerson bargaining solution is that, for our experimental parameters (and for a broad range of other parameters), all supplier types benefit from their cost information being private. This means that suppliers can use this private information to their advantage while bargaining and earn strictly higher expected profits compared to the full information case. This is one of the key theoretical predictions that we seek to test.

In addition to the normative theoretical benchmarks, we formulate a set of behavioral hypotheses that we also test in our experiment. We accomplish this through a two-treatment experimental design which manipulates whether the supplier's cost information is known or not by the retailer while bargaining. Our experiments yield a number of insights. Of them, one important result is that high-cost suppliers, under private information, earn a disproportionately low share of total supply chain expected profits: 20.16% on average. This stands in stark contrast to the normative theoretical benchmark, which predicts that they should earn *more* than 50%.

Upon further examination, our data suggest that this result is largely due to the bargaining dynamics under private information. For instance, retailers' first offers to suppliers under private information are virtually identical to their first offers to the lowest-cost suppliers under full information. Indeed many of the retailer offers under private information would actually provide higher-cost suppliers with a *negative* expected profit. In short, under private information, retailers act as if they are bargaining with the lowest-cost supplier, which translates into lower wholesale prices and higher stocking quantities for high-cost suppliers. Suppliers, in turn, do not appear to blame retailers for behaving this way: aggressive offers by retailers do not decrease the likelihood of coming to an agreement under private information (but do under full information).

Given these findings, we then explore managerial interventions with the aim of improving profits for high-cost suppliers under private information. We accomplish this through two additional experiments. In one, suppliers have the ability to verifiably disclose their private costs, in the other, suppliers have the option to send a non-verifiable message about their costs that need not be truthful. Supporting our primary results, we observe that high-cost suppliers choose to disclose their costs nearly 75% of the time under verifiable disclosure and that this significantly increases their profits. Overall, these additional experiments indicate that high-cost suppliers can, counter-intuitively, gain by revealing their private information, as long as they can do so credibly.

## 2. Related Literature

The literature most related to our study includes research that investigates wholesale price contracts, unstructured dynamic bargaining processes, and/or private information. Below we highlight a subset of important works and refer the reader to more comprehensive summaries.

Regarding wholesale price contracting theoretically, Lariviere and Porteus (2001) consider a two-stage supply chain and investigate how demand variability affect prices and the distribution of profits. Tomlin (2003) demonstrates how price-only contracts can allocate total supply chain profit between a manufacturer and a supplier who can both invest in capacity. Bernstein et al. (2006) identify how wholesale price contracts can coordinate a supply chain with a single supplier and multiple retailers. Cachon (2003) provides a more general summary of this theoretical literature. Turning to experiments, some papers which investigate supply chain contracting include Ho and Zhang (2008), who study how framing a fixed fee can affect overall supply chain efficiency and Kalkanci et al. (2011), who demonstrate how simple price-only contracts can perform well in a setting where the retailer has accurate information regarding demand. Davis et al. (2014) investigate wholesale price contracts in three alternative inventory risk arrangements, while Zhang et al. (2015)

compare buy-back and revenue-sharing contracts under alternative overage and underage costs with loss-averse suppliers. For a comprehensive summary of the experimental supply chain contracting literature we refer the interested reader to Chen and Wu (2019).

A majority of the above-mentioned papers assume that one party in the supply chain makes an ultimatum offer to the other party. Some studies have extended this setting by allowing for a more natural bargaining process. Theoretically, an important framework for solving these problems under full information is the Nash bargaining solution (Nash 1950). Experimentally, the supply chain papers that we are aware of which consider dynamic bargaining are Leider and Lovejoy (2016), Davis and Leider (2018) and Davis and Hyndman (2019a). Leider and Lovejoy (2016) consider back-and-forth bargaining in a three-stage supply chain with chat box communication. Davis and Leider (2018) allow for unstructured bargaining and evaluate which contracts can alleviate underinvestment in capacity by suppliers. Davis and Hyndman (2019a) study which contract terms should be included in an unstructured negotiation with full information. In many ways, our work can be considered an extension of Davis and Hyndman (2019a), with a critical difference being that we investigate one-sided private information, which is directly relevant to practice.

The supply chain literature frequently assumes full information of price, demand, and cost parameters, with some notable exceptions (especially in an ultimatum-offers setting). One example includes papers in which the retailer may have private knowledge about consumer demand (e.g., Cachon and Lariviere (2001) from a theoretical perspective and Ozer et al. (2011) from an experimental perspective). In a private information setting, Corbett et al. (2004) adopt a mechanism design framework in which a powerful supplier offers menus of contracts to screen buyer cost-types. More relevant to our work are those papers in supply chain management which consider private information combined with a more natural bargaining interaction between two parties. Feng et al. (2015) is one example. They investigate multiple alternating offers where both parties are impatient and the buyer has private information about their type. They show how quantity distortion and information rents may or may not be avoided depending on the patience of the parties involved.

There is also a rich literature in experimental economics pertaining to bargaining (see Roth (1985), Roth (1995), Muthoo (1999), and Camerer (2003) for summaries). Early work demonstrates that pairs tend to agree on a 50/50 split of a surplus (Nydegger and Owen 1974). However, a number of other experiments extend this research by having pairs bargain not over payoffs, but lottery tickets, and show that participants can differ in their focal points for what they deem as fair outcomes (Roth and Malouf 1979, Roth et al. 1981, Roth and Murnighan 1982). Other papers have shown similar effects of “self-serving” biases (Babcock and Loewenstein 1997) which

differ from more standard models of social preferences (Fehr and Schmidt 1999, Bolton and Ockenfels 2000). This is especially relevant to our study as retailers have some leeway as to how they interpret unknown supplier costs. In another bargaining study, Roth et al. (1988) demonstrate a robust behavioral result in that pairs often come to agreements during the final seconds of a negotiation, which they deem the “deadline effect.” Regarding private information, Forsythe et al. (1994) conduct a novel unstructured bargaining experiment with one-sided private information and investigate when disagreements take place. Mitzkewitz and Nagel (1993) experimentally study the ultimatum game with private information and manipulate whether the proposer offers an amount to the receiver (i.e., the receiver only knows their own earnings) or an amount for themselves (i.e., the receiver only knows what the proposer earns). Valley et al. (2002) consider two-sided private information in a double-auction environment and show that pre-play communication can help contribute to less disagreements. More recently, Camerer et al. (2019) apply insights from mechanism design (like us) and take a machine-learning approach to analyzing short unstructured negotiations with one-sided private information.

### 3. Theoretical Background

In this section we provide a theoretical analysis for the bargaining institutions that we will test in the lab. The basic framework consists of a retailer with selling price  $p$  and a supplier with per-unit cost of production,  $c$ , who must negotiate both a wholesale price,  $w$ , and an order quantity,  $q$ . For ease of exposition and because it conforms to our experimental parameters, underlying demand,  $D$ , is drawn uniformly from  $[0, 100]$ , but the actual realization of demand is unknown at the time of bargaining. We also assume that the supplier bears the risk of unsold inventory. We include this last assumption for three reasons. First, it represents a scenario where both parties face demand risk.<sup>1</sup> Second, it is consistent with settings in practice, such as drop-shipping and e-commerce. Third, in a related bargaining study on full information, Davis and Hyndman (2019a) find that many behavioral results do not depend on which party holds the inventory risk. However, we recognize that this assumption does not represent all types of supply chain risk environments.

We consider two settings which differ as to whether the supplier’s cost is full or private information. For the full information case we provide a more general but brief analysis. For the private information case we present a general approach to solving the problem and provide some general insights based on the notion of incentive compatibility. Due to the highly computational nature of the specific bargaining solution, some predictions are based on the parameters in our experiment, which will be outlined later (but see Remark 1 below).

<sup>1</sup> When the retailer incurs the cost of unsold inventory, the supplier avoids both inventory and random demand risk.

### 3.1. Bargaining with Full Information

Under full information the supplier's cost,  $c$ , is common knowledge while bargaining. Because our experiment implements an unstructured bargaining protocol, the relevant theoretical lens for the full information case is the Nash bargaining solution (Nash 1950). Denote by  $\pi_i(w, q)$  the expected profits for firm  $i \in \{r(\text{retailer}), s(\text{supplier})\}$ , from an agreement with wholesale price,  $w$ , and order quantity,  $q$ . The expected profits can be expressed as:

$$\pi_r(w, q) = \frac{p-w}{100} \int_0^{100} \min\{q, x\} dx; \quad \pi_s(w, q) = \frac{w}{100} \int_0^{100} \min\{q, x\} dx - cq. \quad (1)$$

The disagreement payoff is 0 for both players. The Nash bargaining solution is the solution to:

$$\begin{aligned} \max_{w, q} \quad & \pi_r(w, q) \cdot \pi_s(w, q) \\ \text{s.t.} \quad & c \leq w \leq p \text{ and } a \leq q \leq b. \end{aligned}$$

Since the full information bargaining environment is identical to Davis and Hyndman (2019a), we state without proof the following result:

PROPOSITION 1. *When bargaining under full information:*

- (i) *The supply chain is coordinated,  $q^* = 100^{(p-c)}/p$ .*
- (ii) *Expected profits for the retailer and supplier are split equally, 50%/50%.*
- (iii) *The wholesale price is  $w^* = \frac{p(p+3c)}{2(p+c)} > \frac{p+c}{2}$ .*

Note that the agreed wholesale price,  $w^*$ , under full information is strictly greater than the mid-point between  $c$  and  $p$  (i.e.,  $(p+c)/2$ ). This follows because the supplier bears the inventory risk. Therefore, to equalize the expected payoffs of the retailer and supplier, the wholesale price must increase beyond the midpoint between the retailer's price and the supplier's cost.

### 3.2. Bargaining with Private Information

When supplier costs are private information while bargaining (i.e., unknown to retailers), we assume that the supplier has three, equally likely, possible cost types:  $c_1 < c_2 < c_3 < p$  and that the set of possible costs is common knowledge. In such a setting, we need a suitable generalization of the Nash bargaining solution. Using insights from mechanism design, Myerson (1984) provides such a generalization that has been largely unexplored in the operations literature. The basic idea is that the players negotiate over "mechanisms," which consist of a menu of contracts – one for each possible type of supplier – that are incentive compatible, so that each supplier type truthfully reveals her type.<sup>2</sup> From the set of individually rational and incentive compatible mechanisms, the

<sup>2</sup> To be sure, in actual bargaining, players do not actually negotiate over mechanisms, but the underlying assumption is that the unstructured bargaining process provides an indirect mechanism to implement the bargaining solution.

Myerson (1984) solution then seeks to maximize a weighted sum of the retailer's and supplier's expected profits. The solution must also respect so-called *warrant conditions*, which are the minimum amounts that each player type "warrants" in a fair division. The final complication is that the weights must be derived as part of the solution.

While we will leave most details deriving the Myerson (1984) bargaining solution to the appendix, it is instructive to look at the incentive compatibility constraints. Let  $\mathcal{M} = \{(\gamma_i, w_i, q_i), i = 1, 2, 3\}$  denote a mechanism, where  $(\gamma_i, w_i, q_i)$  denotes a contract intended for supplier type  $c_i$ . The wholesale price and order quantity are  $(w_i, q_i)$  and  $\gamma_i \in [0, 1]$  is the probability of agreement. Given our assumption on the demand distribution, we know that supplier expected profits, conditional on agreement, are  $\pi_s(w_i, q_i, c_i) = (w_i/200)(200q_i - q_i^2) - c_i q_i$ . A mechanism is incentive compatible if:

$$\gamma_i \left( (w_i/200)(200q_i - q_i^2) - c_i q_i \right) \geq \gamma_j \left( (w_j/200)(200q_j - q_j^2) - c_i q_j \right) \quad \forall i = 1, 2, 3 \text{ and } \forall j \neq i.$$

We first provide two preliminary results, the proofs of which are in Appendix A, which follow from incentive compatibility. First, expected quantities decline in supplier cost type. Specifically,

LEMMA 1. *Let  $\mathcal{M}$  be an incentive compatible mechanism. Then  $\gamma_1 q_1 \geq \gamma_2 q_2 \geq \gamma_3 q_3$ .*

Second, we show that it is without loss of generality to look only at mechanisms in which disagreement never occurs. Specifically,

LEMMA 2. *Given any incentive compatible mechanism,  $\mathcal{M} = \{(\gamma_i, w_i, q_i), i = 1, 2, 3\}$ , there exists an alternative mechanism,  $\bar{\mathcal{M}} = \{(1, \bar{w}_i, \bar{q}_i), i = 1, 2, 3\}$ , which (i) is incentive compatible, (ii) has no disagreement, and (iii) generates the same expected profits for each supplier type and the retailer.*

This result is interesting because, when bargaining with private information, the chance of disagreement is often required to generate incentives for truthful revelation. However, since the parties bargain over two parameters: quantity – which determines the size of the pie – and wholesale price – which determines the division of the pie – we can do away with the possibility of disagreement, while still maintaining incentive compatibility. Remark 3 provides further discussion.

