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This paper tests the prediction of three discrete asymmetric duopoly price competition games in the laboratory. The games differ from each other in terms of the size of the cost asymmetry that induces a systematic variation in the difference between the firms' marginal costs. While the standard theory requires the low-cost firm to set a price just equal to the high cost firm's marginal cost, which is identical across all three games, and win the entire market; intuition suggests that market price may increase with a decrease in the absolute difference between the two marginal costs. We develop a quantal response equilibrium model to test our competing conjecture.

Keywords: Asymmetric costs, Price competition, Laboratory experiment.

JEL Classification: L11, L12, C91, D43

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1. Introduction

The study of price competition is an important foundation of oligopoly theory and remains a staple of all microeconomics textbooks. Of all models of price competition, perhaps the most celebrated is the one in which symmetric duopolists engage in a price war that leads to competitive pricing (Bertrand, 1883). Subsequent theoretical and experimental studies have almost exclusively examined predictive power of the symmetric Bertrand-Nash equilibrium and in turn have spawned a sizeable literature.[1] As a result, our knowledge about the predictive power of *asymmetric* Bertrand-Nash equilibrium remains markedly limited. In this study we address this limitation by designing a laboratory experiment that tests prescriptive accuracy of the duopoly price competition model characterized by asymmetric costs of production.

The Nash equilibrium solution for the symmetric duopoly model recommends that two firms charge a price equal to the common marginal cost of production (Tirole, 1988, *p*. 210). When duopolists have commonly known but dissimilar marginal costs of production ($c_1 < c_2$), Nash equilibrium solution prescribes that the low-cost firm charge a price just equal to c_2, steal the entire market and earn a total profit of ($c_2 - c_1$), provided that $p^m(c_1) \geq c_2$ (Tirole, 1988, *p*. 211). The high-cost firm receives zero profit in this equilibrium.[2]

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[1] The symmetric Bertrand-Nash equilibrium solution has generated a string of theoretical studies that report an inconsistency between the equilibrium prediction and observations from the real markets, which is known in the literature as the Bertrand paradox. The theoretical literature has advanced along two lines. First, it has been argued that certain assumptions that underlie the prediction are not realistic (Kreps and Scheinkman, 1983; Friedman, 1977; Hotelling, 1929; and Edgeworth, 1925). The second line of investigation has questioned the game-theoretic foundations of the Bertrand reasoning (Bowley, 1924). Dufwenberg and Gneezy (2000) and Fouraker and Siegel (1963) are two notable experimental studies that have tested the prediction of the symmetric model.

[2] Blume (2003) develops a theory of duopoly price competition with asymmetric (constant) marginal costs, homogenous products, and continuous strategy space and shows that there exists an equilibrium in *undominated* strategies in which the low-cost firm sets a price equal to c_2. Following Blume (2003) we derive the equilibrium for all of our games in the next section. While Blume (2003) uses the standard rationing rule of equal split to break a tie, Baye and Morgan (2004) shows how a continuous strategy model is sensitive to the choice of a tie-breaking rule.

The primary objective of our study is to test the above classic prediction of the asymmetric model. To achieve this goal, we develop three experimental games of asymmetric duopoly price competition. The three games are comprised of an identical discrete strategy-space; however, they differ from each other in terms of the size of the cost asymmetry that induces a systematic variation in the difference between c_2 and c_1 ($c_2 - c_1 > 0$), holding c_2 fixed. We test the Nash equilibrium prediction of these games, which is identical in all of them, under a perfect-stranger matching protocol that allows a group of paired participants to play each game *only once*. At the same time, we repeat each game for 20 rounds.[3] The advantage of such a design is that it retains the one nature of the theory while insulating behavior from incentives for cooperation and reciprocity, but at the same time allowing for experience. If participants choose as per the equilibrium solution, then play can be expected to converge to the *same* equilibrium price of c_2 in all three games, discussed in detail in Section 2.

However, we suspect that market price may increase with a decrease in the absolute difference between the two marginal costs, as is the case in our games. This suspicion stems from our uneasiness with a crucial assumption that underlies the asymmetric Bertrand-Nash prediction. That is, the low-cost firm will charge c_2, *no matter however small* the difference between the firms' marginal cost is. However, the nature of this prediction seems to go against a simple economic intuition that a smaller cost asymmetry might cause the low-cost firm to set prices higher than c_2. This is because when ($c_2 - c_1$) becomes smaller, the cost of departure from the above equilibrium strategy or the profit from sticking to the equilibrium strategy of c_2 becomes considerably smaller for the low-cost firm. As a result, the low-cost firm's inclination to react to monetary incentives the way the standard model predicts diminishes as ($c_2 - c_1$)

[3] There is a large literature on incorporating learning into models of adjustment in games that are played repeatedly with different partners. See Fudenberg and Levine (1998) for a survey.

decreases.[4] More generally, a gradual reduction in ($c_2 - c_1$) may weaken the predictive power of the asymmetric Bertrand-Nash solution. Accordingly, we conjecture that market price may increase with a decrease in the absolute difference between the two marginal costs.[5]

To theoretically account for our conjecture, we develop a decision-error model based on the notion of Quantal Response Equilibrium (QRE) *á la* McKelvey and Palfrey (1995). Our model incorporates boundedly rational choice in that players choose better responses with higher probabilities, but may not necessarily choose the best response with probability one. More precisely, the choice probabilities for strategies are proportional to the expected payoffs associated with such strategies. Within this framework, we include an error parameter μ that determines how sensitive behavior is with respect to payoffs. Depending on μ, completely random behavior and the aforementioned equilibrium appear as different limiting cases in our model. Using this framework, we derive a prediction that captures the essence of our conjecture.

The experimental literature on the *asymmetric* Bertrand model is thin. Argenton and Mueller (2012) study symmetric and asymmetric Bertrand duopolies with *convex cost conditions*. Their experiment consists of 40 rounds and follows a fixed-matching protocol. After

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[4] In the extreme case when ($c_2 - c_1$) = 0, Dufwenberg and Gneezy (2000) find the market price to be considerably higher than the common marginal cost in the symmetric duopoly model. We also test a symmetric model of duopoly price competition as a control treatment.

[5] The aforementioned idea that the drawing power of Nash equilibrium depends on the associated costs of departures is not novel. A few experimental papers demonstrate that a change in payoff structure, which in turn changes costs of departure from equilibrium prediction, can produce a considerable inconsistency between theoretical predictions and behavior in the lab (see Goeree and Holt, 2001 for a list of such games). Dufwenberg *et al*. (2007) consider two- and four-player symmetric price competition games in the presence of varying levels of price floor and experimentally test the standard Nash prediction that a lower price floor would lead to lower market price. Capra *et al*. (2002) consider duopoly price competition games in the presence of meet-or-release contracts between firms and buyers. Price competition, however, is imperfect in their case in the sense that market share of the high-price firm is not zero. They test the Nash prediction that price levels should be independent of market share of the high-price firm. Both studies argue that the associated Nash prediction runs counter to simple economic intuitions and report a systematic disagreement between the respective Nash prediction and the data. Each study attributes the failure of the standard theory to the crucial assumption underlying the Nash prediction that players respond optimally to any potential gain in profit, *no matter however small*. To reconcile the data with the economic intuition, each study develops an equilibrium model of noisy behavior that assumes that players' decision to play the respective Nash strategy may critically depend on costs of departure from the equilibrium.

the conclusion of each round, each pair is presented with a summary screen displaying its own price choices. They do not find any evidence of symmetric markets being more collusive than asymmetric markets. In fact, for some measures of collusion, they find that firms in their asymmetric treatments come closer to the cartel profit. Unlike them, we investigate asymmetric duopoly games with constant cost conditions under a perfect-stranger matching protocol.

