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An Experimental Investigation of Outsourcing through Competition

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Abstract

Our research uses laboratory experiments to examine the theoretical results of competition between suppliers in an outsourcing setup. We consider a supply chain in which a single buyer needs to outsource the manufacturing of a product among N potential suppliers. The buyer allocates demand to suppliers not on the basis of price, but rather on service. We analyze the levels of service suppliers will decide to provide when competing on three different criteria specified by the buyer. For the first, suppliers compete by providing the buyer a specific service level (fill-rate), and for the second by maintaining a specific quantity of on-hand inventory. For the third criteria, suppliers compete based on a parameter designed to optimize the supply chain in favor of the buyer. Prior research and existing theory predict that the decisions will reach stability at the Nash equilibrium for all three types of competition. Theory also predicts these equilibrium points will be ordered, from competitions based on service level as the lowest and those based on the optimal criteria as the highest.

Our experimental results show that the equilibrium points reached by subjects are in fact ordered as theory predicts. However, there are large and statistically significant differences between those equilibrium points and the theoretical predictions. Using the Quantal Response Equilibrium (QRE) we show that random errors can explain some of these discrepancies. Our analyses also suggest that, under optimal criteria for competition, other behavioral factors such as rival chasing and loss aversion can play an influential role.

Keywords: Behavioral Operations Management; Outsourcing; Inventory Competition; Service Competition; Optimal Mechanism

1. Introduction

The importance of outsourcing is widely accepted both in academia and among the practitioners. Outsourcing, among other benefits, let companies focus on their core competencies and be more flexible in this increasingly competitive and volatile business world. What is still debatable among the experts is how to perform the outsourcing. The traditional approach is to negotiate the contract terms with the suppliers. Some buyers then add incentives such as revenue sharing or monetary rewards/penalties based on the quality of service they receive. Another approach, which can save negotiation efforts, is to let the suppliers compete for the buyer's business. Many researchers have studied different forms of supplier competition in an outsourcing setup. Although outsourcing through competition has been widely studied in the literature, the existing theoretical results have never been, to the best of our knowledge, subjected to empirical verification.

In this paper, we use laboratory experiments to investigate whether subjects who play the role of competing suppliers make decisions according to the theoretical predictions. We use the results developed by Elahi (2013) as our theoretical basis. Elahi (2013) provides the theoretical results for different types of competition in an outsourcing setup. The author uses a stylized queuing model to analyze the competition between make-to-stock suppliers when they compete for the demand share of a buyer based on different performance measures (competition criteria). He considers three types of competition. In the first type of competition, each supplier receives a portion of the buyer's demand, which is proportional to the service level he guarantees over the sum of the service levels provided by all suppliers (proportional allocation). Since the demand share is proportional to the service level, this type of competition is called *service competition*. In this type of competition, each supplier can increase his demand share by providing a higher service level (while considering his competitors' service levels). Although higher service level can result in a larger share of the buyer's business, it also means higher service cost for the supplier. Here, we measure service by the probability of meeting the buyer's demand from on-hand inventory (fill rate).

In the second type of competition, the buyer's demand is allocated to the suppliers proportional to the inventory level that each supplier keeps (*inventory competition*). A similar dynamics creates the competition between the suppliers in this case too. In the third type of competition, the buyer’s demand is allocated based on a parameter that is designed to intensify the competition to a level where each supplier exerts his maximum feasible effort (*optimal competition*). This parameter is a combination of service level, inventory level, and suppliers’ cost functions. Although using this parameter (as the competition criteria) is more complicated than using simple criteria such as service or inventory levels, this type of (optimal) competition can produce the best results for the buyer.

Through our experiments, we first want to verify if the subjects’ decisions converge to the predicted Nash equilibrium in the three abovementioned types of competition. We also want to compare the subjects’ decisions under different types of competition and verify if the differences between these decisions follow the same pattern as the theory predicts. We are specifically interested to see if the optimal competition can produce the desirable results for the buyer as the theory promises.

Our results show that the subjects’ decisions do not necessarily converge to the Nash equilibrium. Under service and inventory competitions, subjects’ decisions are usually higher than the Nash equilibrium. Under the optimal competition, the subjects’ decisions are usually lower than the Nash equilibrium, except for the less efficient suppliers when the suppliers’ cost structures are not identical. Although, subjects cannot generally capture the theoretical Nash equilibrium, the experimental results show that the subjects, as theory predicts, exert more efforts under optimal competition than they exert under inventory or service competitions.

We also analyze the subjects’ behavior to provide insights on the reasons behind the deviation of decisions from the Nash equilibrium. We show that subjects’ loss aversion can explain the less-than-predicted decisions under optimal competition, especially when the competing suppliers are identical. When the suppliers have different cost structures under the optimal competition, we show that subjects’ decisions are affected by their tendency to change their next decisions toward the current decisions made by their competitors. We call this behavior “rival chasing”. We also examine the impact of subjects making random error in their decision making process. Using the Quantal Response Equilibrium approach, we show that random error can explain, to some extent, the deviations of the subjects’ decisions from the Nash equilibrium.

The remainder of this paper is organized as follows. In section two, we briefly review the related literature. Section three explains the supply chain model and presents the competition equilibrium results. Section 4 states our hypotheses. Our experimental design and protocol is presented in section 5. We present the result of experiments in section 6. The reasons behind the deviations of the subjects' decisions from the theoretical predictions are discussed in section 7. Section 8 provides our concluding remarks.

2. Related Literature

Outsourcing through competition has been widely studied in the literature. Bell & Stidham (1983) might be the first who study the competition between suppliers (servers). They model the competition between servers in a market place where customers choose their server in a way to minimize their waiting cost. Although it is not an outsourcing model, their socially optimal allocation scheme requires a decision maker who dispatches the customers to servers according to servers' processing rates. This is similar to an outsourcing model where a single buyer allocates her demand to competing suppliers based on a competition criterion. The authors' socially optimal allocation scheme minimizes the long-run average of customers' waiting cost. Since this allocation scheme is based on the suppliers' processing rate, we can consider it as an effort-based competition.

Another paper that models outsourcing through effort-based competition is Cachon & Zhang (2007). The authors model the competition between two identical make-to-order suppliers who supply to a single buyer. The buyer allocates the demand to the suppliers based on their processing rates. The authors show the impact of different allocation schemes. In their model, the buyer's objective is to maximize the service level provided by the suppliers. They show the form of a linear allocation function that can produce the best results for the buyer.

There are others who model outsourcing problems through service-based competition. This stream of research study the competition between suppliers when the share of demand allocated to each supplier depends on the service level the supplier guarantees.

Gilbert & Weng (1998) model a principal who allocates demand to two competing agents (service facilities). The identical agents decide about their costly service rates to attract more demand shares. The principal either allocates the demand to the agents from a single queue or from separate queues (equal expected waiting times). They show the conditions which one allocation might be superior to the other one. Ha et al (2003) model two suppliers who compete for supply to a customer with deterministic demand. When the identical suppliers compete based on delivery frequency, the authors (using an EOQ model) show an allocation scheme that minimizes the customer's inventory cost. Jin & Ryan (2012) model two identical make-to-stock suppliers who compete based on both price and service level (fill rate) for demand shares of a single buyer. The buyer uses an allocation function in which the allocated demand is proportional to an exponential function. This allocation function is characterized by a parameter that shows the relative importance of price versus service level. The authors show the optimal value of this parameter, which minimizes the buyer's cost.