Another typical result when contracting with private information is inefficiency. This can happen either because of the possibility of disagreement or the distortion in key parameters (e.g., quantity) in order to generate the necessary incentives for truthful revelation. However, in our setting, we can prove that efficiency and incentive compatibility *can* simultaneously coexist. That is,

PROPOSITION 2. *There exist incentive compatible mechanisms in which the supply chain is coordinated for all possible supplier types. That is,  $q_i = 100((p-c_i)/p)$  for all  $i$ .*

Therefore, if inefficiency arises, it must be due to the properties of the bargaining solution and not merely because of incentive compatibility.

With these preliminary results, we now provide a brief discussion of Myerson's (1984) bargaining solution. Recall that  $\pi_s(w, q, c_i)$  denotes the expected profits of supplier type  $c_i$  when faced with the contract  $(w, q)$ , while  $\pi_r(w, q, p)$  denotes the expected profits of a retailer with selling price  $p$  facing the contract  $(w, q)$ . The general approach consists of solving:

$$\begin{aligned} \max_{\lambda_i, q_i, w_i \geq 0} \quad & \sum_{i=1}^3 \lambda_i \pi_s(w_i, q_i, c_i) + \frac{1}{3} \sum_{i=1}^3 \pi_r(w_i, q_i, p) \\ \text{s.t.} \quad & \pi_s(w_i, q_i, c_i) \geq \pi_s(w_{i+1}, q_{i+1}, c_i), \quad i = 1, 2. \end{aligned}$$

That is, we maximize a weighted sum of the supplier's and retailer's expected profits subject to incentive compatibility constraints. One complicating factor is that the solution must also determine the weights,  $\lambda_i$ , that we apply to each supplier type  $i$ 's profits. That is, the bargaining solution need not weight each supplier type equally. Without loss of generality, we can take  $\lambda_3 = 1 - \lambda_1 - \lambda_2$ .<sup>3</sup>

We outline the steps to obtain the solution, with technical details relegated to Appendix A.

1. Let  $\alpha_i$  denote the Lagrange multiplier on supplier type  $i$ 's incentive compatibility constraint. Observe that the wholesale price,  $w_i$ , is a linear transfer between the retailer and the supplier (see (2) in Appendix A). Therefore, we can impose the constraints that  $\lambda_1 + \alpha_1 = 1/3$  and  $\lambda_2 + \alpha_2 - \alpha_1 = 1/3$ .
2. Find the optimal order quantities as a function of  $\alpha_i$  and  $\lambda_i$  (see (3)–(5) in Appendix A).
3. Ensure that the *warrant conditions* are satisfied. The warrant conditions dictate the virtual utility,  $W_i^*$ , that each supplier type  $i$  warrants (i.e., “deserves”) in a bargaining solution. This is akin to the standard Nash bargaining solution, but with private information corresponds to half the total virtual surplus generated by the interaction between the retailer and the particular supplier cost type. The system of warrant equations to solve is given by (6)–(8) and the solution by (9)–(11) in Appendix A.
4. The final step is to find values of  $\lambda_i$  and  $w_i$  such that:

$$\begin{aligned} \pi_s(w_i, q_i, c_i) &\geq W_i^*, \quad \text{with equality if } \lambda_i > 0, \\ \pi_s(w_i, q_i, c_i) &\geq \pi_s(w_{i+1}, q_{i+1}, c_i), \quad \text{for } i = 1, 2 \text{ and with equality if } \alpha_i > 0. \end{aligned}$$

<sup>3</sup> Since there is only one retailer type, there are no weights applied to the retailer's payoff, beyond taking expectations over the type of supplier she is matched with. Observe also that we only consider incentive compatibility constraints for the  $c_i$  type to report truthfully, rather than the next highest cost (i.e.,  $c_{i+1}$ ). This is without loss of generality.

With three supplier cost types and two incentive compatibility constraints this is, potentially, a system of five equations in five unknown variables:  $(w_1, w_2, w_3, \lambda_1, \lambda_2)$ . Moreover, one must check boundary conditions on the  $\lambda$ 's and  $\alpha$ 's, making it necessary to consider seven different systems of equations to find the valid solution. Given the parameters of our experiment, the bargaining solution involves  $\lambda_1 = \lambda_2 = 0$ , and the incentive constraints on the  $c_1$  and  $c_2$  supplier types are binding (the equilibrium contract parameters are provided in Table 1 and are discussed when we review our experimental design). We can summarize these results as:

PROPOSITION 3. *When bargaining under private information and given the parameters of our experiment:*

- (i) *The supply chain is coordinated only for the lowest cost supplier ( $c_1$ ).*
- (ii) *All suppliers benefit from private information. In particular, expected profits are strictly higher than under full information and suppliers earn at least half of the expected supply chain profits.*
- (iii) *The wholesale price is higher and the order quantity is lower under private information than under full information.*

As in the Nash bargaining solution with complete information, here too there is a notion of equity between the players involved. In particular, it must be that

$$\sum_{i=1}^3 \lambda_i \pi_s(w_i, q_i, c_i) = \sum_{i=1}^3 (1/3) \pi_r(w_i, q_i).$$

Therefore, when  $\lambda_1 = \lambda_2 = 0$ , the bargaining solution only places weight on the highest-cost supplier type and fairness between the retailer and supplier is judged as being between the high-cost supplier and the expected retailer profits, averaging over all possible supplier-type pairings. However, from the retailer's perspective, she has a chance to bargain with lower-cost suppliers, where she will earn more, this means that she will receive less than half of the supply chain profits when matched with the highest-cost supplier.

A word of discussion on Proposition 3(ii) is merited as it may seem counter-intuitive that even the high-cost supplier benefits from private information. As we show in the appendix, because of the incentive compatibility requirement, the warrant conditions between supplier types are deeply intertwined. Specifically, the warrant condition for the low-cost supplier,  $W_1^*$ , is always half of the full information surplus, and the warrant condition of the medium-cost supplier,  $W_2^*$ , is increasing in  $W_1^*$  (and  $W_3^*$  is increasing in  $W_2^*$ ). Therefore, particularly in our case where  $\lambda_1 = \lambda_2 = 0$ , this serves to push up the earnings of even the high-cost supplier.

REMARK 1. While we focus here on the parameters that we eventually implement in the experiment, we also numerically solved for the Myerson bargaining solution for a wide array of parameters (see Appendix A). If we restrict attention to the more empirically relevant high margin case (i.e.,  $c_3 \leq p/2$ ), then our parameter choices appear to be representative. Specifically, in such cases, about 94% of the time we find that all supplier types benefit relative to full information, while it almost never happens that no types benefit. When we allow that supplier costs may exceed half the retailer’s price, then it is less common that all supplier types benefit (about 54%), but it is still uncommon that no supplier types benefit ( $< 1\%$ ). It may be interesting in future work to study cases in which  $c_i > p/2$  is possible.

REMARK 2. One might find it odd that the private information extension of the Nash bargaining solution – which involves solving an additive optimization problem – is so different from the complete information Nash bargaining solution – which involves solving a multiplicative optimization problem. An earlier extension by Harsanyi and Selten (1972) proposed a multiplicative version. However, as discussed in Myerson (1984), this necessarily violates a probability invariance axiom. We refer the interested reader to these papers for further details.

REMARK 3. It is natural to wonder whether our restriction to mechanisms without disagreement plays a role. In particular, whether there exists another bargaining solution which generates the same expected payoffs but has disagreement. We believe that the answer is no. This is because, in our proof of Lemma 2, the alternative mechanism with no disagreement adds slack to the incentive constraints. On the other hand, in the bargaining solution for our experimental parameters, the incentive constraints are binding. Therefore, we cannot reverse the direction and look for an equivalent mechanism with disagreement. To do so would require removing slack from the incentive constraints, but no such slack exists due to the binding constraints.

#### 4. Experimental Design and Hypothesis Development

In our experiment, participants were assigned a role of supplier or retailer and placed into a group of six, three retailers and three suppliers. Both roles and groups remained fixed for the duration of the experiment. In every round, each supplier was randomly assigned a production cost per unit,  $c \in \{3, 4, 5\}$ , without replacement, and each retailer was randomly assigned a selling price per unit,  $p \in \{10, 11, 12\}$ , without replacement. Retailer and supplier roles were fixed throughout the experiment, but a participant’s cost (if supplier) or price (if retailer) could vary from period to period. The distributions of prices and costs were common knowledge to both parties. This design allows us to test the robustness of results to changes in supplier cost and retailer price. We drew prices and costs without replacement to ensure a more balanced collection of different observations.

Each round began by randomly assigning retailers and suppliers into pairs. Each pair would then bargain over contract terms for a product with uncertain demand. Regardless of the retailer’s selling price and supplier’s production cost, demand for the product was always a random draw from the discrete uniform distribution on  $\{1, 2, \dots, 100\}$ . If the two parties came to an agreement while bargaining, demand would be realized, and retailers would satisfy demand by sourcing product directly from the supplier, such that the supplier incurred the cost of any unsold inventory.

For our unstructured bargaining we followed a protocol similar to Davis and Leider (2018) and Davis and Hyndman (2019a). Specifically, each retailer-supplier pair was given five minutes to negotiate a contract which consisted of two terms, a wholesale price,  $w$ , and a quantity,  $q$ . During this time, retailers and suppliers could make as many offers as they desired at any point in time. If either party chose to accept the most recent offer of the other player, then demand would be realized and participants would receive feedback that included realized profits. If a pair was unable to reach an agreement after five minutes then both players would receive a profit of zero.

While bargaining, we allowed participants to provide feedback about the most recent offer received. In particular, they could “reject” either of the proposed terms through a button for each contract term, which they could click at any time for a currently valid proposal. This feedback would then be displayed on the proposer’s screen. Note that a participant could later accept the offer even if they signaled disapproval with it, so long as a more recent offer was not received. We opted for this type of feedback to simulate a more natural bargaining process while also allowing us to monitor offers and feedback. Lastly, to reduce complexity in the experiment, we provided participants with a decision support tool where they could enter hypothetical values for  $w$  and  $q$ , which would generate a graph showing the profit for both players as a function of demand.

Consistent with our theory section, our experimental design consists of two treatments: one where supplier’s costs were common knowledge (full information) and one where the supplier’s cost information was unknown to retailers (private information). Each treatment consisted of six rounds and included 48 participants across three sessions. Thus each treatment included eight groups of six participants. The experimental software was programmed in z-Tree (Fischbacher 2007), and all sessions took place at a large northeast university. Sessions took roughly 60 minutes with earnings varying considerably: average \$38, maximum \$78, and minimum \$7 (participants were compensated for all rounds of decisions).

#### 4.1. Predictions and Hypotheses

In Table 1 we provide point predictions for our experiment using our theoretical analysis, averaged across all prices for ease of exposition.<sup>4</sup> We will compare our data directly to these predictions.

<sup>4</sup> We provide the individual point predictions for each pair of  $c$  and  $p$  in Appendix B.1.