Boone *et al*. (2012) study asymmetric price competition in duopoly and triopoly markets. They explore two types of triopoly markets: one in which all firms have different marginal costs and another in which two of the three firms share the lowest marginal cost. In each experimental session, the market size and role of each participant in each round are determined quasi-randomly such that within each session each participant is assigned each of the 7 possible firm-roles for 8 rounds. Thus, each session implements a within-subject design and consists of 56 rounds. In each session, firms' marginal costs are randomly assigned. At the end of each round, each participant is shown costs and prices in his/her own market and his/her own profit. Boone *et al*. find that market price converges to the Nash prediction in the duopoly and triopoly markets where all firms have different marginal costs. Also, market price stays above the predicted level in the triopoly market where two of the three firms share the lowest marginal cost.

There exists some important differences between our study and Boone *et al*. Boone *et al*. do not vary the size of the cost asymmetry, allow repeated interaction among firms under a random-matching protocol, adopt a within-subject design and induce random assignment of costs. In comparison, we vary the size of the cost asymmetry, allow repeated interaction among firms but adopt a perfect-stranger matching protocol, implement a between-subject design and induce fixed assignment of costs.[6,7]

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[6] We became aware of Argenton and Mueller (2012) and Boone *et al*. (2012) after an anonymous referee brought these studies to our attention.

Keser (1993) experimentally studies a repeated Bertrand duopoly game with asymmetric costs and 'demand inertia'. She reports a tendency toward more cooperative behavior when participants are experienced with the game. Our objective is clearly different from that of Keser's. We aim to provide a direct test of one-shot asymmetric model, while abstaining away from the issue of demand inertia.

The experimental literature on the *symmetric* Bertrand model is rather large. Dufwenberg and Gneezy (2000) and Fouraker and Siegel (1963) show with random- and fixed-matching protocol, respectively, that duopolies are more likely to sustain collusive prices than triopolies with "maximum" information feedback (all price choices shown after each round of play).[8] Abbink and Brandts (2008) experimentally examine symmetric price competition games characterized by *increasing marginal costs*. They find that only duopolies can sustain collusive prices due to a remarkable degree of price coordination between sellers. Baye and Morgan (2004) is the first study that uses data from the Internet markets to test the competitive prediction of the classic (symmetric) Bertrand model and finds that sellers on the Internet do not price as per the Nash prediction.[9]

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[7] It is difficult to identify a particular design choice of Boone *et al*. (2012) that can explain the differences in behavior between Boone *et al*. (2012) and our study. It may be a combination of design issues that have produced competitive behavior in their duopoly treatment. It may be that large number of repetitions of the stage game and within-subject protocol are instrumental in bringing about competitive outcomes in their duopoly treatment. Boone *et al*. let subjects play close variations of the asymmetric game for 56 rounds in a within-subject design, which provides more opportunities for learning. In contrast, we repeat the stage game only 20 rounds in a between-subject design, thus providing fewer opportunities for learning.

[8] Later, Dufwenberg *et al*. (2007) and Dugar (2007) confirm the main result of Dufwenberg and Gneezy (2000).

[9] There exist a few studies that experimentally investigate the issue of asymmetric cost conditions by focusing on *quantity* competition. Mason *et al*. (1997, 1992) and Rassenti *et al*. (2000) focus on the Cournot competition with asymmetric costs. Mason *et al.* (1992) find that industry outputs are significantly higher in asymmetric than in symmetric markets. Rassenti *et al*. (2000) consider five-firm oligopolies with asymmetric costs and report that the firm level play is inconsistent with the Nash prediction; however the aggregate play pattern is in agreement with the Nash prediction. One should note that the results obtained in the Cournot setting does not necessarily imply that the same results would also be obtained in the Bertrand framework, since the underlying intuitions of quantity *vs.* price competition differ a great deal (see Tirole, 1988, *p*. 207-208 for an overview).

The remainder of the paper is organized as follows. Section 2 derives the Nash equilibrium and QRE prediction for all our games. Section 3 lays out the experimental design. Section 4 reports the results. Section 5 provides a summary.

2. Theory

We begin by presenting a generic duopoly price competition game with asymmetric costs. In particular, our discretized generic game is based on a version of the classic one-shot Bertrand model of price competition introduced by Dufwenberg and Gneezy (2000). Suppose that each firm simultaneously and independently chooses a price from the set {1, 2, 3, … , 50}. Firm 1 has a constant marginal cost of c_1, whereas firm 2's constant marginal cost is c_2. We assume $c_1 < c_2$. On the demand side, there is a perfectly informed single buyer who purchases exactly one unit of the product from the lowest priced firm and this demand is inelastic up to the reservation value of the buyer, which is equal to 50. The firm choosing the lowest price receives a total profit equal to the lowest market price less its own constant marginal cost; the higher priced firm earns zero profit. In case of a tie, each firm's total profit is equal to half of the difference between the common market price and the firm specific constant marginal cost.[10]

We assign three sets of values to the cost pair (c_1, c_2) and thereby generate three games. The experimental design is developed around these games. The pair (c_1, c_2) assumes the values (8, 11), (6, 11), and (4, 11) in the *Small-Diff*, *Medium-Diff*, and *Large-Diff* games, respectively. Given the cost and demand parameters, in each game the classic equilibrium prediction in prices

[10] The above game, inspired by Dufwenberg and Gneezy (2000), captures the following assumptions of a simple Bertrand model with asymmetric costs: firms sell homogeneous products using a constant-returns to scale production function; marginal cost for each firm is therefore constant; the production technologies, however, vary between the firms; there are no capacity constraints; production is instantaneous; and there is no cost or demand uncertainty. The cost conditions are also common knowledge among the firms. This is a model of complete, but imperfect information. Complete, because each player is informed about payoff information (costs, buyer reservation value) for all players; imperfect, because prices are selected simultaneously.

is (c_2, c_2+1); with the firm having a unit cost of c_1 charging a price of c_2 and the other firm charging a price of (c_2+1). In the above equilibrium, the low-cost firm's profit is positive, whereas the profit of the high-cost firm is zero. Table 1 presents an overview of the Nash predictions and the associated payoff for each game.[11]

Blume (2003) examines Bertrand competition with continuous strategy space, homogenous products and different marginal costs and shows that for small enough $\eta > 0$, the following is an equilibrium: The low-cost firm posts a price equal to c_2, and the high-cost firm randomizes uniformly over [c_2, $c_2+\eta$]. Blume argues that from a continuum of equilibria, the case in which the low-cost firm sets a price equal to c_2 represents the only equilibrium in undominated strategies. Owing to discretization in our games, $\eta = 1$, and as a result Blume predicts (c_2, c_2+1) as the only Nash equilibrium in undominated strategies.[12] For the remainder of this study, we will refer to each player's strategy in the above equilibrium as the undominated equilibrium strategy (UES).

Next, we develop a QRE model for a continuous version of the asymmetric price competition game discussed above to account for our conjecture that market price may increase with a decrease in the absolute difference between the two marginal costs.[13] The QRE approach allows for noisy-best responses instead of perfect rationality assumption of the Nash equilibrium

[11] In each game, the set of rationalizable strategies for firm 1 is $\{c_1+1, c_1+2, \ldots, v-1\}$ and for firm 2 is $\{c_1+2, c_1+3, \ldots, v\}$, where v stands for the buyer's maximum willingness to pay. For a definition of rationalizability, see Chapter 4 of Osborne and Rubinstein (1994).