Benjaafar et al (2007) compare two competition mechanisms: supplier allocation (SA) and supplier selection (SS). In a supplier allocation (SA) mechanism, each supplier receives a share of the buyer's demand which increases with the service level that supplier provides. In a supplier selection (SS) mechanism, the buyer selects only one supplier to receive the entire demand. The probability of a supplier being selected increases by the service level he provides. They show (SS) can result in higher service levels. In addition to service level, Benjaafar et al (2007) introduce another competition parameter. The authors show a reformulation of their problem in which they choose the demand-independent component of the service cost (which they name it supplier's *effort*) as the competition parameter. They show that when the demand is allocated proportional to a power function of this competition parameter, supplier service level can be maximized. The authors acknowledge that the service-based and effort-based competitions can lead to different equilibrium service levels. However, they do not actually compare the two types of competition. Elahi (2007) show an optimal form of allocation function for a service-based competition which can result in maximum feasible service level for the buyer. A review of service-based outsourcing can be found in Zhou & Ren (2010).

Elahi (2013) models an outsourcing problem in which make-to-stock suppliers compete for the demand share of a single buyer. In his model, the author considers the suppliers' competition when the buyer's demand is allocated proportional to a competition criterion (competition parameter). Elahi (2013) focuses on the impact of the different competition criteria. He considers three competition criteria: service level (fill rate), inventory level (effort level), and optimal competition criteria. Since our laboratory experiments are based on these three types of competition, we present them in more details in section 3.

In spite of relatively extensive body of theoretical work in this area, there has not been, to the best of our knowledge, any empirical study that examines supplier competition in outsourcing problems. This paper could be a first step along this path. There have been experimental studies, however, in the related fields. Below, we briefly review experimental research in other areas of supply chain and economics that have some similarities to our outsourcing problem.

Economic contests and games have long been subjected to experimental examination. Rent-seeking is one of these games that has the most similarities with the formulation of the supplier competition in our outsourcing problem. In this game, which was first modeled by Tullock (1980), contestants compete to win a prize (rent). The prize could be, for instance, the monopolistic right to provide a service to the public. The probability of winning the prize increases by the amount of contestant's expenditure. Since this expenditure (lobbying efforts, for instance) usually does not create any real value and is spent just to increase the chance of winning the rent, rent-seeking can be considered as a wasteful use of social wealth. Under certain conditions, the total expenditure by all contestants could equal the value of the rent (rent dissipation). Tullock (1980) models the probability of winning the prize as $e_i^r \Big/ \sum_{j=1}^{N} e_j^r$, where e_i is the expenditure of contestant i, $N > 1$ is the number of contestants and $r \geq 0$ determines the impact of a change in expenditure on the probability of winning. For $r = 1$, this form of probability function is similar to the proportional demand allocation function in our problem. Therefore, each contestant's expected profit function would have great similarities to a supplier's expected profit function in our outsourcing problem (see section 3).

Milner and Pratt (1989) were the first to conduct laboratory experiments to verify Tullock's analysis of rent-seeking. Their experiment considers the competition between two (identical) rent-seekers. The authors compare the contestants' mean expenditures for the cases of $r = 1$ and $r = 3$. Their results confirm the theoretical prediction that higher values of r results in higher expenditures. However, they observe that the average expenditure for the case of $r = 1$ is higher than the Nash equilibrium, while the average expenditure for the case of $r = 3$ is lower than what theory predicts. In spite of most experimental researches in this field (including the present research), Milner and Pratt (1989) let the subjects make sequential decisions within a time interval instead of making simultaneous single decisions in a decision period. Moreover, the case of $r=3$ does not have a pure strategy Nash equilibrium. Therefore, we cannot compare the result of their experiment for this case with a theoretical benchmark. In a follow up paper, Milner and Pratt (1991) show that the less risk averse the subjects are, the more their expenditure will be.

Davis and Reilly (1998) also conduct laboratory experiments to examine the outcome of rent-seeking contests. They compare the average expenditures of $r=1$ with a perfectly discriminating rent-seeking in which the contestant with the highest expenditure wins the contest with a probability 100%. This type of rent-seeking corresponds to $r=\infty$ and can be considered as all-pay auction. They report that the perfectly discriminating rent-seeking results in higher expenditures than the case of $r=1$ does. In both cases, the subjects' average expenditures are higher than the Nash prediction. They also show that the subjects' experience reduces the over-dissipation of rent, but cannot eliminate it. This general tendency of competing subjects to make decisions above the Nash equilibrium values is generally what we observe in our outsourcing competition too (especially under service and inventory competitions).

Anderson et al (1998) show that for a perfectly discriminating rent-seeking game ($r=\infty$), the subjects' random error can explain the over-dissipation of rent. They use Quantal Response Equilibrium approach (first introduced by McKelvey and Palfrey, 1995), to analyze the impact of subjects' random error. We will also show how random error can explain (to some extent) the deviation of subjects' decisions from the theoretical predictions. Anderson and Staffor (2003) study the impact of cost heterogeneity and entry fee on the expenditures of contestants in a rent seeking game. Their laboratory experiments show (among other results) that cost heterogeneity does not result in a decrease in the total amount of expenditures (as theory predicts). Our experimental results suggest a similar behavior under service and inventory competition. That is, when the suppliers are heterogeneous, the sum of subjects' decisions is higher than what theory predicts. The literature on experimental studies of rent seeking is not limited to what is mentioned here. A comprehensive review of this literature, however, is beyond the scope of this paper. A more detailed review of experimental studies on rent-seeking can be found in Houser and Stratmann (2012).

The only experimental paper in supply chain that studies simultaneous competition between decision makers is Chen et al (2012). They examine the competition between retailers (buyers) for the limited capacity of a common supplier (seller). They found that the subjects' average order is much less than what Nash equilibrium predicts. They attribute this behavior to subjects' bounded rationality (random errors). The authors use Quantal Response Equilibrium to incorporate random errors in subjects' decisions. Similar to Chen et al (2012), we model the simultaneous competition between decision makers. Our model, however, considers the competition between suppliers (sellers) for the limited demand of a buyer. Moreover, our competition criteria is different from what they use in their model.

3. Theoretical Background

In this section, we describe our supply chain model and present the theoretical formulation of the competition setup for our experiments. We also show the Nash equilibrium decisions for different types of competition we consider in this research. The supply chain setup in this paper follows the setup presented in Elahi (2013). The proofs of all the results of this section can also be found in this reference.

We consider the case of a single buyer who is outsourcing the production of a product among N potential suppliers. The suppliers manufacture this product in a make-to-stock fashion according to a base-stock inventory policy. Demand from the buyer is generated according to a Poisson process with rate λ, with the fraction of demand allocated to supplier i denoted by δ_i, where $0 < \delta_i < 1$ and $\sum_{i=1}^{N} \delta_i = 1$. Accordingly, demand generated by the buyer arrives at each supplier with a rate of $\delta_i \lambda$. The variable δ_i can be viewed as the probability that ongoing demand is allocated to supplier i; in aggregate, this translates to the market share awarded to the supplier.

The suppliers' production times are exponentially distributed with the rate μ_i, and in response to demand from the buyer, suppliers adjust their capacity (production rate) to maintain a fixed target utilization ρ_i, where $\rho_i = \delta_i \lambda / \mu_i$ and $0 < \rho_i < 1$ for supplier i. Hence, for each supplier the production system can be modeled as an M/M/1 queuing system. The assumptions of Poisson arrival and exponential processing times, in addition to being plausible in many practical cases, are common practice in this field since they make the derivations mathematically tractable (see for instance Gilbert and Weng, 1998; Cachon and Zhang, 2007; Benjaafar et al 2007).