**Table 1** Normative Experimental Predictions

	Supplier Share (%)		Efficiency (%)		Wholesale Price ( $w$ )		Quantity ( $q$ )	
	Full	Private	Full	Private	Full	Private	Full	Private
$c = 3$	50.00	61.29	100	100	7.85	8.57	72.58	72.58
$c = 4$	50.00	56.83	100	97.87	8.43	8.62	63.43	54.29
$c = 5$	50.00	61.23	100	88.24	8.93	9.08	54.29	36.01
Average	50.00	59.78	100	95.37	8.41	8.76	63.43	54.29

Note: The supplier's share under private information is based on the *ex ante* expected profits.

Therefore, the point predictions can be considered as a null hypothesis. In addition to this null hypothesis, we also develop three behavioral hypotheses. Because the full information setting has been explored previously, each behavioral hypothesis focuses on the private information case.

Our first hypothesis considers the supplier's share of total expected profits. We know from past research on full information that inventory-risk holders, i.e., suppliers in our study, typically earn less than the normative predictions (Davis and Hyndman 2019a). Hence, a similar result may exist under private information. Further, while the normative theory predicts that suppliers should always be weakly better off under private information, this may not be true with human decision makers. For instance, Schelling (1960) posited that ignorance can be an advantage in negotiations because the uninformed party can bargain more aggressively because she does not "know" what a fair allocation would be, while the informed party may be more accepting of such behavior because he recognizes the informational disadvantage of the uninformed party. In our experiment this suggests that, under private information, higher-cost suppliers may be inclined to accept less favorable offers than compared to full information. In experiments which use abstract settings and/or ultimatum offers, Schelling's hypothesis has found empirical support. For instance, Siegel and Fouraker (1960) and Hamner and Harnett (1975) find that uninformed parties typically set high aspiration levels under private information (i.e., they assume the best case for themselves) and are able to achieve more favorable outcomes compared to a full information scenario. In line with this, Knez and Camerer (1995) conduct an ultimatum game experiment and find that people "egocentrically choose the view which benefits them most" when there is room for interpretation. Overall, this research suggests that uninformed retailers may act *as if* they are bargaining with the lowest-cost supplier ( $c = 3$ ), and that suppliers will not blame them for this. As a result, we expect that the  $c = 5$  (and possibly the  $c = 4$ ) supplier will earn less compared to full information.

**HYPOTHESIS 1 (SUPPLIER SHARE).** *In private information, the observed suppliers' share of expected profits will be less than the normative predictions for all supplier costs. High-cost ( $c = 5$ ) suppliers will earn less than under full information.*

We turn now to supply chain efficiency. Both “strategic ignorance” and anchoring may have an effect, but the direction of the effect depends on the supplier cost. Recall that anchoring is the tendency for agreed quantities to be closer to the mid-point of demand than normative theory predicts. Consider each supplier type separately. For  $c = 3$  under private information, the predicted average quantity is 72.58 (same as full information). Anchoring will pull this down and drive efficiency below the normative prediction. However, strategic ignorance should not play a role because retailers are likely to bargain as if they are matched with the low-cost supplier – which they are in this case. At the other extreme, for the  $c = 5$  supplier, both anchoring and strategic ignorance should work to push quantities and, therefore, efficiency up. This is because the predicted quantity for the  $c = 5$  supplier is below both the mean and the quantity for the low-cost supplier. For the  $c = 4$  supplier, anchoring and strategic ignorance work in opposite directions. The predicted average quantity is 54.29, which is greater than the mean demand but less than the  $c = 3$  quantity. Therefore, anchoring pushes the quantity down, while strategic ignorance pushes it up. It is not clear which effect will dominate, making it difficult to predict whether efficiency is higher or lower than the normative prediction. Fortunately our experiment can assist with this.

**HYPOTHESIS 2 (EFFICIENCY).** *In private information, the observed supply chain efficiency will be lower than the normative theory for the  $c = 3$  supplier and higher than the normative theory for the  $c = 5$  supplier.*

Lastly, we consider bargaining agreements and duration under private information. Compared to the normative theory, we hypothesize that agreement rates will be less than 100%. Comparing the two information settings to one another, it is not clear how agreement rates may vary. First, one might suspect that the larger contracting space under private information will lead to more disagreement. Malouf and Roth (1981) evaluate this notion through a simple bargaining experiment with full information and find mixed support. Second, Conrads and Irlenbusch (2013) conduct an ultimatum game experiment with private and full information and observe that private information can lead to *higher* agreement rates. Because past experimental research does not provide a clear prediction, and Lemma 2 states that players should not use disagreement as a tool for separating supplier cost types, we follow the null hypothesis that agreement rates will be equal between full and private information. Lastly, regarding bargaining duration, Malouf and Roth (1981) show that a larger contracting space increases bargaining duration. In addition, a study by Loewenstein and Moore (2004) shows that information revelation decreases bargaining duration, provided that the information is not subject to interpretation. This suggests that bargaining duration should be shorter in our full information treatments.

HYPOTHESIS 3 (BARGAINING). *In private information, for all supplier costs:*

- (i) *Agreements will be less than 100% and equal to the full information case.*
- (ii) *Bargaining duration will be longer than the full information case.*

Ultimately, through our human-subjects experiment we can determine which of these hypotheses are supported and simultaneously evaluate Myerson’s normative benchmarks.

## 5. Results

We present our experimental results in two subsections. In §5.1 we investigate outcomes and in §5.2 we analyze the bargaining dynamics. Because six participants interacted with each other throughout a single session (through random matching and random prices/costs each round), we take a conservative approach for all hypothesis tests and use  $t$ -tests where a group of six is an independent observation. For instance, for a particular metric (e.g., supplier share of profit for  $c = 3$ ), we first calculate the supplier’s share for all rounds and participants where  $c = 3$ . We then average these values for each particular group of six, yielding eight independent observations in each treatment. Also, we run all regressions with random effects and clustered standard errors at the group level. Lastly, we note that there is no significant difference in agreement rates between treatments. Therefore, while we will investigate agreements in detail later, all outcome results in §5.1 are conditional on a bargaining agreement.

### 5.1. Outcomes

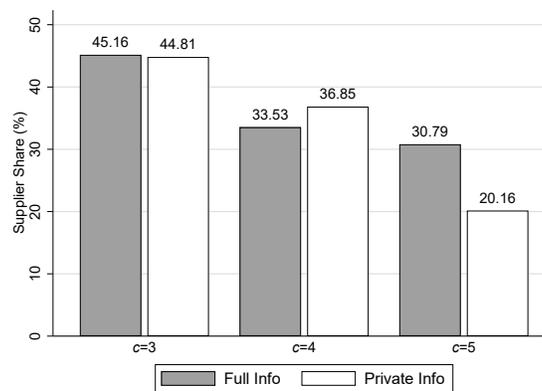
**SUPPLIER’S SHARE OF PROFITS.** Normative theory predicts that suppliers should earn 50% of total expected profits under full information and at least 50% under private information. Yet, *Hypothesis 1 (Supplier Share)* posits that suppliers will earn less than 50% for all supplier costs. Moreover, because of strategic ignorance,  $c = 5$  suppliers will earn a significantly lower share under private information. Figure 1 depicts the supplier’s share of total supply chain expected profit under full and private information, averaged across all retailer prices and conditional on agreement.<sup>5</sup> One can see that suppliers do indeed earn less than 50% on average in both treatments (overall average of 36.89% for full and 33.56% for private, both  $p < 0.01$ ).<sup>6</sup> There is also a clear decreasing relationship between supplier cost and supplier share of total profits. Comparing the two treatments to one another, there are virtually no differences between full and private information for  $c = 3$  and  $c = 4$ .

<sup>5</sup> One observation was removed before creating this figure, where a participant’s supplier share was -100% of the supply chain expected profit, which occurred in the first period. Also, please see Appendix B for figures and tables which report all results for each combination of  $c$  and  $p$ .

<sup>6</sup> In full information, this result is a minor robustness check for Davis and Hyndman (2019a), who only considered  $p = 15$  and  $c = 3$ , and found that the inventory risk holder consistently earns less than 50% of the total profits.

However, there is a stark difference between the two treatments for  $c = 5$ . While normative theory predicts that  $c = 5$  suppliers should earn a higher share of total profits compared to full information (61.23% versus 50%, see Table 1), we observe that  $c = 5$  suppliers earn a disproportionately lower share of total profits in private information, 20.19%. Overall, we find support for both parts of *Hypothesis 1 (Supplier Share)*: under private information, suppliers' shares of total supply chain expected profits are significantly below the normative predictions and decreasing in cost. Also, high-cost ( $c = 5$ ) suppliers earn lower profits in private information than full information.

**Figure 1 Observed Supplier Share (%) of Supply Chain Expected Profit, Conditional on Agreement**



**EFFICIENCY.** Table 2 provides results for supply chain efficiency and shows that it is 91.66% under full information, on average. This is consistent with past bargaining studies on full information that consider only a single  $c$  and single  $p$ . It is also not statistically different from the average 92.20% efficiency under private information. Turning to *Hypothesis 2 (Efficiency)*, which states that efficiency under private information will be lower than the normative prediction for the  $c = 3$  supplier and higher than the normative prediction for the  $c = 5$  supplier, we find support for both: observed efficiency is significantly lower for  $c = 3$  (91.53% versus 100%,  $p < 0.01$ ) and marginally higher than the normative prediction for  $c = 5$  (91.05% versus 88.24%,  $p = 0.097$ ). In addition, recall that a clear hypothesis for the  $c = 4$  supplier was unavailable. For this case we observe that efficiency is significantly lower than the normative prediction (94.16% versus 97.87%,  $p = 0.011$ ).

**CONTRACT TERMS.** To gain a better understanding as to what is driving our profit and efficiency results, we now focus on the agreed upon contract terms. Table 3 illustrates the agreed upon wholesale prices and quantities in our experiment, averaged across all retailer prices. Beginning with wholesale prices, one can see that average wholesale prices are too low relative to the normative predictions, by 0.75 under full information (8.41 versus 7.66,  $p < 0.01$ ) and by 1.22 under private

**Table 2** Observed Efficiency (%), Conditional on Agreement

	Predicted		Observed	
	Full	Private	Full	Private
$c = 3$	100***	100***	90.96 (1.85)	91.53 (1.80)
$c = 4$	100***	97.87**	91.04 (2.16)	94.16 (1.10)
$c = 5$	100***	88.24*	92.83 (1.57)	91.25 (1.42)
Average	100***	95.37**	91.66 (1.33)	92.20 (1.01)

Note: Standard errors across groups are reported in parentheses. Significance of  $t$ -tests between observed values and the normative predictions are given in the left two columns. Significance of  $t$ -tests between full and private information are given in the “Private” column. All differences are denoted by \*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , and \*  $p < 0.10$ .

information (8.76 versus 7.54,  $p < 0.01$ ). This result holds for all supplier costs as well (all six  $p < 0.01$ ), which goes a long way to explaining why suppliers earn less than the normative theory predicts. Comparing wholesale prices under full versus private information, we find that there are no significant differences. Although, the difference is largest in the  $c = 5$  case, where average wholesale prices are 8.11 under full information and 7.89 under private information.

**Table 3** Observed Wholesale Prices and Quantities, Conditional on Agreement

	Predicted				Observed			
	Wholesale Price ( $w$ )		Quantity ( $q$ )		Wholesale Price ( $w$ )		Quantity ( $q$ )	
	Full	Private	Full	Private	Full	Private	Full	Private
$c = 3$	7.85**	8.57***	72.58***	72.58***	7.20 (0.17)	7.22 (0.18)	56.21 (2.74)	54.98 (3.30)
$c = 4$	8.43***	8.62***	63.43*	54.29	7.68 (0.23)	7.47 (0.21)	56.31 (3.97)	52.61 (2.13)
$c = 5$	8.93***	9.08***	54.29**	36.01***	8.11 (0.10)	7.89 (0.12)	49.09 (1.68)	50.47 (3.13)
Average	8.41***	8.76***	63.43***	54.29	7.66 (0.13)	7.54 (0.14)	54.07 (2.61)	52.65 (2.42)

Note: Standard errors across groups are reported in parentheses. Significance of  $t$ -tests between observed values and the normative predictions are given in the left four columns. Significance of  $t$ -tests between full and private information are given in the “Private” column. All differences are denoted by \*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , and \*  $p < 0.10$ .