[12] Aside from discretization, the only other difference between Blume's game and ours is that Blume describes a continuously decreasing demand schedule faced by the firms, whereas we present a unitary demand schedule that is inelastic up to the reservation value of the buyer.

[13] Although our experiment tests the predictions of the asymmetric games with a discrete strategy-space, the decision-error model we develop involves a continuum strategy-space.

concept (Anderson *et al*., 2002).[14] The noise in the QRE models may arise due to preference shocks, experimentation, updating of beliefs, or actual mistakes in judgment.

To account for noisy decision-making, we assume that each firm best responds with an error to its rival's price choice. The expected profit for firm *i* is given by

$$\pi_i^e(p) = (p - C_i) \underbrace{\left[1 - F_j(p)\right]}_{prob\ i\ wins\ market}, \quad i \neq j, \quad p \in \left[\underline{P},\ \overline{P}\right] \tag{1}$$

where $p =$ price charged by the i^{th} firm, $C_i =$ (symmetric) constant average cost of the i^{th} firm, $F_j(.) =$ cumulative distribution of the j^{th} firm's price choice ($f_j(.)$ being the corresponding density).[15] The logit choice density (with error parameter μ) for each *i* is given by

$$f_i(p) = \frac{\exp[\pi_i^e(p)/\mu]}{\int_{\underline{P}}^{\overline{P}} \exp[\pi_i^e(y)/\mu]dy} \tag{2}$$

The denominator of the right hand side of (2) is a constant such that the density integrates to one. Equation (2) states that the choice density is increasing in a firm's expected payoff. Note that when the error parameter μ tends to infinity, the equilibrium choice probabilities are drawn from a uniform distribution, which indicates a completely random pricing behavior by firms. In the other extreme situation, when the error parameter μ tends to zero, the equilibrium choice

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[14] There are a few other approaches to explaining departures from Nash prediction. For example, one approach relaxes the assumption of perfect rationality (Akerlof and Yellen, 1985), while other approaches consider concepts of e-equilibria (Radner, 1980) or probabilistic choice models of boundedly rational behavior (Rosenthal, 1989). Still, some other approaches are based on models that limit players' capacity for introspection (see, for example, Nagel, 1995; Stahl and Wilson, 1995).

[15] Baye and Morgan (2004) investigate symmetric Bertrand competition in experimental duopoly, triopoly and quadropoly markets. Their main goal is to analyze the incidence of dispersion in posted prices at a price comparison website on the Internet, as well as in the laboratory. They use three different equilibrium concepts, including the QRE for their purposes. We, in contrast, focus on how an introduction of asymmetry in the cost structure between firms impacts price choices in experimental duopoly markets. There is an important technical difference between our study and that of Baye and Morgan insofar the QRE model is concerned. In their study the posted price can lie between (and including) the common unit cost and the monopoly price, whereas in our study the posted price can be lower than a firm's own cost. We thank an anonymous referee for drawing our attention to the study by Baye and Morgan.

probabilities generate a mass-point, signifying Nash equilibrium behavior. These two limiting cases are consistent with the models presented in Capra *et al*. (2002) and Anderson *et al*. (2002).

For each i the logit differential equation is obtained by differentiating (2) with respect to p and rearranging terms.

$$\mu f_i'(p) = \pi_i^{e'}(p) f_i(p) \tag{3}$$

Equation (3) indicates a basic property of the logit equilibrium (see Anderson *et al*., 2002, p. 25): that when the expected payoff function is increasing, the choice density of decisions is also increasing in equilibrium. Equation (3) can be modified to include the cost parameter as

$$\mu f_i'(p) = \left[\{1 - F_j(p)\} - (p - C_i) f_j(p)\right] f_i(p) \tag{4}$$

where the term $\pi_i^{e'}(p)$ in (3) is substituted by differentiating (1) with respect to p. Equation (4) provides a differential equation for the equilibrium choice density. The existence of a logit equilibrium for this set up is ensured by proposition 1 in Anderson *et al*. (2002).

We can rewrite (4) as

$$\frac{d^2 F_i(p)}{dp^2} \Big/ \frac{dF_i(p)}{dp} = \frac{1}{\mu}\left[\{1 - F_j(p)\} - (p - C_i)\frac{dF_j(p)}{dp}\right]$$

Integrating both sides with respect to p, one can obtain

$$\ln\left(\frac{dF_i(p)}{dp}\right) = \frac{1}{\mu}\left[\int dp - \int F_j(p)dp - \left[(p - C_i)\int \frac{dF_j(p)}{dp}dp - \int\left\{\frac{d(p - C_i)}{dp}\int \frac{dF_j(p)}{dp}dp\right\}dp\right]\right] + k$$

In the above equation, k is an integration-constant. In two steps, this equation can be further simplified to

$$\ln\left(\frac{dF_i(p)}{dp}\right) = \frac{1}{\mu}\left[p - \int F_j(p)dp - \left[(p - C_i)F_j(p) - \int\{1.F_j(p)\}dp\right]\right] + k$$

$$\Rightarrow \frac{dF_i(p)}{dp} = f_i(p) = K\, exp\left[\frac{p - (p - C_i)F_j(p)}{\mu}\right]$$

where $K = \exp(k)$ is a positive constant. Letting i be the low-cost firm (L) and and j be the high-cost firm (H), respectively, the last equation modifies to

$$\Rightarrow \frac{dF_L(p)}{dp} = f_L(p) = K\ exp\left[\frac{p - (p - C_L)F_H(p)}{\mu}\right] \quad (5)$$

The following proposition predicts how, under the logit equilibrium, a change in C_L impacts the low-cost firm's equilibrium choice density.

Proposition 1: *In a logit equilibrium, an increase in C_L results in the low-cost firm posting higher prices, in the sense of first-degree stochastic dominance*.[16]

Proof: See Appendix.

Being equipped with the standard prediction and the prediction of the QRE model for our games, Section 3 develops experimental environments that are designed to test these predictions.

3. Experimental Procedure

The experimental sessions were conducted at a large Canadian University's experimental economics laboratory during 2010-2011. Four sessions were conducted for each of the three treatments: *Small-Diff*, *Medium-Diff*, and *Large-Diff*. 40 undergraduate students took part in each session. Special care was taken to make sure that none of the students took part in more than one session. Each session lasted for about an hour. The participants were given sufficient time to fully understand the instructions and all of their queries were answered before they made their first decision. There was no practice round. At the start of each session 40 participants were randomly matched into groups of two to form 20 duopoly markets. In each session, the same

[16] A seemingly similar result can be found in the second part of the Corollary presented in Dufwenberg *et al.* (2007), who study symmetric competition with price floors. The similarity can be noticeable if we compare the price floor in their study with the low-cost firm's unit cost in ours. The text in the proposition is patterned after that Corollary.

game was repeated for 20 rounds. We employed the perfect-stranger matching protocol. Under this protocol, each participant competed in price with a new counterpart in every round. Thus, 20 new duopoly markets were formed in each of the 20 rounds in a session. At the beginning of the first round, each participant was randomly assigned either the role of a "low-cost type" or a "high-cost type", and this role remained fixed throughout a session.[17]

After the completion of each round, each participant was notified of only his/her and counterpart's price choices and his/her own profit. Communication amongst the participants was strictly prohibited. In each round the participants were rewarded in terms of points and at the end of the session all such points earned by a participant were added up and the total was converted into Canadian dollars at an exchange rate of $1.00 per 8 points. Note that with this exchange rate, a participant who was a "low-cost type" would earn $0.38, $0.63, and $0.88 per round in the *Small-Diff*, *Medium-Diff*, and *Large-Diff* treatment, respectively, assuming that the low-cost firm played its UES and the high-cost firm played any strategy weakly higher than its UES.