Finished goods at the suppliers are managed according to a base-stock policy with base stock level z_i ($z_i > 0$) at supplier *i*. This means that the arrival of demand at supplier *i* always triggers a replenishment order with the supplier's production system. Suppliers incur the inventory holding cost. That is, each supplier *i* incurs a holding cost h_i per unit of inventory per unit time. Moreover, each supplier incurs a production cost c_i per unit produced, and a capacity cost k_i per unit of capacity (measured in terms of the associated production rate). The revenue for each supplier is based on the demand they are allocated and the price of the product, *p* per unit, at which the buyer procures it. We assume that this price is the same across all suppliers. This can be the case when the buyer is powerful enough to set the price, or when market mechanisms set the price (the case of a commodity product for instance). This assumptions means the competition is based on criteria other than price.

When a supplier cannot fulfill the buyer's demand from on-hand inventory, we assume the buyer will wait until the supplier produces the backordered units. We exclude the possibility of the buyer switching to another supplier. We also exclude the possibility of the buyer procuring the product from a supplier outside of the pool of competing suppliers, assuming that the product is not readily available in the market. The assumption of backordering the demand when it cannot be satisfied from on-hand inventory is consistent with the assumptions in earlier papers such as Cachon & Zhang (2007) and Benjaafar et al. (2007). Netessine et al. (2006) also use this assumption in studying the impact of customers' backordering behavior on the performance of competing firms in a market. The assumption of backordering the unfulfilled demand is particularly essential in our competition model, since switching to another supplier violates the demand allocation rule, which is (as we will discuss below) the basis of the competition.

Backordered demand is costly for the buyer. It might lead to delayed delivery or incomplete orders shipped to the buyer's own customers. Backorders can also negatively affect the buyer's production system, which are possibly accentuated if a just-in-time system is used. Therefore, the buyer measures each supplier's service level in terms of fill rate, $s_i = \Pr(I_i > 0)$. That is, the probability that a unit demand allocated to a supplier is not backordered and can be fulfilled immediately from on-hand inventory (I_i is the inventory level at supplier *i*). Hence, the buyer's objective is to maximize the average service level she receives from her suppliers,

$$q = \sum_{i=1}^{N} \delta_i s_i \ . \qquad (1)$$

Maximizing the average service level is equivalent to minimizing the probability of backordered orders, which in turn means low backordering cost for the buyer.

To encourage the suppliers to provide higher service levels, the buyer let them compete for larger shares of her demand based a performance measure. The buyer announces this performance measure, as the criteria for demand allocation, before the competition starts. The suppliers then simultaneously commit to a level of the announced performance measure, based on which the demand share of each supplier is determined. We examine three different types of performance measures, based on which the buyer stages the competition. The buyer's demand can be allocated based on the suppliers' fill-rates (termed here as a *service competition*), or it can be allocated based on suppliers' base-stock level (termed here as an *inventory competition*). We also examine the competition based on a combined performance measure designed to intensify the competition to its highest level. This competition (termed here as *optimal competition*) can result in the best outcome for the buyer.

To make a decision, each supplier needs to consider the trade-off between higher revenue from a larger share of demand and the higher costs of committing to a higher level of the announced performance measure. Each supplier makes his decision attempting to maximize his expected profit in light of their competitors' possible decisions. Below, we explain in more details each of these three types of competition.

In service competition, each supplier is awarded a demand share proportional to the fill rate he guarantees. The buyer uses a proportional allocation function $\alpha_i^S(s_i, s_{-i})$ which specifies the fraction of demand allocated to supplier i based on his fill rate s_i and the fill rates $s_{-i} = (s_1, ..., s_{i-1}, s_{i+1}, ..., s_N)$ offered by supplier i's competitors. In other words,

$$\delta_i = \alpha_i^S(s_i, s_{-i}) = \frac{s_i}{\sum_{j=1}^{N} s_j}. \tag{2}$$

In inventory competition, a supplier's demand share depends on his base stock level. In this type of competition, the buyer uses a proportional allocation function $\alpha_i^I(z_i, z_{-i})$ which specifies the fraction of demand allocated to supplier i based on his base stock level z_i and the base stock levels $z_{-i} = (z_1, ..., z_{i-1}, z_{i+1}, ..., z_N)$ offered by supplier i's competitors, which means

$$\delta_i = \alpha_i^I(z_i, z_{-i}) = \frac{z_i}{\sum_{j=1}^{N} z_j}. \tag{3}$$

In optimal competition, buyer's demand is allocated according to a performance measure, ξ_i, that is a combination of fill-rate and base-stock level.

$$\xi_i = \frac{1}{N}\left[\frac{Nh}{\lambda(p-c-k/\rho_i)}\left(z_i - \frac{\rho_i}{1-\rho_i}s_i\right)\right]^{\frac{N}{N-1}}. \tag{4}$$

Therefore, the demand share allocated to supplier *i* in optimal competition will be

$$\alpha_i^O(\xi_i, \xi_{-i}) = \frac{\xi_i}{\sum_{j=1}^{N}\xi_j}. \tag{5}$$

This type of competition can induce the maximum feasible service level for the buyer[1]. The performance measure defined in (4) is more complicated and less intuitive than direct measures like fill rate or base stock level. It is, in fact, an abstract measure that can set the shape of the profit function such that the competition equilibrium point occurs when each supplier exerts his maximum effort. In other words, this performance measure can intensify the competition to its maximum level, where each supplier spends all his revenue (and zero out his profit) to provide the maximum feasible level of ξ_i. While under the service and inventory competitions, the suppliers can earn positive profit, supplier's profit under optimal competition is always zero. Note, in the definition of this performance measure, z_i and s_i are interdependent parameters ($s_i = 1-\rho^{z_i}$). It is not very difficult to show that ξ_i is an increasing function of either z_i or s_i. Therefore, when a supplier guarantees the maximum feasible level of ξ_i, it means that he guarantees the maximum feasible service level for the buyer, as well[2].

Suppliers' profit functions under each of these competitions are

$$\pi_i^S(s_i, s_{-i}) = \alpha_i^S(s_i, s_{-i})\lambda(p-c_i-k_i/\rho_i) - h_i\left(\frac{\ln(1-s_i)}{\ln\rho_i} - \frac{\rho_i}{1-\rho_i}s_i\right), \tag{6}$$

$$\pi_i^I(z_i, z_{-i}) = \alpha_i^I(z_i, z_{-i})\lambda(p-c_i-k_i/\rho_i) - h_i\left(z_i - \frac{\rho_i}{1-\rho_i}(1-\rho_i^{z_i})\right), \text{ and} \tag{7}$$

$$\pi_i^O(\xi_i, \xi_{-i}) = \alpha_i^O(\xi_i, \xi_{-i})\lambda(p-c_i-k_i/\rho_i) - \frac{\lambda(p-c-k/\rho_i)}{N}(N\xi_i)^{\frac{N-1}{N}}. \tag{8}$$

[1] Suppliers are bound to provide a positive service level as a participation condition under this type of competition.

[2] Elahi (2013) shows a general form of the performance measure for optimal competition that has the ability to induce any predefined set of demand shares at the competition equilibrium. The specific form shown in (4) induces identical demand shares for all suppliers ($\delta_i = 1/N$). This is an intuitive selection when the suppliers are identical. The buyer may also decide to allocate equal demand shares to heterogeneous suppliers to minimize the risk of relying on a specific supplier. For more detailed discussion see section 6 of Elahi (2013).

This formulation of the problem assumes (a) the buyer can enforce the fill rates or base stock levels chosen by the suppliers, (b) suppliers' cost structures are common knowledge (a complete information setup), and (c) suppliers participate in the competition as long as they can earn a non-negative expected profit.