For quantities, all of them are at least marginally significantly different than the normative predictions. The lone exception to this statement is in private information for  $c = 4$ . In particular, recall the discussion around *Hypothesis 2 (Efficiency)* suggested that anchoring should pull quantities down for  $c = 4$  but, if retailers assume they are bargaining with a  $c = 3$  supplier, this may push quantities up. These effects appear to be supported as observed quantities are not statistically different from the normative theory for  $c = 4$  (although it did not translate into an efficiency equal to the normative prediction). Also, in comparing quantities between the full and private information

treatments, there are no statistically significant differences.

While there are no statistically significant differences between full and private information for wholesale prices and quantities, a combination of small deviations can translate into meaningful differences in profits. Consider the case of  $c = 5$  and  $p = 10$ , taken from Table B.3. The average wholesale prices are 7.68 and 7.54 in full versus private information, and quantities are 49.34 and 56.86. Importantly, neither difference is statistically significant, but together they have a dramatic effect on a supplier’s share of profits. In Table 4 we provide the details. A slight decrease of 0.14 ( $7.68 - 7.54$ ) in the wholesale price lowers the supplier’s share by 4.16%. On top of this, because the supplier stocks a larger quantity, it requires them to take more risk and reduces their share by another 8.46%. Indeed, these differences in wholesale prices and quantities for  $c = 5$  suppliers are directionally opposite to what the normative theory predicts. In particular, Proposition 3(iii) showed that wholesale prices should be *higher* and stocking quantities should be *lower* under private information, but we observe the reverse for  $c = 5$ . In sum, for  $c = 5$  suppliers under private information, a combination of slightly lower wholesale prices and higher quantities contributes directly to a disproportionately low split of total supply chain expected profits.

**Table 4** Impact of Small Contract Term Deviations on Supplier’s Share of Profits ( $c = 5$  and  $p = 10$ )

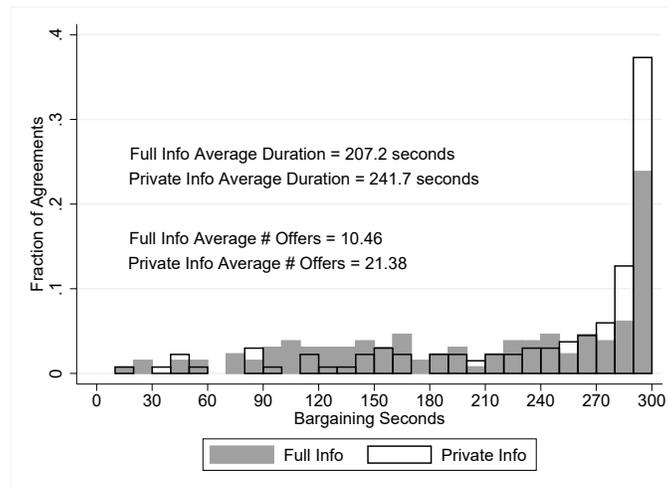
	Wholesale Price ( $w$ )	Quantity ( $q$ )	Supplier Share	Difference
Full Information	$w=7.68$	$q=49.34$	31.00%	-
Lower Wholesale Price	$w=7.54$	$q=49.34$	26.84%	4.16%
Higher Quantity	$w=7.54$	$q=56.86$	18.38%	8.46%

## 5.2. Bargaining Dynamics

In an effort to understand how participants arrived at such contract terms and outcomes, we now turn our attention to bargaining dynamics. Specifically, we provide results on bargaining agreements and duration, anchoring on initial offers, and the concession process over time.

AGREEMENTS AND DURATION. Retailer-supplier pairs came to a bargaining agreement at a similar rate between full and private information, 90.28% under full and 93.06% under private ( $p = 0.525$ ). This result validates Lemma 2 and shows that players do not use disagreement as a tool for separating supplier cost types. It is also consistent with the first part of *Hypothesis 3 (Bargaining)* which stated that agreement rates will be less than 100% and similar between full and private information.

While the agreement rates are similar between the two information conditions, we do observe differences in bargaining duration. Figure 2 shows a histogram for the bargaining duration (in seconds), between full and private information. It also includes the average number of offers. First,

**Figure 2** Observed Frequency of Bargaining Duration

there is clearly a deadline effect in both conditions – under private information 37% of agreements are reached in the last 10 seconds, while under full information, 24% of agreements are reached in the last 10 seconds. This is consistent with Roth et al. (1988). Second, one can see that the bargaining duration is shorter under full information, with an average of 207.2 seconds, versus private information, with an average of 241.7 seconds. While this did not have a meaningful consequence in our experiment, in practice, longer negotiations can incur additional costs. Thus we support the second part of *Hypothesis 3 (Bargaining)* as well.

**OPENING OFFERS AND ANCHORING.** Past studies have shown that first offers can have an anchoring effect on negotiations (Galinsky and Mussweiler 2001) and influence the final agreement that is reached. Our data allow us to analyze opening offers and determine if there is a similar effect in our experiments. In the interest of brevity, we focus on opening wholesale price offers. The results on opening quantity offers have a similar qualitative interpretation. Table 5 provides the results. Specifically, it depicts two random effects regressions with first offers for wholesale prices as the dependent variable for retailers and suppliers. In both models,  $c = 3$  and  $p = 10$  under full information are the baseline. For the full information case, it is unsurprising to see both the suppliers’ and retailers’ first offers are increasing in the supplier’s cost and the retailer’s price.

The main distinction between retailers and suppliers arises when we consider private information. Suppliers’ first wholesale price offers under private information are indistinguishable from those under full information, as the coefficients on the three `PrivateInfo` terms are insignificant for the supplier. The implication is that suppliers do not appear to exploit their private information by proposing a higher wholesale price. In contrast, for retailers, their first offer under private information is virtually identical to the opening offer made to a  $c = 3$  supplier under full information.

**Table 5** The Effects on Opening Wholesale Price Offers by Role

	Suppliers		Retailers	
$c = 4$	0.511*	(0.289)	0.371	(0.236)
$c = 5$	0.538***	(0.093)	0.981***	(0.099)
$p = 11$	0.836***	(0.127)	0.484***	(0.092)
$p = 12$	1.174***	(0.166)	0.681***	(0.191)
PrivateInfo	0.192	(0.268)	-0.066	(0.304)
$(c = 4) \times (\text{PrivateInfo})$	-0.095	(0.319)	-0.471	(0.297)
$(c = 5) \times (\text{PrivateInfo})$	0.225	(0.176)	-0.965***	(0.148)
Period	0.068***	(0.026)	0.020	(0.039)
Constant	7.037***	(0.213)	5.841***	(0.234)

Note: The dependent variable is the first wholesale price offer, by role. Standard errors, corrected for clustering at the session level, in parentheses. Significance given by \*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , and \*  $p < 0.10$ .

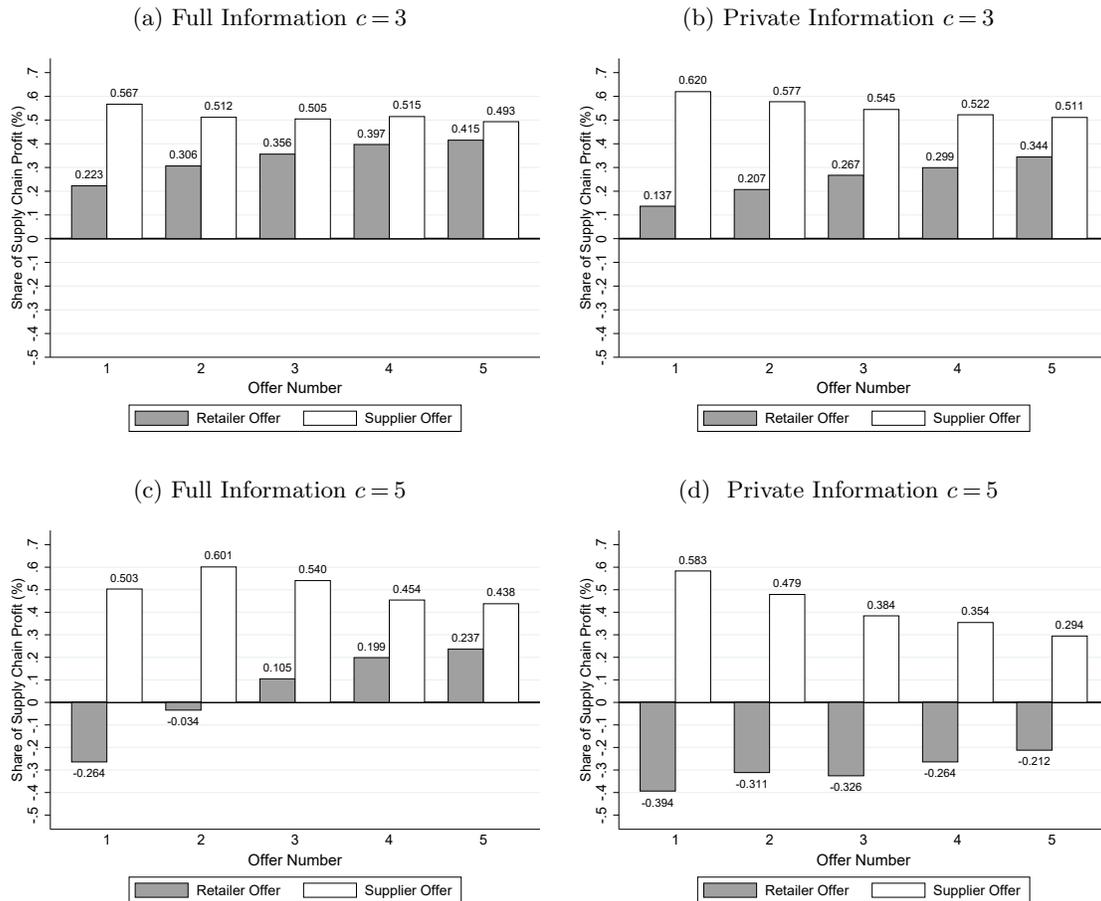
Specifically, under full information for retailers, the coefficient on  $c = 4$  is 0.371 and for  $c = 5$  it is 0.981. However, under private information, the coefficients on the interaction terms (-0.471 for  $c = 4$  and -0.965 for  $c = 5$ ) completely wash away these effects. This means that under private information, retailers begin bargaining as if they are negotiating with the lowest cost supplier.

Building on this analysis, we examine how final agreed upon contract terms are potentially anchored on such opening offers. While the detailed results of a series of random effects regressions of agreed contract terms on opening offers are in Table B.4 in Appendix B, they show that final agreements are indeed significantly and positively associated with each party's first offer. This helps explain why high cost suppliers earn a disproportionately small share of the supply chain expected profits under private information. That is, retailers make opening offers *as if* they were matched with a low cost supplier, and final agreements are anchored on opening offers.

CONCESSION PROCESS. Because players negotiate over both the wholesale price and order quantity simultaneously, we can also evaluate the expected profits of each offer to both players and get a better understanding as to how opening offers translate into final terms. Figure 3 depicts the supplier's average share of the total supply chain expected profit, by offer number, for those negotiations in which a player made at least five offers and an agreement was eventually reached.

We provide plots for  $c = 3$  and  $c = 5$  under full and private information. In all four plots there is a clear concession pattern over time. What is especially striking are the retailers' offers (grey columns) when a supplier has a higher cost,  $c = 5$ . In this case retailers make initial offers that would leave the supplier with a *negative* share of expected total profits. This effect is especially pronounced under private information where the concession process is "flatter" for retailer offers (Figure 3d): even after five offers the retailer is providing the supplier with a negative share.