The experiment was fully computerized with the Z-Tree software (Fischbacher, 2007). Each participant received an instruction sheet at the beginning of each session. Each instruction sheet had a registration number written at the top that identified him/her during a session. The computer screen also showed each participant's registration number and the cost type. In each round each participant recorded his/her price choice by writing down a number from the price set {1, 2, 3,… , 50} in a space provided on the computer screen. Each participant was presented with a payoff table that described his/her own payoff as a function of the two price choices and his/her

[17] Although it is usually considered a good practice to avoid references to any economic or market terms, we have used "high" and "low" cost types in the instructions. There is no reason to believe that these terms are emotive enough to introduce unobserved personal preferences or aversions for particular player types and thereby may have influenced participants' choices. Moreover, the initial cost-type assignment was random so there is no reason for a specific seller-type to develop a sense of unfairness against us, the experimenter. See Davis and Holt (1993, *p*. 27) for a discussion on possible tradeoffs between emotive terms and economic behavior.

own cost type.[18] In all sessions, each participant started with an initial endowment of \$7 (56 points) to cover any possible losses. Note that a participant could incur a loss in our experiment if s/he won or tied in a round and made some specific price choices. However, no such case was observed in any of the sessions. At the conclusion of the experiment, each participant's earning was computed by adding up the initial endowment and the net profits made. To prevent any possible post-play side payments, we paid participants sequentially with sufficient time gap between any two of them.

At this point, our experimental design choices deserve a careful discussion. First, we employed the perfect-stranger matching protocol. This matching protocol retains one-shot nature of a game, and moreover, it completely shuts off any channel of future cooperation among participants (repeated game effects) by fully eliminating the chance of more than one interaction between a given pair. We could have adopted the random-matching protocol, but that assigns a very small (yet positive) probability to the event where a given pair of participants meets with each other for more than one round. We wanted to avoid any such repeated game/reputation effects. Since we were interested in the behavior of experienced participants, we let our participants play the same game for 20 rounds.[19]

Second, we fixed the role (low or high cost type) of a participant in a session. This role assignment process was adopted to eliminate any potential channel of cooperation among participants. For example, if we had adopted a random role assignment process in each round, then this could have introduced possibilities for cooperation in the following manner. A participant assigned the role of a low-cost type in the current round may fear that harsh play now

[18] The use of payoff tables in the laboratory experiments is by now a well-accepted methodological tool and its early use can be found in Fouraker and Siegel (1963).

[19] Since participants in our experiment decide about prices under the perfect-stranger matching protocol, we do not worry about any repeated interactions that could give rise to coordination on higher prices as has been shown in a theoretical study by Benoit & Krishna (1985).

may lead to the development of a group norm that would be detrimental to him/her in future, as on average half of the time s/he would be assigned the high-cost firm's role. Hence, the random role assignment process may not be the most conservative one to test one-shot Nash prediction as it does not completely eliminate shadow of future cooperation and thereby does not reproduce one-shot game conditions. Our choice of a fixed role assignment process avoids such a concern.

Third, we chose own market feedback as opposed to entire group feedback, which is referred to in the experimental literature as the "maximum feedback". Variations in feedback have been shown to affect outcomes, sometimes drastically, in a variety of experimental market games (see Altavilla *et al*., 2006; Offerman *et al*., 2002; Huck *et al*., 1999 for examples). Own market feedback has been shown to induce competitive behavior in similar Bertrand environments by precluding group dynamics (see Bruttel 2009; Dufwenberg and Gneezy, 2002). Furthermore, we also implemented "zero perfect recall" by *not* making available information about past earnings and choices to participants. This almost forces participants to focus only on current round of play and not condition his current play on past profit conditions.

Fourth, we repeated the same game for 20 rounds in a session, unlike Dufwenberg and Gneezy (2002, 2000) where each stage game was repeated for ten rounds. It could be argued that 20 rounds of play along with own-market feedback in our experiment may produce a reaction to the information about average behavior of others. If a participant observes that others choose prices above Nash prediction in a given treatment, this may cause prices to lie above the Nash prediction in general. Therefore 20 rounds of play along with own-market feedback may not necessarily cause participants to converge towards Nash play.[20]

[20] We are thankful to an anonymous referee for this point.

4. Results

The Aggregate Data

We start by discussing behavior in the first-round, because at this stage no element of experience exists. The three first-round average winning prices, each based on 80 independent price points, are 27.26, 24.64, and 15.75 in the *Small-Diff*, *Medium-Diff*, and *Large-Diff*, respectively. No statistical test is needed to infer that the UES of the low-cost firm, which is 11 in all three treatments, was not achieved in the first round of any of the three treatments. Most notably, the first-round average winning prices in the *Small-Diff*, *Medium-Diff*, and *Large-Diff* treatments can be ranked in descending order of their magnitude of departure from the UES of the low-cost firm.[21]

Since there are 80 independent first-round winning prices in each treatment, we perform a standard *t*-test to check the null hypothesis of the equality of the average winning prices between a given pair of treatments against the one-sided alternative hypothesis as reported in Table 2 along with the test results. For all three treatment pairs, we reject the respective null hypothesis. Therefore, we conclude that before any learning has taken place, the average winning price in the *Small-Diff* treatment is significantly higher than that of in the *Medium-Diff* treatment, and the average winning price in *Medium-Diff* treatment is significantly higher than that of in the *Large-Diff* treatment.

[21] We conducted two sessions of the *Symmetric* cost treatment, where both firms have a marginal cost of 11. The average posted prices in these sessions are 39.56 and 39.27. The corresponding average winning prices are 36.14 and 35.66. A t-test for the equality of the average posted price in the symmetric treatment and the average posted price in the *Small-Diff* treatment (against the alternative that the former is greater than the latter) yields a t-statistic of 17.21 (n = 1600 for *Symmetric,* and 3200 for *Small-Diff*). A t-test for the equality of the average winning price in the symmetric treatment and the average winning price in the *Small-Diff* treatment (against the alternative that the former is greater than the latter) yields a t-statistic of 15.83 (n = 800 for *Symmetric*, and 1600 for *Small-Diff*). Needless to say, similar comparison between the *Symmetric* treatment and *Medium-Diff* or *Large-Diff* will produce a larger t-statistic. We are thankful to an anonymous referee for bringing our attention to the *Symmetric* treatment.

Figures 2 – 4 show the evolution of the session-specific average winning prices in the *Small-Diff*, *Medium-Diff*, and *Large-Diff* treatment, respectively. Focusing on the dynamics of price choices, we observe that by the final round the average winning prices in all three treatments have mostly stabilized. Within each treatment, all session averages behave in the same fashion over time. Therefore, the price behavior within a treatment seems to be broadly invariant to any participant-specific shocks. The three average winning prices, based on the data from all rounds, are 31.66, 25.30, and 15.27 in the *Small-Diff*, *Medium-Diff*, and *Large-Diff*, respectively. Four important observations emerge. First, repetition of the stage game still preserves the same ranking of the average winning prices, as already observed in the first-round data. Second, the UES prediction is not borne by each treatment data. Third, the average winning price is the highest in the *Small-Diff*, followed by *the Medium-Diff* and *Large-Diff*. Fourth, the last-round average winning prices in the *Small-Diff* and *Medium-Diff* are considerably higher than the UES of 11, whereas the last-round average winning price in the *Large-Diff* seems to approach the UES. The last observation should discard concerns that fairness considerations among participants may have generated our data. If this were the case, then we will not observe close-to-the UES play in the *Large-Diff* treatment, which translates into large payoff inequality between participants playing in the role of high- and low-cost firms. Figures 2 to 4 should also assuage concerns about market-specific dynamics leading to very different behaviors (with the possible exception of session 1 in Medium-Diff) in different treatments.