These three forms of competition have unique Nash equilibrium. For the case of identical suppliers, these equilibrium points can be found from

Service Competition:
$$s_S^* = \left(\frac{N-1}{N^2}\right) \frac{\lambda(p-c-k/\rho)}{h\left[\frac{1}{(1-s_S^*)\ln(1/\rho)} - \frac{\rho}{1-\rho}\right]} \tag{9}$$

Inventory Competition:
$$z_I^* = \left(\frac{N-1}{N^2}\right) \frac{\lambda(p-c-k/\rho)}{h\left[1-\frac{\rho^{z_I^*+1}}{1-\rho}\ln\frac{1}{\rho}\right]} \tag{10}$$

Optimal Competition:
$$\xi_O^* = \frac{1}{N} \tag{11}$$

When the suppliers are not identical, we do not have closed form solutions. Numerical methods should be used to calculate the equilibrium points. It can be shown that the service competition results in the lowest service level for the buyer and the optimal competition results in the highest service level. The inventory competition results in a service level that is in between. As mentioned before, there is a one to one correspondence between the service level that a supplier provides and the base-stock level that he keeps. As a result, the highest service level in an optimal competition means that the suppliers provide the highest level of base-stock under the optimal competition. Similarly, the lowest level of service in a service competition means that the suppliers provide the lowest level of base-stock under service competition. We will refer to this result in our experimental design.

4. Hypotheses

Game theoretic models predict that rational player make decisions according to Nash equilibrium. Our first three hypotheses then concern the comparison between the subjects' average decisions and the corresponding Nash equilibriums under different competition setups.

Hypothesis 1: The average subjects' decisions is equal to the corresponding Nash equilibrium under service competition with (a) identical suppliers, (b) suppliers with different production costs, and (c) suppliers different inventory holding costs.

Hypothesis 2: The average subjects' decisions is equal to the corresponding Nash equilibrium under inventory competition with (a) identical suppliers, (b) suppliers with different production costs, and (c) suppliers different inventory holding costs.

Hypothesis 3: The average subjects' decisions is equal to the corresponding Nash equilibrium under optimal competition with (a) identical suppliers, (b) suppliers with different production costs, and (c) suppliers different inventory holding costs.

The theoretical results also predict that our optimal competition results in the highest service level for the buyer, while service competition results in the lowest service level for the buyer.

Our next two hypotheses then concern the comparison of the subjects' average decisions under different types of competition. As we mentioned in section 3, there is a one-to-one correspondence between the service level (fill-rate) and the suppliers' base-stock levels. Therefore, comparing subjects' decisions (base-stock levels) under different types of competition is equivalent to comparing the service levels (fill rates) provided by the suppliers.

Hypothesis 4: The average subjects' decisions under service competition are smaller than the average subjects' decisions under inventory competition with (a) identical suppliers, (b) suppliers with different production costs, and (c) suppliers different inventory holding costs.

Hypothesis 5: The average subjects' decisions under inventory competition are smaller than the average subjects' decisions under optimal competition with (a) identical suppliers, (b) suppliers with different production costs, and (c) suppliers different inventory holding costs.

5. Experimental Design

To investigate how decision makers perform under the competition and compare the results with theory, we conducted a series of experiments using nine different treatments. These consisted of three treatments for each of the service, inventory, and optimal competitions. For each type of competition, a single treatment was used for suppliers with identical cost structures, and two treatments were used for heterogeneous costs. The heterogeneity in cost structure was either because of different production costs or because of different inventory holding costs.

In all experiments the buyer's demand was assumed to arrive at a rate of λ and the price of the product, p, to be 100. The suppliers incurred a capacity cost of $k = 5$ per unit product per unit time to adjust their capacity and keep their utilization at $\rho = 0.93$. When the suppliers had identical cost structures, their production costs and inventory holding costs were the same, with $c_1 = c_2 = 20$ and $h_1 = h_2 = 1$, respectively. For experiments with heterogeneous production costs the values $c_1 = 20$ and $c_2 = 60$ were used for production coasts. For heterogeneous inventory holding costs, the values $h_1 = 1$ and $h_2 = 2$ were incorporated. We deliberately chose a relatively large difference between the production costs and inventory holding costs so that the extent of an impact from heterogeneity would be more clearly evident.

Subjects in our experiments assumed the role of competing suppliers with the overall goal of maximizing profits. Each experiment consisted of 30 independent rounds in which a decision needed to be made. In order to maximize profits, the subjects needed to consider how the buyer was allocating her demand as well as possible decisions their competitors might make. Under all forms of competition the decisions subjects made was in the form of base-stock levels. As we mentioned in section 3, there is a one-to-one correspondence between different performance measures. Therefore, when a subject selects a certain level of base-stock, the values of fill rate and optimal performance measure are also set. The reason that subjects' decisions under all forms of competition are the base-stock level is the fact that base-stock level is the only practical decision that can be made in reality. For instance, a supplier cannot directly set a desired fill-rate in practice. It can only be done through choosing a base-stock level that guarantees that fill-rate.

The subjects for all of our experiments were College of Management students at the University of Massachusetts, Boston. We conducted the experiments in the College of Management P5 Computer Lab. The instructors of selected courses let us run the experiments in their class times as a required class activity.

To provide incentive for students to focus on maximizing profits during the experiment, we presented each experiment as a contest through which the students could find out how good they were at making decisions under an uncertain competitive environment. In addition, we offered cash prizes ($40, $30, and $20) to the three students having the highest total profits after 30 rounds of decision-making. We conducted the experiments in a mix of graduate and undergraduate classes. Past experimental research in operations management has found that decisions made by undergraduate and graduate students are not statistically different. See, for instance, Katok & Wu (2009) and Elahi (2013).

Since the calculation of a supplier's profit could be complicated, the experiment software provided an interactive calculation tool. This tool, which was available throughout the experiments, enabled subjects to enter a prospective decision and see their profits as a function of the full range of decisions a competitor could make. The appendix shows the user-interface including the calculation tool.

A strict protocol was followed for conducting all experiments. At the start of each experiment session, subjects were asked to read a two-page handout describing the supply chain setup and the decision-making process for the competition. The content of the handout and a short demonstration of the experiment software was presented orally next. This presentation was followed by answering any questions that subjects might have.

The next step in our protocol was to let subjects work with the software and, in particular, examine the calculation tool. After subjects were familiar with the software and had a sense of how their decisions, in combination with potential decisions by their competitors, would affect their profits, we had subjects compete in a 5-round practice session. With any remaining questions answered, we proceeded to start the actual competition. During the first 10 rounds of competition, the subjects had 75 seconds to make a decision. Pre-testing showed that after 10 rounds subjects had grasped the competition and no longer needed as much time. We therefore reduced the time limit to 45 seconds for each of the remaining rounds.

After all subjects had entered a decision or the time limit had expired, a round would end. The software then paired subjects as competitors randomly (any subject not making a decision was not paired and assigned a profit of zero). With decisions and competitors assigned, the software calculated each subject's share of demand and profit, along with their competitor's share and profit. These results, alongside the total profit the subject had accumulated, were displayed on the screen. At that point, the next round of the competition was begun. See the appendix for a sample screenshot of the user interface during a competition.

Before the competitions started for experiments involving treatments with heterogeneous suppliers, the software randomly divided subjects into one of two sets. One set was assigned a higher cost than the other for either c or h, depending on the particular experiment. We then apprised all subjects of which set they were assigned to and that those with higher costs could expect lower profits than their competitors. Subjects were also made aware that, at the end of experiments, we would normalize all subjects' profits with respect to their costs; hence, everyone had a fair chance of winning the prize money.

6. Results

Tables 1 and 2 show the results of our experiments as well as the corresponding theoretical Nash equilibrium for identical and heterogeneous suppliers, respectively. To analyze the results of our experiments, throughout this research, we use Wilcoxon rank sum test (Levine et al 2011, pp. 447-451). The unit of our analysis is the average base-stock decisions made by each subject.