These bargaining results demonstrate both the importance of first offers and concessions on the bargaining outcome. One caveat to anchoring, however, is that aggressive opening offers could also

**Figure 3** The Concession Process within a Bargaining Round: Supplier's Share of Expected Supply Chain, Conditional on Agreement ( $c = 3$  and  $c = 5$ )

Note: Includes subject-periods in which 5 or more offers were made. A similar pattern is observed for  $c = 4$ .

reduce the likelihood that the players are able to reach an agreement. In Table 6, we report the results of a random effects logit regression where the dependent variable is an indicator for whether an agreement was reached and the explanatory variables are the opening offers of suppliers and retailers as well as indicators for retailer price and supplier cost parameters. Under full information, we see that the higher is the retailer's opening wholesale price (i.e., the *less* aggressive it is), the higher is the likelihood of agreement. However, under private information, there is no such effect. Thus, under private information, we see that retailers make more aggressive opening offers (Table 5), which lead to less favorable agreements for suppliers without increasing the likelihood of disagreement (Table 6). This is consistent with the idea that high-cost suppliers do not blame retailers for being more aggressive under private information, which ultimately leads to less favorable terms.

**Table 6** The Effects on Agreements: First Offers

	Full Information	Private Information
Retailer Wholesale Price	0.873*** (0.320)	0.082 (0.210)
Retailer Quantity	-0.005 (0.013)	-0.026 (0.022)
Supplier Wholesale Price	-0.447 (0.436)	-0.748 (0.480)
Supplier Quantity	-0.031 (0.024)	0.020 (0.043)
$p = 4$	-0.762 (1.240)	-0.415 (0.774)
$c = 5$	-2.071* (1.187)	1.910 (2.156)
$p = 11$	-1.248 (0.775)	-0.318 (1.212)
$p = 12$	0.787 (1.668)	-0.209 (1.159)
Constant	3.681 (3.854)	9.964* (5.565)

Note: The dependent variable is an indicator for whether or not an agreement was reached. Standard errors, corrected for clustering at the session level, in parentheses. Significance given by \*\*\*  $p < 0.01$ , \*\*  $p < 0.05$ , and \*  $p < 0.10$ .

### 5.3. Results Summary

In summary, our experimental results provide support for all three hypotheses. First, consistent with *Hypothesis 1 (Supplier Share)*, all suppliers earn less than 50% of total supply chain profits under private information. Moreover, high-cost suppliers earn a significantly lower share under private information than full information. Second, in line with *Hypothesis 2 (Efficiency)*, supply chain efficiency under private information is significantly below the normative theory for low-cost suppliers and above the normative theory for high-cost suppliers. Third, consistent with *Hypothesis 3 (Bargaining)*, agreement rates are less than 100% and similar between private and full information, and, bargaining duration does indeed take longer under private information.

Our analyses shed light on the drivers of some of these hypothesis test results, particularly *Hypothesis 1 (Supplier Share)*. For instance, as in the full information case, contract terms under private information do not adequately adjust for the risk of unsold inventory. Because this risk is more consequential for high cost suppliers, it is they who disproportionately suffer. Indeed, the bargaining dynamics exacerbate this pain further due to the conflation between private information and the anchoring of initial offers on final agreements. Specifically, because of private information, retailers make significantly more aggressive opening offers (as if they were paired with a low-cost supplier). Final agreements are anchored on these opening offers and, consequently, high-cost suppliers earn lower profits. In what follows, we investigate whether there is an intervention that can help increase profits of high-cost suppliers under private information. To this end, we explore the issue of communication – in particular, providing a supplier with the ability to send a verifiable or non-verifiable message regarding its cost.

## 6. Verifiable Disclosure versus Non-Verifiable Communication

### 6.1. Normative Theory

We now modify our setting by adding, before bargaining, a stage in which the supplier is able to send a message to the retailer. We consider two variants: (1) “verifiable” information disclosure, in which the supplier has the option to disclose her true cost; and (2) “non-verifiable” communication, in which the supplier has the option to send a message about her cost which may not be true.<sup>7</sup>

Consider first the case of verifiable disclosure. Given Proposition 3(ii), since all supplier types benefit from private information, they would never disclose. Doing so would only give up their information rents with no compensating benefit. Thus, theory predicts no disclosure.

Now consider the game with non-verifiable communication and suppose that supplier  $c$  sent a message that her unit-cost is  $c'$ . If this is believed, then the subsequent bargaining outcome must be the Nash bargaining solution under full information given cost  $c'$  and price  $p$  – since, otherwise, it would reveal the supplier to have lied about her cost. Using the wholesale price and quantity derived in Proposition 1, we can compute the supplier’s expected profits from reporting  $c'$  when her true cost is  $c$ :

$$\pi^s(c'|c) = \frac{25(p + 3c' - 4c)(p - c')}{p}.$$

Observe that the partial derivative of profits with respect to reported cost,  $c'$  is:

$$\frac{\partial \pi^s(c'|c)}{\partial c'} = \frac{50(p - 3c' + 2c)}{p},$$

which will be positive so long as  $c' \leq (p+2c)/3$ . Given the parameters of our experiment, this condition is always satisfied. Therefore, all supplier types would strictly prefer to report that they are the highest-cost supplier. Of course, this means that retailers will ignore the message that they receive and the outcome of the game corresponds to the private information bargaining game without communication. We summarize this discussion as follows:

**PROPOSITION 4.** *Given the parameters of our experiment, when bargaining under private information but in which suppliers can communicate:*

- (i) *Under verifiable information disclosure, no supplier discloses their cost and bargaining proceeds as under private information without communication.*

<sup>7</sup> This differs from the classical “cheap talk” experiments which test variants of the Crawford and Sobel (1982) model of strategic information transmission. Specifically, we provide suppliers with the option of not sending any message. Beyond this, after any message is potentially sent, the players engage in a dynamic bargaining process, versus a unilateral decision by the receiver of the message in the classical environment.

- (ii) *Under non-verifiable communication, suppliers have an incentive to inflate their cost. Consequently, retailers ignore any messages and bargaining proceeds as under private information without communication.*

Before proceeding we note that both of these settings exist in practice. Regarding verifiable information disclosure, there are a number of examples of buyers collaborating with suppliers who are transparent about their true costs. For instance, a study on Toyota’s best practices with suppliers includes a quote from a supplier reporting that “We are willing to share our cost structure with Toyota” (Boston Consulting Group 2007). Indeed, disclosure of costs generally requires opening one’s books and does not necessarily pose the same challenges as credibly communicating more latent aspects of supply chains, such as environmental and working conditions (Bateman and Bonanni 2019). Turning to our non-verifiable variant, it is feasible that a company can state their costs without providing supporting evidence. For further details on how companies exchange sensitive information in practice, please see Lamming et al. (2005).

## 6.2. Experimental Design and Hypothesis Development

We conducted new experiments that followed the same procedures as the private information treatment, except that after observing their cost but prior to being matched, suppliers were given the *option* to send a message to the retailer they will be matched with. As with our main experiment, each treatment included 48 participants in groups of six. In one treatment messages were verifiable and in the other treatment messages were non-verifiable (i.e., suppliers could report that their cost was either 3, 4 or 5, or to not send any message, regardless of their true cost). The only other difference was that these treatments included eight rounds (rather than six) because we anticipated it could take time for suppliers to settle upon an optimal policy.

Moving to hypotheses, Proposition 4 represents the null hypothesis based on normative theory. Specifically, (a) no suppliers will disclose under verifiable information disclosure, and (b) suppliers have an incentive to report the highest cost under non-verifiable communication. However, our original experiment gives reason to be skeptical about these predictions with human decision makers. Since high-cost suppliers are disproportionately hurt under private information, they have an incentive to disclose their cost when messages are verifiable. This provides a credible commitment to demand a better initial offer, which should translate into higher earnings. On the other hand, recalling Figure 1, since the lower-cost suppliers are not harmed by private information, we do not expect them to disclose when messages are verifiable. One might question whether disclosure by the high-cost supplier would trigger a cascade effect in which all suppliers disclose. In a previous

working paper, Davis and Hyndman (2018), which this paper supersedes, we show that even if the high-cost supplier discloses, the remaining supplier types still prefer not to disclose. Thus, we have:

**HYPOTHESIS 4 (DISCLOSURE ALT 1).** *When suppliers can disclose their costs through verifiable messages, only high-cost suppliers do so, which leads to higher profits for such suppliers.*

There are also behavioral reasons for why we might expect disclosure to take place for all suppliers in the verifiable variant. Recall the normative theory predicts that, under private information, the supply chain is only coordinated for  $c = 3$ . Therefore, higher cost suppliers with social preferences may opt to disclose in order to increase efficiency. To be sure, if they played the full information Nash bargaining solution, their payoff would suffer but this would be more than offset by the retailer's gain. Past studies have found that some participants are willing to sacrifice their own payoff (up to a point) if efficiency is enhanced (e.g., Charness and Rabin 2002). Additionally, it is plausible that retailers could view disclosure as a kind act and reciprocate by giving suppliers a greater share of the full information surplus. Indeed, there is a non-degenerate set of contract parameters that would represent a Pareto improvement over the private information outcome. Lastly, there is evidence that even non-verifiable communication can be efficiency enhancing (e.g., Ozer et al. 2011, Hyndman et al. 2013, Siegenthaler 2017). Therefore, we include the following alternative hypothesis and use our experimental data to determine which hypothesis, if either, is supported:

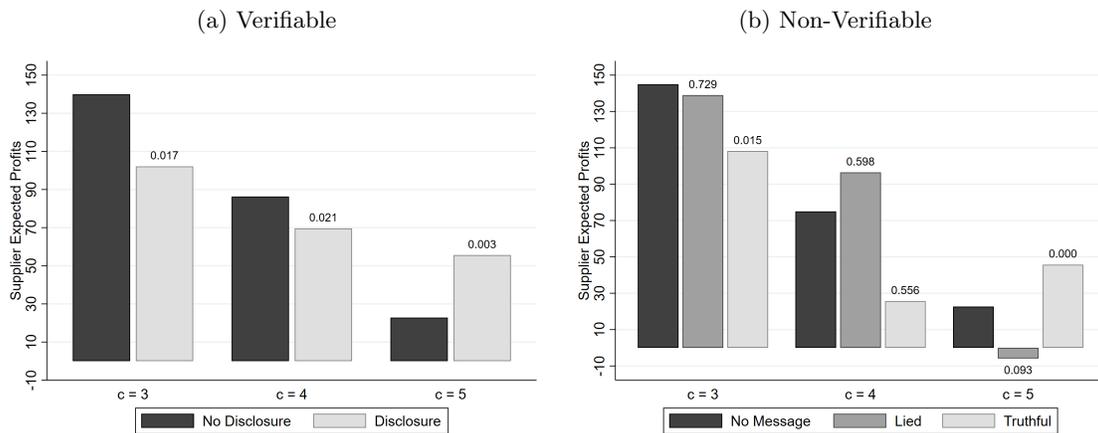
**HYPOTHESIS 5 (DISCLOSURE ALT 2).** *When suppliers can send a message to the retailer before bargaining, all supplier types disclose their cost when verifiable and, when non-verifiable, send truthful messages. In doing so, both efficiency and supplier profits are increased.*

### 6.3. Results

Table 7 reports supplier messages in both treatments. First, under verifiable information disclosure,  $c = 3$  suppliers rarely disclose their cost and  $c = 5$  suppliers disclose their cost nearly 75% of the time. This is consistent with *Hypothesis 4 (Disclosure Alt 1)*. Second, under non-verifiable communication, all supplier cost types report that their cost is  $c = 5$  a majority of the time and in only about 5% of the cases do suppliers with cost  $c \in \{3, 4\}$  report their true cost. This is consistent with the null hypothesis (i.e., normative prediction). Thus, we reject the first part of *Hypothesis 5 (Disclosure Alt 2)*. We also note that, despite our prior belief that there may be learning for suppliers, we found very little: only under verifiable information disclosure did low-cost suppliers learn to disclose significantly less frequently over the course of the experiment.