Strictly speaking, the perfect-stranger matching design makes observations of price choices over-time non-independent, and therefore we have four observations per treatment, where each observation is a session-specific average. We perform a nonparametric Mann-Whitney-Wilcoxon test based on the ranks for each of the three treatment pairs with the null hypothesis that for a given pair of treatments the average winning prices are statistically identical against a one-sided alternative hypothesis. Test results are reported in Table 3. We reject each null hypothesis in favor of the respective alternative hypothesis. We also perform a Jonckheere-Terpstra test to check if the average winning price in the *Small-Diff* treatment is higher than the same in the *Medium-Diff* treatment, and the average winning price in the *Medium-Diff* treatment is higher than the same in the *Large-Diff* treatment. The Jonckheere-Terpstra test result confirms the above statistical conjecture. To test our main hypothesis that the posted price by the low-cost firm will increase as the difference between the firms' marginal costs narrows, we also performed similar tests by using the average posted prices by the low-cost firm (Table 4). Qualitatively similar results emerge. Thus, the data strongly indicate that there exists an inverse relationship between the size of the cost asymmetry and the market price. This finding goes against the standard prediction that pricing behavior in the asymmetric Bertrand duopoly model is independent of the size of the cost asymmetry.

Table 5 reports the actual total profit earned by each type of firm in each of the three treatments for 20 rounds of play.[22] Recall that according to the theory: (1) the high-cost firm should receive zero profit in each treatment, (2) the low-cost firm should make positive profit in any of the equilibria in each game, and (3) the low-cost firm's equilibrium profit is maximized at the UES price in each treatment.

In the data, the actual profit earned by the high-cost firm in each treatment is, however, far from zero. The high-cost firm's average profit decreases as the size of the cost asymmetry goes up. We also compute, for each treatment, the standard deviation of prices posted by the high-cost firms. In the *Small-Diff* treatment, the first and last round standard deviations of prices

[22] We compute the theoretical profit figures for the low-cost firm in each treatment by assuming that the low-cost firm chooses a price of 11, which is the UES price for the low-cost firm.

are 8.81 and 7.40. The corresponding figures for the *Medium-Diff* and *Large-Diff* are 8.87 and 7.99, and 10.05 and 8.66, respectively. The respective figures for the other rounds, which we do not report here, exhibit a clear trend of decrease over time. These figures provide evidence of a clear decline in the volatility of prices by the high-cost firms.

The magnitude of the actual profit of the low-cost firm decreases as the size of the cost asymmetry increases across treatments. In fact, the difference between the theoretical profit (as per the UES prediction) and the average profit earned by the low-cost firm diminishes as the cost asymmetry increases. Overall, the profit figures again negate the UES prediction. The average earnings for participants playing in the role of low- and high-cost firm in *Small-Diff*, *Medium-Diff*, and *Large-Diff* are approximately ($45, $12), ($37, $9), and ($25, $2), respectively, excluding the show-up fee.

Individual & Market Data

The above analyses have established that different sizes of cost asymmetry generate different levels of competitive behavior. However, all the evidence presented above is at an aggregate level. One may, in addition, want to have an idea of composition effects. For instance, the high average winning price in the *Small-Diff* treatment might be the combined result of certain duopolies achieving cooperation at really high prices, while other duopolies playing the UES. To shed light on the issue of whether we observe similar behavior across all the markets in a given treatment, we plot the percentage deviation of market prices from the UES prediction for each treatment. Figure 5 displays the evolution of these deviations for the *Small-Diff*, *Medium-Diff*, and *Large-Diff* treatment, respectively. The vertical axis in each figure represents the percentage deviation of actual winning price from the UES price of 11. The size of each circle in these figures is proportional to the number of observations that fall in a specific percentage deviation category. The central observation that results from a careful inspection of figure 5 is this: The magnitude of deviations of the winning prices from the UE price diminishes as we move from *Small-Diff* treatment to *Medium-Diff* treatment followed by *Large-Diff* treatment. Overall, these figures accord well with our earlier observation that there is an inverse relationship between the size of the cost asymmetry and the number of markets that exhibit higher percentage deviations from the UE price.

Distribution of Price Choices by Firm Type

Panel A in Figure 6 depicts the distribution of posted prices by the low-cost firms in each treatment. Note that in each treatment there are 400 posted prices set by the low-cost firms. In the *Small-Diff* treatment, less than 5% of all the prices belong to the price interval that includes the UES of the low-cost firm. In contrast in the *Medium-Diff* treatment 21% of all the posted prices and in the *Large-Diff* treatment about 43% of all the posted prices belong to the price interval that includes the UES of the low-cost firm. Thus, the higher is the level of guaranteed profit; the lower is the percentage of posted prices, set by the low-cost firms, which strictly exceeds the UE price. Panel B in Figure 6 shows the distribution of posted prices set by the high-cost firms in each treatment. First, we investigate how the high-cost firms' preferences for high prices correlate with the low-cost firms' pricing preference in a given treatment. In the *Small-Diff* and *Medium-Diff* treatments, all the posted prices by the high-cost firms are strictly higher than 10. In the *Large-Diff* treatment, 99% of the posted prices are strictly higher than 10. These percentages may indicate that the high-cost firms realized the low-cost firms pricing incentive in each treatment, and thus behaved accordingly. Second, there may be a concern that those participants who played in the role of the high-cost firm may have chosen prices randomly upon realization that they will make zero profit in any case. We examine this possibility. There are

1600 prices chosen by all the high-cost firms in each treatment. The number of observations for which the high-cost firm posts a price less than 11 in the Small-Diff and Medium-Diff treatments is zero. The minimum posted prices by the high-cost firm in the Small-Diff and Medium-Diff treatments are 11 and 12, respectively. For the Large-Diff treatment, there are a total of 6 observations for which a high-cost firm posted a price less than 11, and the minimum posted price is 2. One may form a conjecture that since each participant's role remained fixed throughout a session, a high-cost firm may get frustrated and might vent their frustration by occasionally choosing a price strictly less than c2 = 11. The above data, however, does not support such a conjecture.

Similar behavioral trends across treatments can be detected when we focus on the distribution of market wining prices. Figure 7 shows the distribution of market winning prices in each treatment. An inspection of Figure 7 shows that there exists a positive relation between the size of the cost asymmetry and the incidence of the UES play.

To sum up, our main result is that there exists an inverse relationship between the size of the cost asymmetry and market price in asymmetric Bertrand duopolies. This lends sufficient credibility to our argument that the low-cost firm's behavior may be determined by the size of the cost asymmetry.

5. Summary

The objective of this study was to provide experimental evidence regarding the predictive power of Nash equilibrium (in undominated strategies) as applied to one-shot asymmetric duopoly price competition model. Standard theory predicts that when duopolists have *different* constant marginal costs (say, $c_1 < c_2$), the low-cost firm should set a price just equal to c_2 and earn a profit equal to ($c_2 - c_1$). However, it is intuitively possible that the size of the cost asymmetry might determine the low-cost firm's willingness to set a price equal to c_2. Specifically, we conjecture that as the size of the cost asymmetry decreases; the low-cost firm would demonstrate a higher tendency to depart from the equilibrium strategy.