As we can see from these, the subjects' behaviors under service and inventory competitions are different from their behaviors under optimal competition. Under service and inventory competitions, the subjects' average base-stock decisions are always greater than the corresponding Nash equilibriums. The *p*-values listed in tables 1 and 2 show that these differences are statistically significant. The only exceptions happen under service competition for both suppliers with different production costs and for the more efficient supplier when inventory-holding costs are different. For these cases, the subjects' average decisions are statistically equivalent to the Nash equilibrium. As a result, we can reject Hypothesis 1(a) and all parts of hypothesis 2. We can also reject hypothesis 1(c) for the less efficient supplier. Hence, we can conclude that the subjects, under service and inventory competitions, tend to choose base-stock levels higher than or at least equal to the Nash equilibrium.

On the other hand, under optimal competition, we can see that the subjects' average decisions are smaller than the corresponding Nash equilibrium when the suppliers are identical. We can observe the same behavior for the subjects who play the role of more efficient supplier (supplier 1), when the suppliers are not identical. The subjects who play the role of less efficient supplier (supplier 2), however, do not follow this pattern. Under the optimal competition, all the differences are significant except for the less efficient supplier when the production costs are different. Therefore, we can reject hypotheses 3(a) and 3(c). We can also reject 3(b) only for the more efficient supplier.

Competition Type	Sample Size	Nash Equilibrium Base-stock Level	Experimental Base-stock Level	*p*-value (two tail)
Service Competition	13	19	24	<0.01
Inventory Competition	12	34	54	<0.01
Optimal Competition	22	77	68	<0.01

Table 1 – Subjects' average decisions vs. Nash equilibrium (identical suppliers)

Competition Type	Sample Size	Supplier 1 Base-Stock Level			Supplier 2 Base-Stock Level		
		Nash	Experiment	*p*-value (two tailed)	Nash	Experiment	*p*-value (two tailed)
Heterogeneous Suppliers (different production costs: c_1=20, c_2=60)							
Service Competition	18	19	19	>0.05	13	15	>0.05
Inventory Competition	24	32	41	0.02	18	26	0.04
Optimal Competition	28	77	51	<0.01	42	43	>0.05
Heterogeneous Suppliers (different inventory holding costs: h_1=1, h_2=2)							
Service Competition	17	19	21	>0.05	14	19	<0.01
Inventory Competition	25	33	36	0.04	19	34	<0.01
Optimal Competition	27	77	58	<0.01	44	51	0.01

Table 2 – Subjects' average decisions vs. Nash equilibrium (Heterogeneous suppliers)

Tables 3 and 4 compare the subjects' average decisions under different competition types. As we can see, the experiment results strongly reject all parts of Hypotheses 4 and 5. This means that the competition type indeed affects the subjects' decisions. Although our results show that the subjects' average base-stock decisions under optimal competition are smaller than what theory predicts, the optimal competition still results in average base-stock levels which are considerably higher than the base-stock levels resulted from the other two forms of competitions. Therefore, the optimal competition can indeed provide the highest level of average service level for the buyer.

Competition Types	N_A	N_B	Competition (A)	Competition (B)	*p*-value (one tail)
Service (A) vs. Inventory (B)	13	12	24	54	<0.001
Inventory (A) vs. Optimal (B)	12	22	54	68	<0.001

Table 3 – Subjects' average base-stock decisions (identical suppliers)

Competition Type	Supplier Type	N_A	N_B	Competition (A)	Competition (B)	*p*-value (one tail)
Heterogeneous Suppliers (different production costs: c_1=20, c_2=60)						
Service (A) vs. Inventory (B)	Supplier 1	9	11	19	41	<0.005
	Supplier 2	9	12	15	27	<0.005
Inventory (A) vs. Optimal (B)	Supplier 1	11	7	41	51	<0.001
	Supplier 2	12	6	27	43	<0.001
Heterogeneous Suppliers (different inventory holding costs: h_1=1, h_2=2)						
Service (A) vs. Inventory (B)	Supplier 1	8	12	21	36	<0.005
	Supplier 2	9	13	19	34	<0.001
Inventory (A) vs. Optimal (B)	Supplier 1	12	5	36	58	<0.001
	Supplier 2	13	5	34	51	<0.001

Table 4 – Subjects' average base-stock decisions (Heterogeneous suppliers)

7. Discussion

The results of our experiments suggest that the assumption of perfectly rational decision-makers, which is the underlying assumption in the derivation of Nash equilibrium, does not necessarily hold for the competition setups studied in this research. To explain the subjects' behaviors under different competition setups, we examine different behavioral factors. These behavioral factors consist of context dependent factors such as loss-aversion and rival chasing, as well as context independent factors such as random errors. Since our experimental design considers only the case of competition between two suppliers, we limit our discussion in this section to the competition between two suppliers too.

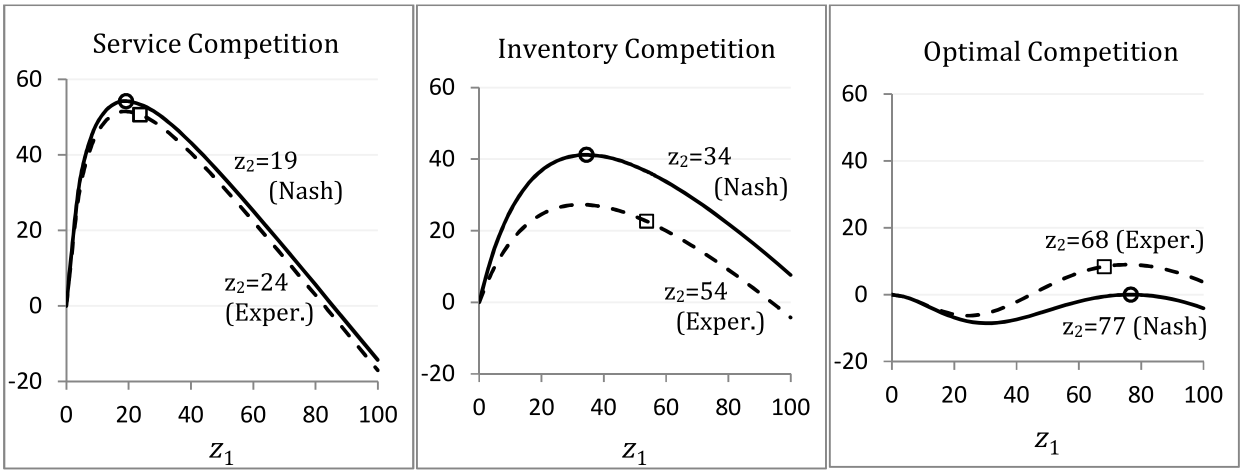
7.1. Loss Aversion and Rival Chasing

We can see that under service and inventory competition, the subjects' average decisions are greater than the Nash equilibrium or at least (statistically) equal to it. Under optimal competition, however, we cannot see this pattern. Subjects' average decisions, under optimal competition, are smaller than the corresponding Nash equilibrium, except for the less efficient supplier when the suppliers are heterogeneous.

To provide some insight on this behavior we first look at a supplier's profit function in response to a decision made by his competitor. More specifically, we look at a supplier's profit when his competitor chooses either the Nash equilibrium or the average decision we have observed in our experiments. Figures 1 to 3 show these profit functions. The curves with the solid lines in these figures show a supplier's expected profit for different values of his decisions when his competitor's decision is the Nash equilibrium value. The curves with the broken line is the supplier's expected profit when his competitor's decision is the average decisions made by subjects in our experiments.