**Table 7** Observed Frequency of Supplier Messages

(a) Verifiable		(b) Non-Verifiable				
Supplier Type	Disclosure Frequency	Supplier Type	Frequency of Message			
			None	$c' = 3$	$c' = 4$	$c' = 5$
$c = 3$	9.72	$c = 3$	31.25	6.25	7.81	54.69
$c = 4$	37.50	$c = 4$	23.44	0.00	4.69	71.88
$c = 5$	73.61	$c = 5$	23.44	1.56	3.13	71.88

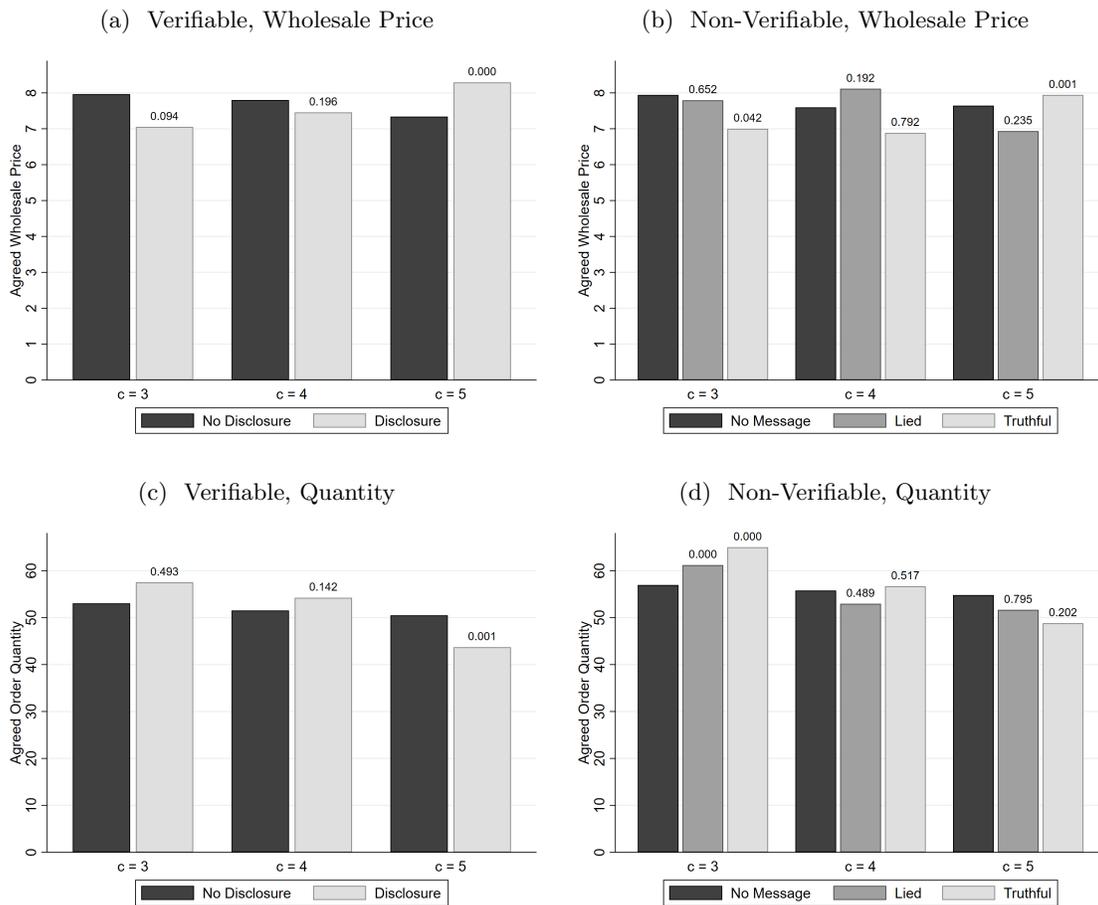
**Figure 4** Observed Supplier Expected Profits and Messages

Note: The numbers on top of the bars represent  $p$ -values of the estimated marginal effects of sending the given message against the baseline of not sending a message.

We turn now to how suppliers' profits are affected by the various messages.<sup>8</sup> Given that, under verifiable information disclosure, disclosure rates are consistent with *Hypothesis 4 (Disclosure Alt 1)*, we expect that such disclosures hurt the  $c = 3$  supplier and help the  $c = 5$  supplier. Figure 4(a) confirms this prediction ( $p = 0.017$  for  $c = 3$  and  $p < 0.01$  for  $c = 5$ ). This further supports *Hypothesis 4 (Disclosure Alt 1)* and indicates that, in practice, high-cost suppliers should attempt to credibly reveal their costs in an effort to achieve more favorable outcomes. We also conducted an additional test (not shown in Figure 4(a)) comparing supplier profits in the original full information treatment with participants who disclosed in the verifiable disclosure treatment. For no supplier cost types is the difference significant.

In contrast, under non-verifiable communication, given that messages are consistent with the null hypothesis, we expect that retailers should ignore them, which should lead to no differences in earnings depending on the message. However, as can be seen, when suppliers are truthful it hurts  $c \in \{3, 4\}$  suppliers and helps the  $c = 5$  supplier, relative to not sending a message. When

<sup>8</sup> Agreement rates are similar to each other and our main experiment, 90.74% in verifiable and 91.67% in non-verifiable.

**Figure 5** Observed Wholesale Price, Quantity, and Messages, Conditional on Agreement

Note: The numbers on top are  $p$ -values of the marginal effects of the given message against the baseline of not sending any message.

suppliers lie about their cost, there is no significant effect for the  $c \in \{3, 4\}$  suppliers and, not surprisingly, a negative effect for the  $c = 5$  supplier. Again, these results lend further support to the null hypothesis with respect to non-verifiable communication.

Figure 5 shows the effects of supplier messages on the contract parameters. The results are intuitive, for the  $c \in \{3, 4\}$  suppliers, both disclosing and sending a truthful message leads to a lower wholesale price and higher order quantity, which explains why they earn less. On the other hand, for the  $c = 5$  supplier, both disclosing and sending a truthful message leads to a higher wholesale price *and* a lower order quantity, which has a favorable compound effect on earnings.

Our results on supplier messages and earnings are largely supportive of *Hypothesis 4 (Disclosure Alt 1)*. However, this could also co-exist with the aforementioned behavioral factors which suggest that disclosure and truthful messages could grow the pie and allow retailers to benefit as well. However, as Table 8 shows, retailers significantly benefit following a message that supplier cost

**Table 8** The Effects of Messages on Retailer Expected Profits

	Verifiable		Non-Verifiable	
Message = 3	37.611***	(10.058)	57.398***	(14.355)
Message = 4	11.004	(7.718)	16.305	(20.794)
Message = 5	-29.583***	(6.975)	-13.773**	(6.820)
$p = 11$	21.017***	(6.027)	19.269***	(5.848)
$p = 12$	34.680***	(4.129)	54.326***	(7.777)
Constant	101.980***	(6.142)	105.167***	(6.462)

is 3 (whether verifiable or not) and significantly suffer following a message that supplier cost is 5 (whether verifiable or not). These were precisely the cases in which suppliers suffered and gained. The punchline is that suppliers' gains or losses are offset by nearly equivalent losses or gains by retailers, rejecting *Hypothesis 5 (Disclosure Alt 2)*. From a managerial standpoint, this indicates that while truthful messages by lower-cost suppliers are rare in the non-verifiable condition (around 5%), when they do take place, they are not beneficial to suppliers. Instead, retailers use the information to squeeze suppliers. This result runs counter to related experiments on private information in operations management, such as Ozer et al. (2011), who consider an environment where a buyer has private information about a forecast and find that messages are much more informative about the true state than theory predicts, which leads to significantly higher supply chain efficiency.

## 7. Conclusion

In practice it is not common for buyers in a B2B setting to have perfect information about their supplier's cost. Further, many companies negotiate with one another in a more equitable back-and-forth bargaining environment. In this study we investigate private supplier cost information in a two-stage supply chain with dynamic unstructured bargaining. We first examine this setting theoretically and find that, given our experimental parameters, suppliers should benefit from their private cost information while bargaining.

Despite this theoretical benefit, however, our human-subjects experiment shows that certain types of suppliers are actually disadvantaged by having private cost information. In particular, high-cost suppliers under private information earn the lowest share of overall supply chain expected profit. Through our experimental data, we are able to determine that this is driven by a number of behavioral bargaining tendencies by buyers and suppliers, rather than, say, social preferences. Indeed, fairness concerns cannot be the main driver because our result that high-cost suppliers earn less than half the surplus holds under full information as well, where we would expect a 50-50 norm to hold for all costs.

Instead, we see that under private information, buyers make opening offers that are similar to their initial offers to the lowest-cost supplier under full information and that final agreements are anchored on these opening offers. As a result, high-cost suppliers not only end up with slightly lower wholesale prices but also higher quantities, which contributes directly to a low share of the overall supply chain expected profits. Lastly, under private information, buyers appear to be able to hide behind a veil of ignorance: aggressive opening offers by buyers do not increase the chance of disagreement like they do under full information.

Our study provides a number of insights for managers in practice. First, while some suppliers may be reluctant to share their private cost information with buyers, our work indicates that such an action is beneficial for certain types of suppliers. In particular, our additional experiments find that high-cost suppliers earn significantly higher profits when they can credibly disclose their private cost information. Second, private information does not necessarily lead to a higher rate of disagreement, however, it does lead to longer negotiation times. In practice, where longer negotiations can require additional expenses, both parties may benefit from a supplier's cost being full information in the hopes of coming to an agreement in a timely manner. Both of these recommendations could foster further collaborative interactions between buyers and suppliers and yield additional benefits.

One limitation of our study relates to the timing of disclosure. Specifically, our results suggest that, for a given buyer, the high-cost supplier earns more and the low-cost supplier earns less when they disclose their cost. That is, disclosure does not appear to create goodwill in our setting, which could limit its value. However, if disclosure occurs before the retailer and supplier are committed to a relationship, then the both the low-cost and high-cost supplier face a tension: for a given buyer she will earn less (low-cost supplier) or more (high-cost supplier) during bargaining, but by disclosing one's cost the supplier reveals her desirability as a matching partner. Specifically, the low-cost supplier reveals herself to be desirable, while the high-cost supplier is revealed to be undesirable. Thus, the type of retailer a supplier can match with may change, which affects the overall size of the pie. Davis and Hyndman (2019b) study this tension between matching and disclosure in supply chains. Therefore, our results suggest that high-cost suppliers should delay their disclosure decision until they are bargaining with a buyer. In addition, while we believe that it is possible for companies to open their books and credibly reveal their private costs (e.g. Boston Consulting Group 2007, Jackson and Pfitzmann 2007), we admit that this may not be feasible for all suppliers.

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## Appendix

### A. Details and Proofs: Bargaining with Private Information

#### A.1. Proofs

The expected profits of the retailer can be written as:

$$\pi_r(p, c, w, q) = \frac{p-w}{200} (200q - q^2),$$

while the expected profits of the supplier can be written as:

$$\pi_s(p, c, w, q) = \frac{w}{200} (200q - q^2) - cq.$$

LEMMA 1. *Let  $\mathcal{M}$  be an incentive compatible mechanism. Then  $\gamma_1 q_1 \geq \gamma_2 q_2 \geq \gamma_3 q_3$ .*

*Proof:* Observe that incentive compatibility requires:

$$\begin{aligned} \gamma_i \left( \left( \frac{w_i}{200} \right) (200q_i - q_i^2) - c_i q_i \right) &\geq \gamma_j \left( \left( \frac{w_j}{200} \right) (200q_j - q_j^2) - c_i q_j \right) \\ &\geq \gamma_j \left( \left( \frac{w_j}{200} \right) (200q_j - q_j^2) - c_j q_j \right) \\ &\geq \gamma_i \left( \left( \frac{w_i}{200} \right) (200q_i - q_i^2) - c_j q_i \right) \end{aligned}$$

This means that, for  $j > i$ :

$$\gamma_i q_i (c_j - c_i) \geq \gamma_j q_j (c_j - c_i).$$

Hence,

$$(\gamma_i q_i - \gamma_j q_j)(c_j - c_i) \geq 0,$$

which, upon recognizing that  $c_j - c_i > 0$  for  $j > i$ , completes the proof. Q.E.D.