Contrary to the standard prediction and in accordance with our main hypothesis, the data exhibit that as the cost difference between firms increases, the low-cost firm deviates less and less from the UES strategy. It turns out that the market price on average becomes more competitive as the cost difference increases. Expressed differently, when firms do not differ a great deal from each other in terms of cost advantages, price competition actually lowers the likelihood of lower prices. The potential for worse outcomes with a small difference in cost efficiency may at first seem paradoxical. However, in view of our argument this result may offer valuable insight about the nature of price competition under such market conditions.

So, how might our main finding inform competitive behavior in real markets? The primary lesson is that firms with considerably greater cost advantages would drive cost-inefficient firms out of business whereas firms that are nearly equal in cost advantages would sustain supracompetitive prices. However, it should be kept in mind that our results could also be due to the abstract and artificial environment of laboratory experiments. On the theory side, our results may highlight a possible weakness of economic models in which there is little incentives for players to stick with equilibrium strategy. In this regard, we think our paper contributes to a small but growing literature (specifically, marked by the contribution from Goeree and Holt, 2001) that tries to find game theoretic situations where a clear contradiction exists between Nash equilibrium predictions and simple economic intuitions. Future research could attempt to test the robustness of our main result in other market forms such as triopoly and quadropoly.

References

Abbink, K., & Brandts, J. (2008). 24. Pricing in Bertrand competition with increasing marginal costs. *Games and Economic Behavior*, *63*(1), 1-31.

Akerlof, G. A., & Yellen, J. L. (1985). Can small deviations from rationality make significant differences to economic equilibria?. *American Economic Review*, *75*(4), 708-720.

Altavilla, C., Luini, L., & Sbriglia, P. (2006). Social learning in market games. *Journal of Economic Behavior & Organization*, *61*(4), 632-652.

Anderson, S. P., Goeree, J. K., & Holt, C. A. (2002). The logit equilibrium: a perspective on intuitive behavioral anomalies. *Southern Economic Journal*, *69*(1), 21-47.

Argenton, C., & Müller, W. (2012). Collusion in experimental Bertrand duopolies with convex costs: the role of cost asymmetry. *International Journal of Industrial Organization*, *30*(6), 508-517.

Baye, M. R., & Morgan, J. (2004). Price dispersion in the lab and on the Internet: theory and evidence. *RAND Journal of Economics*, *35*(3), 449-466.

Benoit, J. P., & Krishna, V. (1985). Finitely repeated games. *Econometrica*, *53*(4), 905-922.

Bertrand, J. (1883). Théorie mathematique de la richesse sociale. *Journal des Savants*, 499-508.

Blume, A. (2003). Bertrand without fudge. *Economics Letters*, *78*(2), 167-168.

Boone, J., Larraín Aylwin, M. J., Müller, W., & Ray Chaudhuri, A. (2012). Bertrand competition with asymmetric costs: experimental evidence. *Economics Letters*, *117*(1), 134-137.

Bowley, A. (1924). *Mathematical Foundations of Economics*. Oxford University Press. New York.

Bruttel, L. V. (2009). Group dynamics in experimental studies—the Bertrand paradox revisited. *Journal of Economic Behavior & Organization*, *69*(1), 51-63.

Capra, C. M., Goeree, J. K., Gomez, R., & Holt, C. A. (2002). Learning and noisy equilibrium behavior in an experimental study of imperfect price competition. *International Economic Review*, *43*(3), 613-636.

Davis, D. D., & Holt, C. A. (1993). *Experimental Economics*. Princeton University Press. New Jersey.

Dufwenberg, M., & Gneezy, U. (2002). Information disclosure in auctions: an experiment. *Journal of Economic Behavior & Organization*, *48*(4), 431-444.

Dufwenberg, M., & Gneezy, U. (2000). Price competition and market concentration: an experimental study. *International Journal of Industrial Organization*, *18*(1), 7-22.
Dufwenberg, M., Gneezy, U., Goeree, J. K., & Nagel, R. (2007). Price floors and competition. *Economic Theory*, *33*(1), 211-224.

Dugar, S. (2007). Price-matching guarantees and equilibrium selection in a homogenous product market: an experimental study. *Review of Industrial Organization*, *30*(2), 107-119.

Edgeworth, F. Y. (1925). *Papers Relating to Political Economy.* Macmillan Publishers. London.

Fischbacher, U. (2007). z-Tree: Zurich toolbox for ready-made economic experiments. *Experimental Economics*, *10*(2), 171-178.

Fouraker, L. E., & Siegel, S. (1963). *Bargaining Behavior*. McGraw-Hill Publishers. New York.

Friedman, J. W. (1977). *Oligopoly and the Theory of Games*. North-Holland Publishing Company. Amsterdam.

Fudenberg, D., Levine, D. K. (1998). Learning in games. *European Economic Review*, *42*(3), 631-639.

Goeree, J. K., & Holt, C. A. (2005). An experimental study of costly coordination. *Games and Economic Behavior*, *51*(2), 349-364.

Goeree, J. K., & Holt, C. A. (2001). Ten little treasures of game theory and ten intuitive contradictions. *American Economic Review*, *91*(5), 1402-1422.

Hotelling, H. (1929). Stability in competition. *Economic Journal*, *39*(153), 41-57.

Huck, S., Normann, H. T., & Oechssler, J. (1999). Learning in Cournot oligopoly–an experiment. *Economic Journal*, *109*(454), 80-95.

Jia, P. (2008). What happens when Wal-Mart comes to town: an empirical analysis of the discount retailing industry. *Econometrica*, *76*(6), 1263-1316.

Keser, C. (1993). Some results of experimental duopoly markets with demand inertia. *Journal of Industrial Economics*, *41*(2), 133-151.

Kreps, D. M., & Scheinkman, J. A. (1983). Quantity precommitment and Bertrand competition yield Cournot outcomes. *Bell Journal of Economics*, *14*(2), 326-337.

Mason, C. F., & Phillips, O. R. (1997). Information and cost asymmetry in experimental duopoly markets. *Review of Economics and Statistics*, *79*(2), 290-299.

Mason, C. F., Phillips, O. R., & Nowell, C. (1992). Duopoly behavior in asymmetric markets: an experimental evaluation. *Review of Economics and Statistics*, *74*(4), 662-670.

Nagel, R. (1995). Unraveling in guessing games: an experimental study. *American Economic Review*, *85*(5), 1313-1326.

Offerman, T., Potters, J., & Sonnemans, J. (2002). Imitation and belief learning in an oligopoly experiment. *Review of Economic Studies*, *69*(4), 973-997.

Osborne, M. J., & Rubinstein, A. (1994). *A Course in Game Theory*. MIT Press. Cambridge.

Radner, R. (1980). Collusive behavior in noncooperative epsilon-equilibria of oligopolies with long but finite lives. *Journal of Economic Theory*, *22*(2), 136-154.

Rassenti, S., Reynolds, S. S., Smith, V. L., & Szidarovszky, F. (2000). Adaptation and convergence of behavior in repeated experimental Cournot games. *Journal of Economic Behavior & Organization*, *41*(2), 117-146.

Rosenthal, R. W. (1989). A bounded-rationality approach to the study of noncooperative games. *International Journal of Game Theory*, *18*(3), 273-292.

Stahl, D. O., & Wilson, P. W. (1995). On players' models of other players: theory and experimental evidence. *Games and Economic Behavior*, *10*(1), 218-254.

Tirole, J. (1988). *The Theory of Industrial Organization*. MIT Press. Cambridge.