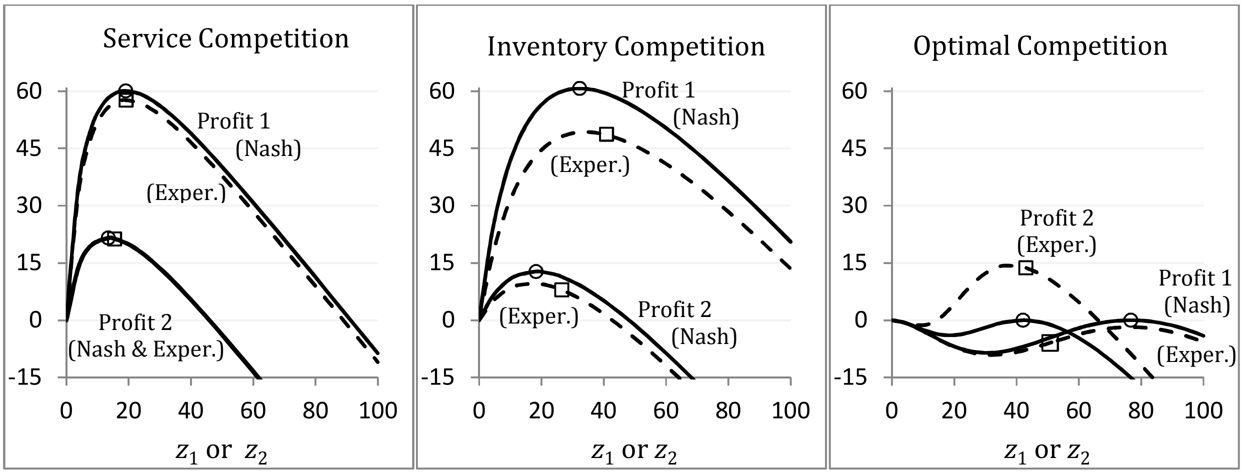
We first notice that the rate of change in a supplier's profit around its maximum point is much steeper under the service competition than that of the inventory or optimal competitions. In other words, any deviation from the optimal decision is more costly for the suppliers under service competition than it is under inventory or service competitions. This observation explains why the gap between subjects' average decisions and the corresponding Nash equilibrium points under service competition is (almost always) smaller than the same gap under inventory or optimal competitions. We can see that, under service competition with heterogeneous suppliers (different production costs), the subjects have actually managed to (statistically) capture the Nash equilibrium. This is also the case for the more efficient supplier under the service competition when the suppliers have different inventory holding costs. This means that although optimal competition can provide the best results for the buyer (highest service level), it is more difficult for the subjects to capture the best decisions under optimal competition due to the relatively flat profit functions around the optimal point. The opposite is true for the service competition, under which the buyer receives the lowest service level. However, it is easier for the subjects to capture the optimal point under this competition.

We can also see that if a supplier's competitor chooses according to the Nash equilibrium, under optimal competition, any deviation from the best decision will result in a negative profit for that supplier. Therefore, subjects' loss aversion can play an important role in this type of competition. When the suppliers are identical, the only way suppliers can earn positive profit under optimal competition is when both suppliers' decisions are lower than the Nash equilibrium. Although this is not an equilibrium condition, to stay away from the condition that might result in negative profit, this is exactly what subjects have done in our experiments.



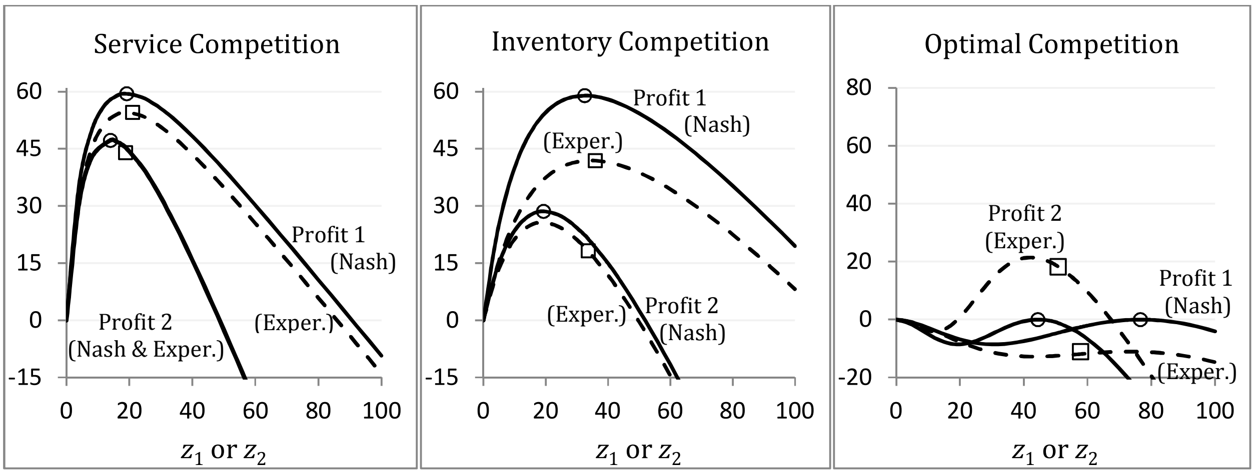
○ Nash Equilibrium □ Experiment Result

Figure 1 – Supplier 1's profit when the suppliers are identical



○ Nash Equilibrium □ Experiment Result

Figure 2 – Suppliers' profit when the suppliers heterogeneous (different *c*)



○ Nash Equilibrium □ Experiment Result

Figure 3 – Suppliers' profit when the suppliers heterogeneous (different *h*)

When the suppliers are heterogeneous, however, the subjects' behaviors under the optimal competition depend on the type of the supplier. The subjects who play the role of the more efficient supplier (supplier 1) still chose base-stock levels that are less than the Nash equilibrium. The subjects who play the role of the less efficient supplier (supplier 2), on the other hand, choose base-stock levels that are more than (or equal to) the Nash equilibrium. This different behavior might be explained by a phenomenon that we observed through examining subjects' decisions. It seems that the subjects have a tendency to change their decisions toward their competitors' last decisions (rival chasing behavior). To formally investigate this tendency we define the following parameter for each subject *i* at decision round *t*.

$$q_i^t = (z_i^t - z_i^{t+1})(z_i^t - z_j^t)$$

When this parameter is positive, it means supplier *i*'s next decision (z_i^{t+1}) moves toward his competitor's last decision (z_j^t). A negative value for q_i^t means the supplier's next decision moves away from his competitor's last decision. When $q_i^t = 0$, either the supplier does not change his decision, or the supplier's and his competitor's decisions are the same. Table 5 shows the percentage of positive, negative, and zero values of q_i^t for all suppliers in each competition setup.

We can see from table 5 that the tendency of subjects to move toward their competitors' last decision is much stronger than to move away from it. This is the case for all types of competition and for both types of suppliers. When the competing suppliers are identical, this tendency should not have a major impact on the subjects' average decisions (since their optimal decisions are the same at the equilibrium point). This rival chasing tendency might result in faster convergence of subjects' decisions when the suppliers are identical (even when they converge to an average decision that is different from the Nash equilibrium). When the suppliers are heterogeneous, the two types of suppliers have different Nash equilibrium decisions. The rival chasing behavior might then cause the subjects of type 1 and 2 to converge to decisions that are closer to each other than the corresponding Nash equilibrium points. We can see this behavior under all types of competition (the only exception is under inventory competition with different *c*, in which the gap between the Nash equilibrium points is almost the same as the gap between the subjects' average decisions). This behavior is particularly clear under optimal competition where the profit functions are much flatter around the equilibrium points. A flatter profit function means it is more difficult for the subjects to identify the optimal point. As a result, the rival chasing tendency could play a more influential role. This strong tendency pulls the average decisions of the subjects of the two types toward each other (lower than Nash equilibrium decisions for type 1 subjects and higher than Nash equilibrium decisions for type 2 subjects). As we can see from figures 2 and 3, this behavior does not have the same impact on the two types of suppliers. When the decisions of the two types of the suppliers are pulled toward each other, the more efficient supplier (supplier 1) ends up with a negative profit, while the less efficient supplier ends up with a positive profit. We can also see that the difference between the subjects' average decisions and the Nash equilibrium is considerably larger for supplier 1 than for supplier 2. Since this pulling effect result in negative profit for supplier 1, the subjects who play the role of this supplier are more desperate to improve their profit and therefore they tend to chase their rivals more than their competitors do. The percentages of positive and negative q_i^t in Table 5 support this argument.