LEMMA 2. *Given any incentive compatible mechanism,  $\mathcal{M} = \{(\gamma_i, w_i, q_i), i = 1, 2, 3\}$ , there exists an alternative mechanism,  $\bar{\mathcal{M}} = \{(1, \bar{w}_i, \bar{q}_i), i = 1, 2, 3\}$ , such that disagreement never happens which is also incentive compatible and generates the same expected profits for each supplier type and the retailer.*

*Proof:* Given the mechanism,  $\mathcal{M}$ , the expected profits of the type  $i$  supplier and of the retailer (conditional on matching with this supplier) are:

$$\begin{aligned} \pi_s^i &= \gamma_i \left( \left( \frac{w_i}{200} \right) (200q_i - q_i^2) - c_i q_i \right) \\ \pi_r^i &= \gamma_i \left( \left( \frac{p-w_i}{200} \right) (200q_i - q_i^2) \right). \end{aligned}$$

Therefore, to find the alternative mechanism with no disagreement, we must solve the following system of equations:

$$\begin{aligned} \left( \left( \frac{\bar{w}_i}{200} \right) (200\bar{q}_i - \bar{q}_i^2) - c_i \bar{q}_i \right) &= \pi_s^i \\ \left( \left( \frac{p-\bar{w}_i}{200} \right) (200\bar{q}_i - \bar{q}_i^2) \right) &= \pi_r^i. \end{aligned}$$

Note that a solution to this system is guaranteed because, by varying  $\bar{q}_i$  from zero to the efficient quantity, any channel profit level that was possible under  $\mathcal{M}$  is obtainable. Furthermore, by varying  $\bar{w}_i$ , from  $c_i$  to  $p$ , any division of profits between the retailer and supplier is achievable. One can show that:<sup>9</sup>

$$\bar{q}_i = \frac{-\sqrt{4p(200c_i\gamma_i q + \gamma_i p q_i^2 - 200\gamma_i p q_i) + (200p - 200c_i)^2} - 200c_i + 200p}{2p}.$$

It remains to be seen that the new mechanism preserves incentive compatibility. It is sufficient to show that (i.e., that expected profits from misreporting are lower in the new mechanism):

$$\gamma_{i+1} \left( (w_{i+1}/200)(200q_{i+1} - q_{i+1}^2) - c_i q_{i+1} \right) \geq \left( (\bar{w}_{i+1}/200)(200\bar{q}_{i+1} - \bar{q}_{i+1}^2) - c_i \bar{q}_{i+1} \right).$$

By adding and subtracting  $\gamma_{i+1}c_{i+1}q_{i+1}$  to the left-hand side and then substituting for the payoff equivalent contract, we can simplify the above inequality to:

$$\gamma_{i+1}q_{i+1} \geq \bar{q}_{i+1}.$$

Finally, if (for ease of notation) we drop the subscripts, the above expression is equivalent to:

$$\frac{\sqrt{10000c^2 + 200cp(\gamma q - 100) + p^2(\gamma(q - 200)q + 10000)} + 100c + \gamma pq - 100p}{p} \geq 0.$$

After some algebraic manipulations (taking parts outside the square-root sign to the other side and then squaring both sides), this can be simplified to:

$$(1 - \gamma)\gamma p^2 q^2 \geq 0,$$

and it is easy to see that the above inequality holds.

Q.E.D.

**PROPOSITION 2.** *There exist incentive compatible mechanisms in which the supply chain is coordinated for all possible supplier types. That is,  $q_i = 100((p - c_i)/p)$  for all  $i$ .*

*Proof:* One can show that the mechanism is both fully efficient and incentive compatible if the following inequalities hold:

$$w_i \geq \frac{p^2 - c_j^2}{p^2 - c_i^2} w_j + \frac{2pc_i(c_j - c_i)}{p^2 - c_i^2}$$

$$w_i \leq \frac{p^2 - c_j^2}{p^2 - c_i^2} w_j + \frac{2pc_j(c_j - c_i)}{p^2 - c_i^2}$$

for  $i = 1, 2$ ,  $j = 2, 3$  and  $j \neq i$ . Moreover, one can also show that there do exist efficient mechanisms. While it is computationally tedious, if we let  $w_3 = p^{(p+3c_3)}/(2(p+c_3))$  and then take the smallest  $w_2$  for the given  $w_3$  and the smallest  $w_1$  for the given  $w_2$ , then the above inequalities are all satisfied.

Q.E.D.

<sup>9</sup> As will become apparent, the solution for  $\bar{w}_i$  is not necessary so we omit it, also because it is particularly messy.

## A.2. Myerson's Bargaining Solution

We can set up the objective function as:

$$\begin{aligned} \max_{q_i, w_i} &= \lambda_1 \pi_s(p, c_1, w_1, q_1) + \lambda_2 \pi_s(p, c_2, w_2, q_2) + (1 - \lambda_1 - \lambda_2) \pi_s(p, c_3, w_3, q_3) \\ &+ \frac{1}{3} (\pi_r(p, c_1, w_1, q_1) + \pi_r(p, c_2, w_2, q_2) + \pi_r(p, c_3, w_3, q_3)) \end{aligned}$$

subject to the incentive compatibility constraint that the supplier type  $c_i$  does not mimic the supplier type  $c_{i+1}$  for  $i = 1, 2$ :

$$\begin{aligned} \pi_s(p, c_1, w_1, q_1) &\geq \pi_s(p, c_1, w_2, q_2) \\ \pi_s(p, c_2, w_2, q_2) &\geq \pi_s(p, c_2, w_3, q_3). \end{aligned}$$

The Lagrangean can be rewritten as:

$$\begin{aligned} \mathcal{L} &= \frac{1}{3} \left( 3(\lambda_1 + \alpha_1) \left( \frac{w_1}{200} (200q_1 - q_1^2) - c_1 q_1 \right) + \frac{p - w_1}{200} (200q_1 - q_1^2) \right) \\ &+ \frac{1}{3} \left( 3(\lambda_2 + \alpha_2) \left( \frac{w_2}{200} (200q_2 - q_2^2) - c_2 q_2 \right) - 3\alpha_1 \left( \frac{w_2}{200} (200q_2 - q_2^2) - c_1 q_2 \right) + \frac{p - w_2}{200} (200q_2 - q_2^2) \right) \quad (2) \\ &+ \frac{1}{3} \left( 3(1 - \lambda_1 - \lambda_2) \left( \frac{w_3}{200} (200q_3 - q_3^2) - c_3 q_3 \right) - 3\alpha_2 \left( \frac{w_3}{200} (200q_3 - q_3^2) - c_2 q_3 \right) + \frac{p - w_3}{200} (200q_3 - q_3^2) \right) \end{aligned}$$

Observe that the linearity in  $w$  implies that  $\lambda_1 + \alpha_1 = 1/3$  and  $\lambda_2 + \alpha_2 - \alpha_1 = 1/3$ . The next step is to optimize with respect to  $q_i$ .

This yields:

$$q_1 = \frac{100(p - w_1 + 3(\lambda_1 + \alpha_1)(w_1 - c_1))}{p - w_1 + 3(\lambda_1 + \alpha_1)w_1} \quad (3)$$

$$q_2 = \frac{100(p - w_2(3(\lambda_2 + \alpha_2 - \alpha_1) - 1) - 3(\lambda_2 + \alpha_2)c_2 + 3\alpha_1 c_1)}{p + w_2(3(\lambda_2 + \alpha_2 - \alpha_1) - 1)} \quad (4)$$

$$q_3 = \frac{100(p + w_3(3(1 - \lambda_1 - \lambda_2) - 3\alpha_2 - 1) - 3(1 - \lambda_1 - \lambda_2)c_3 + 3\alpha_2 c_2)}{p + w_3(3(1 - \lambda_1 - \lambda_2) - 3\alpha_2 - 1)}. \quad (5)$$

With these values for quantities and also using the relationship between the  $\alpha$  and  $\lambda$  variables, we obtain the value of the objective function (as a function of the  $\lambda$ s):

$$\frac{50}{3} \left( \frac{(p - c_1)^2}{p} + \frac{(p + c_1 - 3\lambda_1 c_1 + c_2(3\lambda_1 - 2))^2}{p} + \frac{(p + c_2(2 - 3\lambda_1 - 3\lambda_2) - 3c_3(1 - \lambda_1 - \lambda_2))^2}{p} \right)$$

The warrant conditions imply that:

$$(\lambda_1 + \alpha_1)W_1 = \frac{1}{2} \frac{50}{3} \left( \frac{(p - c_1)^2}{p} \right) \quad (6)$$

$$(\lambda_2 + \alpha_2)W_2 - \alpha_1 W_1 = \frac{1}{2} \frac{50}{3} \left( \frac{(p + c_1 - 3\lambda_1 c_1 + c_2(3\lambda_1 - 2))^2}{p} \right) \quad (7)$$

$$(1 - \lambda_1 - \lambda_2)W_3 - \alpha_2 W_2 = \frac{1}{2} \frac{50}{3} \left( \frac{(p + c_2(2 - 3\lambda_1 - 3\lambda_2) - 3c_3(1 - \lambda_1 - \lambda_2))^2}{p} \right). \quad (8)$$

This yields:

$$W_1^* = \frac{25(p - c_1)^2}{p} \quad (9)$$

$$W_2^* = \frac{25(p^2 + c_1^2(1 - 3\lambda_1) + c_2^2(2 - 3\lambda_1) - 2c_1 c_2(1 - 3\lambda_1) - 2c_2 p)}{p} \quad (10)$$

$$W_3^* = \frac{25(c_1^2(3\lambda_1 - 1)(3\lambda_1 + 3\lambda_2 - 2) - 2c_1c_2(3\lambda_1 - 1)(3\lambda_1 + 3\lambda_2 - 2) + c_2^2(18\lambda_1^2 + 3\lambda_1(9\lambda_2 - 8) + 9\lambda_2^2 - 18\lambda_2 + 8))}{3p(1 - \lambda_1 - \lambda_2)} \quad (11)$$

$$+ \frac{25(-6c_2c_3(3\lambda_1^2 + \lambda_1(6\lambda_2 - 5) + 3\lambda_2^2 - 5\lambda_2 + 2) + 3(\lambda_1 + \lambda_2 - 1)(3c_3^2(\lambda_1 + \lambda_2 - 1) + 2c_3p - p^2))}{3p(1 - \lambda_1 - \lambda_2)}. \quad (12)$$

It remains to solve for  $\lambda_1$ ,  $\lambda_2$ ,  $w_1$ ,  $w_2$  and  $w_3$ . To do this, we use the expressions for  $W_i$ , where we impose that  $W_i$  is greater than or equal to the expected profits for supplier type  $i$  (with equality if  $\lambda_i$  is interior) and the incentive compatibility constraints (which must be satisfied with equality if  $\alpha_i > 0$ ). Specifically, the solution must satisfy:

$$\begin{aligned} \pi_s(w_i, q_i, c_i) &\geq W_i^*, \text{ with equality if } \lambda_i > 0, \\ \pi_s(w_i, q_i, c_i) &\geq \pi_s(w_{i+1}, q_{i+1}, c_i), \text{ for } i = 1, 2 \text{ and with equality if } \alpha_i > 0. \end{aligned}$$

This leads to many cases to consider.

Using the values that we implemented in the experiment, the relevant case is  $\lambda_1 = \lambda_2 = 0$ . In this case, we have:

$$\begin{aligned} w_1 &= \frac{p(-22c_1^2 + 32c_1c_2 - 40c_2^2 + 48c_2c_3 + 3(-9c_3^2 + 2c_3p + p^2))}{6(p^2 - c_1^2)}, & q_1 &= \frac{100(p - c_1)}{p} \\ w_2 &= \frac{p(2c_1^2 + 8c_1c_2 - 40c_2^2 + 48c_2c_3 + 3(-9c_3^2 + 2c_3p + p^2))}{6(-c_1^2 + 4c_1c_2 - 4c_2^2 + p^2)}, & q_2 &= \frac{100(p - 2c_2 + c_1)}{p} \\ w_3 &= \frac{p(2c_1^2 - 4c_1c_2 + 8c_2^2 + 12c_2c_3 + 3(-9c_3^2 + 2c_3p + p^2))}{6(-4c_2^2 + 12c_2c_3 - 9c_3^2 + p^2)}, & q_3 &= \frac{100(p - 3c_3 + 2c_2)}{p} \end{aligned}$$

Upon substituting for prices for the retailer prices ( $p \in \{10, 11, 12\}$ ) and supplier costs ( $c_1 = 3$ ,  $c_2 = 4$  and  $c_3 = 5$ ) that we implemented, the precise numerical predictions are depicted in Table B.1.