Appendix

Proof of Proposition 1: We assume that p stands for the posted price by L. Suppose the unit cost of L increases from C_L^I to C_L^{II}, and the corresponding CDFs are given by $F_L^I(p)$ and $F_L^{II}(p)$. We need to show that if $C_L^I < C_L^{II}$ in two different equilibria, then $F_L^I(p)$ produces stochastically lower prices for L, that is $F_L^I(p) > F_L^{II}(p)$.

We begin by partially differentiating both sides of (5) in the main text with respect to C_L.

$$\frac{\partial}{\partial C_L}\left(\frac{dF_L(p)}{dp}\right) = \left\{\frac{F_H(p) + (C_L - p)\frac{\partial F_H(p)}{\partial C_L}}{\mu}\right\} K\, exp\left[\frac{p - (p - C_L)F_H(p)}{\mu}\right] \qquad (6)$$

Note that $\frac{\partial}{\partial C_L}\left(\frac{dF_L(p)}{dp}\right) \gtreqless 0 \iff \left\{F_H(p) + (C_L - p)\frac{\partial F_H(p)}{\partial C_L}\right\} \gtreqless 0$, as all other terms on the right hand side of equation (6) are positive. We now investigate the sign of the expression $\left\{F_H(p) + (C_L - p)\frac{\partial F_H(p)}{\partial C_L}\right\}$, which critically hinges on the sign of $\frac{\partial F_H(p)}{\partial C_L}$.

It what follows we first show that in a logit equilibrium, $\frac{\partial F_H(p)}{\partial C_L} < 0 \;\forall\, p \in [\underline{P}, C_L)$ and $\frac{\partial F_H(p)}{\partial C_L} \leq 0 \;\forall\, p \in \left[C_L, \overline{P}\right]$. Suppose, by contradiction, that $\frac{\partial F_H(p)}{\partial C_L} > 0$. Then we have $\forall\, p < C_L$, $\left\{F_H(p) + (C_L - p)\frac{\partial F_H(p)}{\partial C_L}\right\} > 0$, which implies that $\frac{\partial}{\partial C_L}\left(\frac{dF_L(p)}{dp}\right) > 0$. In other words, the condition $\frac{\partial}{\partial C_L}\left(\frac{dF_L(p)}{dp}\right) > 0 \;\forall\, p < C_L$ implies that if C_L increases, the firm assigns higher densities ($f_L(p)$) in the price range $\underline{P} \leq p < C_L$. Now, according to (2), $f_L(p)$ can increase only when $[\exp[\pi_L^e(p)/\mu]]$ increases, i.e., $\pi_L^e(p)$ increases. Since $\pi_L^e(p) = \left[(p - C_L)[1 - F_H(p)]\right]$, it follows that for any given $p \in [\underline{P}, C_L)$, the term $(p - C_L)$ has become more negative with the increase in unit cost of L from C_L^I to C_L^{II}. Therefore, $\pi_L^e(p)$ can increase (in other words, becomes less negative) only if $[1 - F_H(p)]$ decreases, i.e., the probability that H wins the market increases, which can only happen if H decides to increase its densities in the range $[\underline{P}, C_L)$.

However, since $\pi_H^e(p_H) = (p_H - C_H)$*[probability H wins the market], an increase in H's densities in the range $[\underline{P}, C_L)$ means that $\pi_H^e(p_H)$ would be more negative than before in the same price range. This outcome contradicts equation (2), which states that for *each* firm density increases with expected profit. As a result, the assumption that $\frac{\partial F_H(p)}{\partial C_L} > 0$ is void, which establishes the first part our claim that $\frac{\partial F_H(p)}{\partial C_L} < 0 \ \forall \ p \in [\underline{P}, C_L)$.

Now, we prove the second part of the proof, that is, $\frac{\partial F_H(p)}{\partial C_L} \leq 0 \ \forall \ p \in \left[C_L, \overline{P}\right]$. Suppose, following an increase in C_L, if H reduces $x \in (0,1)$ amount of area by reducing its densities from each $p \in [\underline{P}, C_L)$, then: (i) the same amount of area must be added to the other part of the distribution ($F_H(p)$) that lies in the range $\left[C_L, \overline{P}\right]$ (since the total area under the distribution must be unity), and therefore (ii) some $p \in \left[C_L, \overline{P}\right]$ will receive the added density. As such, the loss of area x to the left of the distribution: (a) may not be fully regained till p becomes equal to $\overline{P}$, in which case $\frac{\partial F_H(p)}{\partial C_L} < 0 \ \forall \ p \in [C_L, \ \overline{P})$ and $\frac{\partial F_H(p)}{\partial C_L} = 0$ at $p = \overline{P}$, or, (b) may be fully regained before p becomes equal to $\overline{P}$, in which case $\frac{\partial F_H(p)}{\partial C_L} \leq 0 \ \forall \ p \in \left[C_L, \overline{P}\right]$. Combining (a) and (b) the condition $\frac{\partial F_H(p)}{\partial C_L} \leq 0 \ \forall \ p \in \left[C_L, \overline{P}\right]$ must hold.

Now given that $\frac{\partial F_H(p)}{\partial C_L} < 0 \ \forall \ p \in [\underline{P}, C_L)$, if the price posted by L is $p < C_L$, then it implies $\left\{F_H(p) + (C_L - p)\frac{\partial F_H(p)}{\partial C_L}\right\} < 0$ (since $F_H(p)$ is positive but very small). Thus if $p < C_L$, then $\frac{\partial}{\partial C_L}\left(\frac{dF_L(p)}{dp}\right) < 0$ (using (6)), which means when C_L rises $\pi_L^e(p)$ becomes more negative and as a result L lowers its density $\forall \ p \in [\underline{P}, C_L)$. Therefore, $\forall \ p \in [\underline{P}, C_L^{II})$, $F_L^{II}(p)$ will be flatter than $F_L^I(p)$.

On the other hand, if L posts a price $p \geq C_L$, then $\left\{F_H(p) + (C_L - p)\frac{\partial F_H(p)}{\partial C_L}\right\} > 0$, since $\frac{\partial F_H(p)}{\partial C_L} \leq 0 \; \forall \; p \in \left[C_L, \overline{P}\right]$. Thus for $p \geq C_L$, $\frac{\partial}{\partial C_L}\left(\frac{dF_L(p)}{dp}\right) > 0$ (using (6)), which implies when C_L rises, L increases its density $\forall \; p \in \left[C_L, \overline{P}\right]$. Therefore $\forall \; p \in \left[C_L^{II}, \overline{P}\right]$, the CDF of L will be steeper when $C_L = C_L^{II}$ compared to when $C_L = C_L^{I}$.

The above comparative statics results can also be understood with the aid of Figure 1. When C_L increases from C_L^{I} to C_L^{II}, the corresponding CDFs under the two cost situations can be represented by $F_L^{I}(p)$ and $F_L^{II}(p)$, respectively. As drawn, $F_L^{II}(p)$ will be flatter for $p \in [\underline{P}, C_L^{II})$ and steeper for $p \in \left[C_L^{II}, \overline{P}\right]$, in comparison to $F_L^{I}(p)$. Therefore, $F_L^{I}(p)$ must lie above $F_L^{II}(p)$.

Finally, what if $F_L^{I}(p)$ does not lie above $F_L^{II}(p)$? For example, assume that $F_L^{II}(p)$ intersects $F_L^{I}(p)$ from below (not shown in the figure) at a price $p > C_L^{II}$. Then it must be the case that for a certain (higher) range of prices, $F_L^{II}(p)$ is flatter than $F_L^{I}(p)$. However, this violates the condition that for $p \in \left[C_L^{II}, \overline{P}\right]$, $F_L^{II}(p)$ is steeper than $F_L^{I}(p)$. To sum it up, since $F_L^{I}(p)$ always lies above $F_L^{II}(p)$, it implies that $F_L^{I}(p)$ always produces stochastically lower prices, that is $F_L^{I}(p) > F_L^{II}(p) \; \forall \; p$, which completes the proof. In addition, if Proposition 1 holds, market price will also increase (in a probabilistic sense) when C_L increases, for a given C_H.