Competition Type	Suppliers	Supplier Type	q_i^t			Δ
			(+)	(0)	(−)	
Service	identical		52%	26%	23%	29%
	Heterogeneous (different c)	1	55%	10%	35%	20%
		2	51%	25%	24%	26%
	Heterogeneous (different h)	1	42%	34%	24%	18%
		2	52%	24%	24%	29%
Inventory	identical		44%	29%	27%	17%
	Heterogeneous (different c)	1	52%	5%	43%	9%
		2	53%	15%	32%	21%
	Heterogeneous (different h)	1	50%	11%	38%	12%
		2	60%	7%	33%	26%
Optimal	identical		56%	10%	35%	21%
	Heterogeneous (different c)	1	56%	16%	28%	29%
		2	46%	28%	27%	19%
	Heterogeneous (different h)	1	54%	18%	29%	25%
		2	46%	19%	35%	10%

Δ: difference between the percentage of positive and negative q_i^t

Table 5 – Subjects' average base-stock decisions (Heterogeneous suppliers)

7.2. Random Error in Suppliers' Decisions

One of the approaches used in the literature (both in behavioral economics and experimental operations management) to explain the potential reasons behind the deviation of subjects' decisions from the theoretical results is the occurrence of random errors in subjects' decisions. For instance, Su (2008) and Kremer et al (2010) apply random error to their model to see if it can explain the deviation of newsvendors' decisions from the optimal value. Kremer et al (2010) conclude that the random error cannot explain the gap between the theory and the experimental results. Anderson et al (1998) apply the concept of contestants' random errors in an all-pay auction (in the context of rent seeking contexts) to see if this model can explain the experimental results. By incorporating the occurrence of random error, they manage to explain the over-dissipation of rents observed in experiments. Chen et al (2012) model an allocation problem in which two retailers compete for the limited capacity of a common supplier while the retailers make random error in placing their optimal order quantities. They show that retailers' random error can explain the lower than Nash equilibrium order quantities that they observed in their laboratory experiments.

All these papers use the concept of Quantal Response Equilibrium (QRE) to model the randomness in players' decisions. This type of equilibrium, which was first introduced by McKelvey and Palfrey (1995), assumes that each player aims to make the best decision but makes random error in the process. Therefore, each player's decision follow a probability distribution, in which, the best decision (the decision that maximizes the player's expected profit) has the highest probability of occurrence. The equilibrium probability distribution is a fixed point. That is, at the equilibrium, the belief distribution of each player about his opponent's decisions is the same as the choice distribution of his opponent. The belief distributions determine a player's expected profit for each decision he makes, while the choice distribution is determined by the expected profit. Chen et al (1997) show the existence and uniqueness of this equilibrium when the players' set of choices is discrete and the choice probabilities are described by a logit distribution. As we explained in section 5, the suppliers' decisions (choices) in our three forms of competition are considered to be their base-stock levels, z_i. Let Ω_i be the set of possible decisions for supplier *i*. Using a logit form, the choice probabilities can then be defined as

$$\Pr(z_i) = \frac{\exp\left[\dfrac{E\pi_i(z_i)}{\beta}\right]}{\sum_{\omega_i \in \Omega_i} \exp\left[\dfrac{E\pi_i(\omega_i)}{\beta}\right]}, \quad \forall z_i \in \Omega_i . \tag{12}$$

In equation (12), $E\pi_i(z_i)$ is the expected profit of supplier *i* over all possible random decisions that can be made by his competitors (according to the belief distribution) when supplier *i* chooses a base-stock level of z_i. Therefore, the probability of each decision increases with the expected profit of that decision. Parameter β shows the supplier's limitation in choosing the best decision. It is easy to see that when $\beta \to \infty$ then all possible decisions will have the same probability (uniform distribution). In other words, when $\beta \to \infty$ the supplier has no tendency toward the best decisions (the decisions are made in a completely random fashion). On the other hand, $\beta = 0$ means that the supplier is perfectly rational and the best decision will always be chosen with a probability of one.

Using an iterative algorithm, we can numerically find the equilibrium probability distribution of suppliers' decisions. Figure 1 shows, for example, the equilibrium distributions for different values of β under the service competitions when the suppliers are identical. The problem parameters are the same as what we used in our laboratory experiments. As we can see, the equilibrium distribution becomes flatter as β increases.

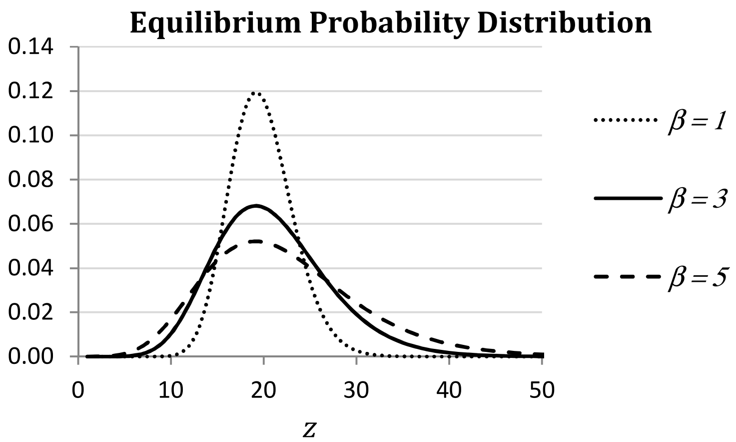


Figure 1 –Equilibrium Probability Distribution of Decisions (QRE) under Service Competition with Identical Suppliers

We use the Maximum Likelihood Estimation (MLE) method to find the best value of β that best explains the subjects' behavior under each type of competition. More specifically, in this method, we find the value of β that maximizes the likelihood of the occurrence of the observed decisions under each type of competition. Let T be the total number of decisions made by each subject (T=30 in our experiments) and m be the number of subjects. The set of all base-stock decisions made by subjects during an experiment can then be defined as $\mathbb{Z}=\left\{z_{it} \mid i=1,...,m \ \ and \ \ t=1,...,T\right\}$. Hence, the logarithmic form of our likelihood function can be written as

$$L(\beta \mid \mathbb{Z})=\sum_{i=1}^{m}\sum_{t}^{T}\ln\left[\Pr(z_{it})\right], \tag{13}$$

where $\Pr(z_{it})$ is calculated by (12). Tables 6 and 7 show the best values of β that maximize the likelihood function under different types of competition, along with the corresponding expected base-stock level, z^{*}_{QRE}. Since different types of competition impose different levels of decision complexity to the subjects, we have considered a different value of β for each type of competition. The value of z^{*}_{QRE} is, in fact, the average base-stock level under the Quantal Response Equilibrium for the value of β that maximizes the likelihood of observing the experimental data. The tables also list the p-values (one tailed test) that show the significance of the differences between the Quantal Response Equilibrium and the subjects' average decisions. We can see the optimal value of β for the inventory competition is larger than the optimal value of β for the service competition. Our discussion in section 7.1 regarding the shape of the profit function should explain this behavior. The sharper slope of the profit function under service competition makes it easier for the subjects to choose base-stock levels closer to the optimal value (behave more rationally). We cannot extend this type argument to the optimal competition. We can see the optimal value of β under optimal competition is smaller than optimal value of β under inventory competition. This could be because random error is no longer the only major factor affecting the subjects' decisions. As we discussed in section 7.1, other factors such as loss aversion and rival chasing play an influential role under this type competition, as well.