As noted in the main text of the paper, regardless of the value of  $p \in \{10, 11, 12\}$ , all supplier cost types are expected to benefit relative to full information. We conducted a numerical analysis of various price/cost scenarios to determine how representative our chosen experimental parameters were. Specifically, for each retailer price, for 5000 trials, we drew three supplier costs from a uniform distribution with various supports and determined which supplier types benefited from private information, relative to full information. The results of this are reported in Table A.1. As can be seen, when the critical fractile is high (i.e.,  $c \leq p/2$ ), about 94% of the time *all* supplier types benefit from private information and it almost never happens that *no* supplier type benefits.

**Table A.1 Myerson Bargaining Solution For Other Parameters**

Price	Cost Draws	Which Supplier(s) Benefit? (%)					
		All	None	$c_1$	$c_2$	$c_3$	Other
10	$c_i \sim U[p/20, p/2]$ , sorted	93.80	0.00	0.00	4.59	1.32	0.29
11	$c_i \sim U[p/20, p/2]$ , sorted	94.65	0.06	0.00	4.01	0.94	0.33
12	$c_i \sim U[p/20, p/2]$ , sorted	94.37	0.02	0.00	4.15	1.19	0.27
10	$c_i \sim U[p/20, p/1.1]$ , sorted	54.41	0.85	0.00	29.00	3.79	11.94
11	$c_i \sim U[p/20, p/1.1]$ , sorted	54.52	0.75	0.00	29.14	3.32	12.28
12	$c_i \sim U[p/20, p/1.1]$ , sorted	54.96	0.73	0.00	28.48	3.08	12.75

In contrast, when supplier costs may exceed half the retailer price, then it becomes less common that all supplier types benefit – about 55%; however, it is still uncommon that no supplier type benefits –  $< 1\%$ . There

is also more room for something else to happen, which is typically the case that only the middle supplier,  $c_2$ , benefits – about 29%. In all of our numerical calculations, it was exceedingly rare that *any* supplier type actually earned strictly less than their full information payoff, and when it did happen, the payoff differences were very small. Thus, we suspect that these events are quite possibly caused by machine precision issues. Thus, our numerical study suggests that suppliers are never *worse off* under private information.

## B. Additional Tables and Figures

**Table B.1 Experimental Predictions**

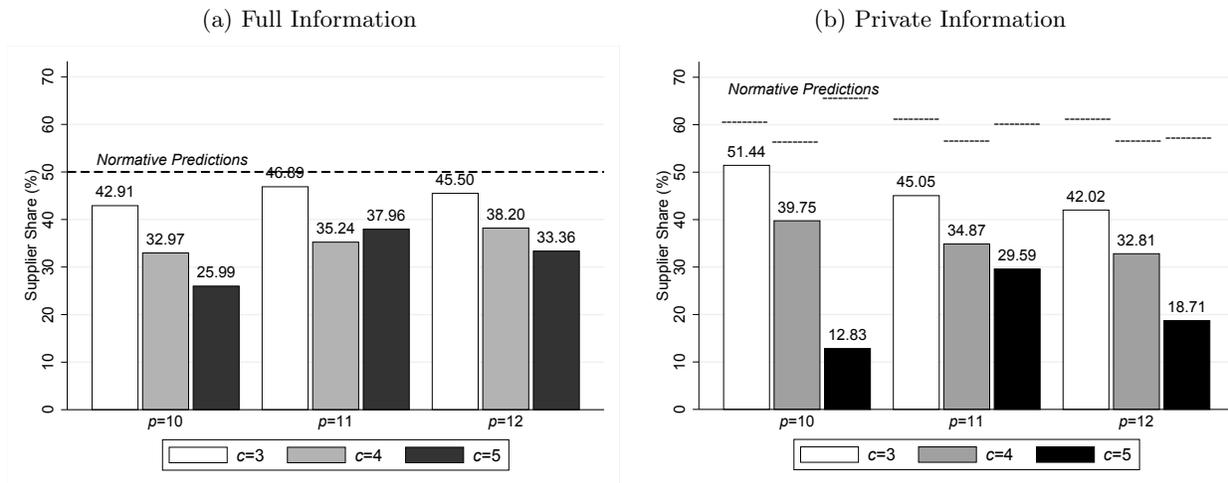
(a) Full Information												
	Supplier Share (%)			Efficiency (%)			Wholesale Price ( $w$ )			Quantity ( $q$ )		
	$p = 10$	$p = 11$	$p = 12$	$p = 10$	$p = 11$	$p = 12$	$p = 10$	$p = 11$	$p = 12$	$p = 10$	$p = 11$	$p = 12$
$c = 3$	50.00	50.00	50.00	100	100	100	7.31	7.86	8.40	70.00	72.73	75.00
$c = 4$	50.00	50.00	50.00	100	100	100	7.86	8.43	9.00	60.00	63.64	66.67
$c = 5$	50.00	50.00	50.00	100	100	100	8.33	8.94	9.53	50.00	54.55	58.33
Average	100			50.00			8.41			63.43		

(b) Private Information												
	Supplier Share (%)			Efficiency (%)			Wholesale Price ( $w$ )			Quantity ( $q$ )		
	$p = 10$	$p = 11$	$p = 12$	$p = 10$	$p = 11$	$p = 12$	$p = 10$	$p = 11$	$p = 12$	$p = 10$	$p = 11$	$p = 12$
$c = 3$	60.88	61.46	61.52	100	100	100	7.89	8.58	9.23	70.00	72.73	75.00
$c = 4$	56.67	56.94	56.88	97.22	97.96	98.44	7.98	8.63	9.26	50.00	54.55	58.35
$c = 5$	65.87	60.42	57.41	84.00	88.89	91.84	8.59	9.06	9.58	30.00	36.36	41.67
Average	95.37			59.78			8.76			54.29		

Note: The supplier's share under private information is based on the *ex ante* expected profits.

**Figure B.1 Supplier Share (%) of Supply Chain Expected Profit, Conditional on Agreement**



**Table B.2 Efficiency (%), Conditional on Agreement**

	Full Info			Private Info		
	$p = 10$	$p = 11$	$p = 12$	$p = 10$	$p = 11$	$p = 12$
$c = 3$	91.70 <sup>‡</sup> (2.77)	90.31 <sup>‡</sup> (2.26)	88.28 <sup>‡</sup> (1.53)	90.52 <sup>‡</sup> (1.54)	89.40 <sup>‡</sup> (2.62)	92.11 <sup>‡</sup> (2.14)
$c = 4$	93.46 <sup>‡</sup> (2.64)	89.12 <sup>‡</sup> (5.25)	88.56 <sup>‡</sup> (3.30)	92.79* (2.33)	95.63 <sup>†</sup> (0.97)	97.26 (0.81)
$c = 5$	92.75 <sup>‡</sup> (1.94)	94.60 <sup>‡</sup> (1.71)	92.93 <sup>‡</sup> (3.13)	94.03 <sup>‡</sup> (2.31)	94.70 <sup>†</sup> (2.18)	87.12 (4.39)
Overall	91.34 <sup>‡</sup>			92.67 <sup>‡</sup>		
Average	(0.95)			(0.82)		

Note: Standard errors across groups are reported in parentheses. Significance of t-tests versus the normative theory given by <sup>‡</sup>  $p < 0.01$ , <sup>†</sup>  $p < 0.05$ , and \*  $p < 0.10$ .

**Table B.3 Quantities and Wholesale Prices, Conditional on Agreement**

	(a) Full Information						(b) Private Information					
	Wholesale Price ( $w$ )			Quantity ( $q$ )			Wholesale Price ( $w$ )			Quantity ( $q$ )		
	$p = 10$	$p = 11$	$p = 12$	$p = 10$	$p = 11$	$p = 12$	$p = 10$	$p = 11$	$p = 12$	$p = 10$	$p = 11$	$p = 12$
$c = 3$	6.74 <sup>†</sup> (0.19)	7.35 <sup>†</sup> (0.15)	7.82 (0.29)	57.31 <sup>‡</sup> (3.18)	53.50 <sup>‡</sup> (3.79)	57.75* (7.23)	7.08 <sup>†</sup> (0.26)	7.23 <sup>‡</sup> (0.23)	7.50 <sup>‡</sup> (0.18)	50.17 <sup>‡</sup> (1.92)	52.38 <sup>‡</sup> (4.01)	57.33 <sup>‡</sup> (3.86)
$c = 4$	7.16 <sup>‡</sup> (0.10)	7.34 <sup>‡</sup> (0.27)	7.97 <sup>‡</sup> (0.23)	56.20 (6.70)	59.29 (6.82)	50.93 <sup>†</sup> (5.29)	7.27 <sup>‡</sup> (0.13)	7.55 <sup>‡</sup> (0.21)	7.73 <sup>†</sup> (0.48)	50.35 (3.33)	56.25 (3.87)	57.81 (1.90)
$c = 5$	7.68 <sup>‡</sup> (0.18)	8.29 <sup>‡</sup> (0.14)	8.42 <sup>‡</sup> (0.12)	49.34 (4.26)	47.19 <sup>†</sup> (2.95)	48.19 <sup>‡</sup> (2.24)	7.54 <sup>‡</sup> (0.15)	7.87 <sup>‡</sup> (0.19)	8.35 <sup>‡</sup> (0.20)	56.86 <sup>‡</sup> (1.69)	46.75 <sup>†</sup> (3.05)	50.93 (6.67)
Overall	7.64 <sup>‡</sup>			53.11 <sup>‡</sup>			7.57 <sup>‡</sup>			53.20		
Average	(0.09)			(1.59)			(0.09)			(1.25)		

Note: Standard errors across groups are reported in parentheses. Significance of t-tests versus the normative theory given by <sup>‡</sup>  $p < 0.01$ , <sup>†</sup>  $p < 0.05$ , and \*  $p < 0.10$ .

**Table B.4 The Effects on Agreed Contract Terms: Anchoring on First Offers**

	Wholesale Price				Order Quantity			
	Suppliers		Retailers		Suppliers		Retailers	
First $w$ Offer	0.350 <sup>‡</sup>	(0.093)	0.255 <sup>‡</sup>	(0.055)	0.450 <sup>‡</sup>	(0.067)	0.364 <sup>‡</sup>	(0.075)
First $q$ Offer					0.450 <sup>‡</sup>	(0.067)	0.364 <sup>‡</sup>	(0.075)
$c = 4$	-0.001	(0.096)	0.209 <sup>†</sup>	(0.094)	-1.155	(1.712)	-1.074	(1.933)
$c = 5$	0.373 <sup>‡</sup>	(0.129)	0.543 <sup>‡</sup>	(0.119)	-1.876*	(1.131)	-3.754 <sup>†</sup>	(1.895)
PrivateInfo	-0.199	(0.166)	0.012	(0.145)	-1.720	(2.296)	-2.024	(2.986)
$p = 11$	0.223 <sup>‡</sup>	(0.071)	0.266 <sup>‡</sup>	(0.091)	-1.127	(1.931)	0.232	(1.848)
$p = 12$	0.489 <sup>‡</sup>	(0.138)	0.565 <sup>‡</sup>	(0.111)	-0.543	(2.427)	-1.004	(2.209)
Period	0.052 <sup>†</sup>	(0.024)	0.040 <sup>†</sup>	(0.016)	-0.731 <sup>†</sup>	(0.333)	-0.814 <sup>†</sup>	(0.421)
Constant	4.248 <sup>‡</sup>	(0.603)	5.291 <sup>‡</sup>	(0.373)	37.007 <sup>‡</sup>	(3.613)	36.271 <sup>‡</sup>	(3.679)

Note: The dependent variable is the agreed wholesale price for the first two regressions and the agreed order quantity for the last two regressions. Standard errors, corrected for clustering at the session level, in parentheses. Significance given by <sup>‡</sup>  $p < 0.01$ , <sup>†</sup>  $p < 0.05$ , and \*  $p < 0.10$ .