	Service Competition					Inventory Competition				
	Identical	different c		different h		Identical	different c		different h	
	$z_1 = z_2$	z_1	z_2	z_1	z_2	$z_1 = z_2$	z_1	z_2	z_1	z_2
Nash Equilibrium	19	19	13	19	14	34	32	18	33	19
Quantal Response Eq.	21	21	16	21	15	43	37	26	35	27
β	3.4					11.2				
Experiment	24	19	15	21	19	54	41	27	36	34
p-value (Experiment vs. z^*_{QRE})	0.000	<0.05	**>0.05**	**>0.05**	<0.05	0.019	**0.139**	**0.244**	**0.500**	0.000

Table 6 –Average QRE base-stock level under service and inventory competitions

Tables 8 and 9 compare the differences between the experimental results (subjects' average decisions) and the Nash equilibrium with the difference between the experimental results and the QRE. These tables show the differences only when they are statistically significant ($p < 0.05$).

	Optimal Competition				
	Identical	different c		different h	
	$z_1 = z_2$	z_1	z_2	z_1	z_2
Nash Equilibrium	77	77	42	77	44
Quantal Response Eq.	67	58	36	63	36
β	8.6				
Experiment	68	51	43	58	51
p-value (Experiment vs. z^*_{QRE})	**0.151**	0.001	0.000	0.001	0.000

Table 7 –Average QRE base-stock level under optimal competition

Tables 8 and 9 compare the differences between the experimental results (subjects' average decisions) and the Nash equilibrium with the difference between the experimental results and the QRE. These tables show the differences only when they are statistically significant ($p < 0.05$).

	Service Competition					Inventory Competition				
	Identical	different c		different h		Identical	different c		different h	
		Supp. 1	Supp. 2	Supp. 1	Supp. 2		Supp. 1	Supp. 1	Supp. 1	Supp. 1
$z_{EXP} - z^*$	4	—	—	—	5	19	9	8	3	14
$z_{EXP} - z^*_{QRE}$	2	—	—	—	4	12	—	—	–4	—

Table 8 –The gap of Nash equilibrium and average QRE base-stock levels from the experimental results (when the difference is statistically significant, $p < 0.05$)

We can see that, for service and inventory competitions, the QRE is either statistically equivalent to the experimental results, or when there is a significant difference, the QRE is closer to the experimental results than the Nash equilibrium. In other words, the QRE falls between the experimental results and the Nash equilibrium. The only exception is the more efficient supplier when the suppliers have different inventory holding costs. In this case the QRE overestimates the subjects' decisions while the Nash equilibrium underestimates the subjects' decisions.

	Optimal Competition				
	Identical	different c		different h	
		Supp. 1	Supp. 2	Supp. 1	Supp. 2
$z_{EXP} - z^*$	–8	–26	—	–19	6
$z_{EXP} - z^*_{QRE}$	4	–8	7	–6	14

Table 9 –The gap of Nash equilibrium and average QRE base-stock levels from the experimental results (when the difference is statistically significant, $p < 0.05$)

Table 9 shows that the Quantal Response Equilibrium approach has less success in predicting subjects' behavior under optimal competition. That is, the difference between the experimental results and the QRE is always statistically significant, and in two cases this difference is even larger than the difference between the experimental results and the Nash equilibrium. As we discussed in section 7.1, under optimal competition, other factors such as loss aversion and rival chasing could play an influential role on subjects' decisions. The QRE results specifically confirms the rival chasing behavior. That is, the subjects' decisions for the more efficient suppliers are less than the QRE and the subjects' decisions for the less efficient suppliers are more than QRE.

8. Concluding Remarks

This research tries to contribute to the existing literature on supplier competition by examining, through laboratory experiments, the theoretical results derived in this field. We conducted experiments under three types of competition: service, inventory, and optimal. In each type of competition, suppliers compete for the demand share of a single buyer based on a performance measure (competition criteria) announced by the buyer. This performance measure is fill-rate under service competition, base-stock level under inventory competition, and a combination of fill-rate and base-stock level under optimal competition. Under each type of competition, we also consider the impact of heterogeneity in suppliers' cost structure.

While the buyer's goal is to elicit high service level from its suppliers, our experimental results confirm the theoretical, but counterintuitive, prediction that the buyer does not get the best result when she uses the same service measure as the competition criteria; based on which the demand is allocated to the competing suppliers. Our results confirm that, using a proportional allocation function, the average service level the buyer receives is higher if she uses suppliers' base-stock level as the competition criteria. In other words, inventory competition is more preferable than the service competition (buyer's perspective).

Our experimental results also confirm the theoretical prediction that the optimal competition criteria can induce the highest service level for the buyer. Although the experimental results for optimal competition are not always as high as the Nash equilibrium prediction, the subjects' average decisions under this type of competition are significantly higher than the subjects' average decisions under service or inventory competitions.

Although our experimental results support the theoretical predictions in terms of the comparative output of different types of competition, the average decisions made by subjects does not always match the value predicted by the Nash equilibrium. The Nash equilibrium values are closer to the experimental results under service competition, while under inventory and optimal competition, the differences are more pronounced. The steeper slope of the suppliers' profit function around the Nash equilibrium point can explain why it is easier for the subjects to find the optimal decision under service competition. This slope gets flatter under inventory competition and is more so under the optimal competition. Therefore, it becomes more difficult for the subjects to find the best decisions. This means, although optimal competition is the most desirable type of competition for the buyer, it comes with the cost of more difficulty for the suppliers to find their best decisions.

The deviation of subjects' decisions from the Nash equilibrium indicates that subjects do not always behave purely in a rational way; as the Nash equilibrium assumes. A rational decision maker always aim to find a decision that maximizes his expected profit, while he has the cognitive power to find that decision. When the subjects' decisions deviate from the Nash equilibrium value, it can be due to the reason that the decision makers care about other factors in addition to maximizing the expected profit. It can also be due to the reason that they do not have the cognitive power to accurately find their best decisions. Our results suggest that the first type of reasons is particularly affecting the subjects' decisions under optimal competition. Loss aversion can explains the less than Nash equilibrium average decisions of identical suppliers under optimal competition. When the suppliers have different costs, rival chasing can explain why the average decisions of the two different types of suppliers move toward each other's decisions (with respect the Nash equilibrium predictions).

The subjects' inability to accurately find their best decisions can be modeled by the Quantal Response Equilibrium. In this equilibrium, the assumption is that each decision maker aims to find the best decisions but makes random error along the way. We can see that the Quantal Response Equilibrium predicts subjects' behavior much better than Nash equilibrium, specifically under service and inventory competition. The Quantal Response Equilibrium, under service and inventory competitions, either captures the subjects' average decisions or underestimates them (with just one exception). The reason behind subjects' tendency to choose base-stock decision that is higher than either Nash equilibrium or Quantal Response Equilibrium is not clear and needs further investigation. Even when the Quantal Response Equilibrium is statistically different from the subjects' average decisions, it makes a prediction that is (almost always) closer to the subjects' average decisions than what Nash equilibrium predicts.

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