Tables

TABLE 1

The Nash Equilibrium Predictions

Small-Diff (8,11)		*Medium-Diff (6,11)*		*Large-Diff (4,11)*	
Nash Equilibrium	Equilibrium Payoff	Nash Equilibrium	Equilibrium Payoff	Nash Equilibrium	Equilibrium Payoff
(11, 12)	(3, 0)	(11, 12)	(5, 0)	(11, 12)	(7, 0)

Note: Within each parenthesis, the first number corresponds to the low-cost firm and the second number corresponds to the high-cost firm.

TABLE 2

Tests for the First-Round Average Winning Prices

Null Hypothesis (H_0)	Alternative Hypothesis (H_1)	*t*-Statistic	Prob (T > *t*)	Decision
Small-Diff = Medium-Diff	*Small-Diff > Medium-Diff*	2.125	0.02	Reject H_0
Small-Diff = Large-Diff	*Small-Diff > Large-Diff*	10.409	0.00	Reject H_0
Medium-Diff = Large-Diff	*Medium-Diff > Large-Diff*	7.598	0.00	Reject H_0

Note: There are 80 observations per treatment.

TABLE 3

Nonparametric Tests of Average Winning Prices Based on All Round Data

Test	Mann-Whitney-Wilcoxon Test Statistic	z (Prob > z)	Decision
Small-Diff vs. *Medium-Diff*	36	2.309 (0.0209)**	*Small-Diff* > *Medium-Diff*
Small-Diff vs. *Large-Diff*	36	2.309 (0.0209)**	*Small-Diff* > *Large-Diff*
Medium-Diff vs. *Large-Diff*	36	2.309 (0.0209)**	*Medium-Diff* > *Large-Diff*
Small-Diff vs. *Medium-Diff* vs. *Large-Diff*	Jonckheere-Terpstra Test Statistic = 108	If J > 40, test statistic is significant at 1% level	*Small-Diff* > *Medium-Diff* > *Large-Diff*

Note: (i) The table represents session level statistical comparisons. The number of observations for each treatment is 4, (ii) The session level average winning prices are (32.01, 31.59, 32.53, 30.51), (23.27, 25.81, 26.18, 25.93) and (16.78, 14.99, 14.58, 14.75) for Small-Diff, Medium-Diff and Large-Diff, respectively, (iii) Jonckheere-Terpstra test statistic in this case is the sum of the pairwise Mann-Whitney-Wilcoxon test statistic.

TABLE 4

Nonparametric Tests of Average Posted Prices by the Low-Cost Firm

Test	Mann-Whitney-Wilcoxon Test Statistic	z (Prob > z)	Decision
Small-Diff vs. *Medium-Diff*	36	2.309 (0.0209)**	*Small-Diff* > *Medium-Diff*
Small-Diff vs. *Large-Diff*	36	2.309 (0.0209)**	*Small-Diff* > *Large-Diff*
Medium-Diff vs. *Large-Diff*	36	2.309 (0.0209)**	*Medium-Diff* > *Large-Diff*
Small-Diff vs. *Medium-Diff* vs. *Large-Diff*	Jonckheere-Terpstra Test Statistic = 108	If J > 40, test statistic is significant at 1% level	*Small-Diff* > *Medium-Diff* > *Large-Diff*

Note: (i) The table represents session level statistical comparisons. The number of observations for each treatment is 4, (ii) The session level average posted prices are (36.07, 35.52, 36.24, 35.19), (28.59, 31.17, 31.26, 30.70) and (23.33, 23.63, 23.68, 23.62) for Small-Diff, Medium-Diff and Large-Diff, respectively, (iii) Jonckheere-Terpstra test statistic in this case is the sum of the pairwise Mann-Whitney-Wilcoxon test statistic.

TABLE 5

Actual Total Profit compared to UE Profit for 20 Rounds of Play by Firm Type

		Small-Diff		*Medium-Diff*		*Large-Diff*	
		LCF	HCF	LCF	HCF	LCF	HCF
UE Profit		60	0	100	0	140	0
Actual Profit	Session I	296.88	161.48	226.93	90.98	197.83	35.50
	Session II	394.20	67.60	337.43	45.28	187.58	19.58
	Session III	404.03	72.35	318.50	66.60	198.13	6.43
	Session IV	359.23	75.35	294.88	80.63	199.83	7.88
Average Profit		363.59	94.20	294.44	70.87	195.84	17.35

Note: LCF stands for low-cost firm, and HCF stands for high-cost firm.

Figures

Figure 1: Equilibrium Choice Distribution of Prices for Low-Cost Firm

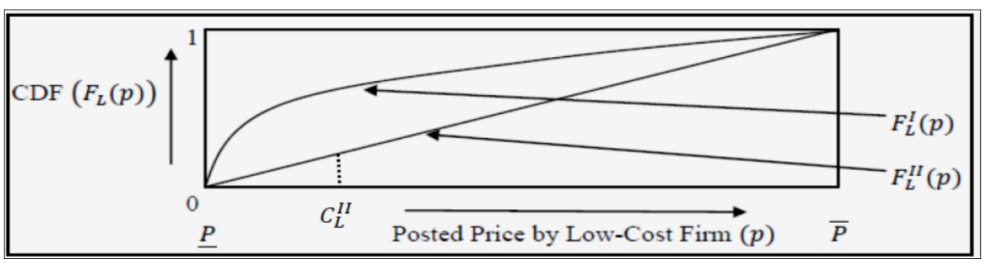


Figure 2: Average Winning Price in *Small-Diff* Sessions

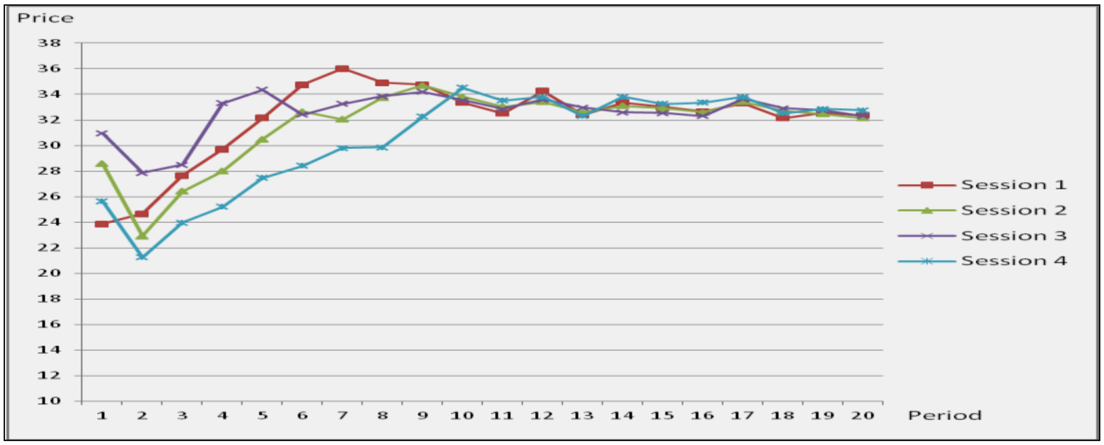


Figure 3: Average Winning Price in *Medium-Diff* Sessions

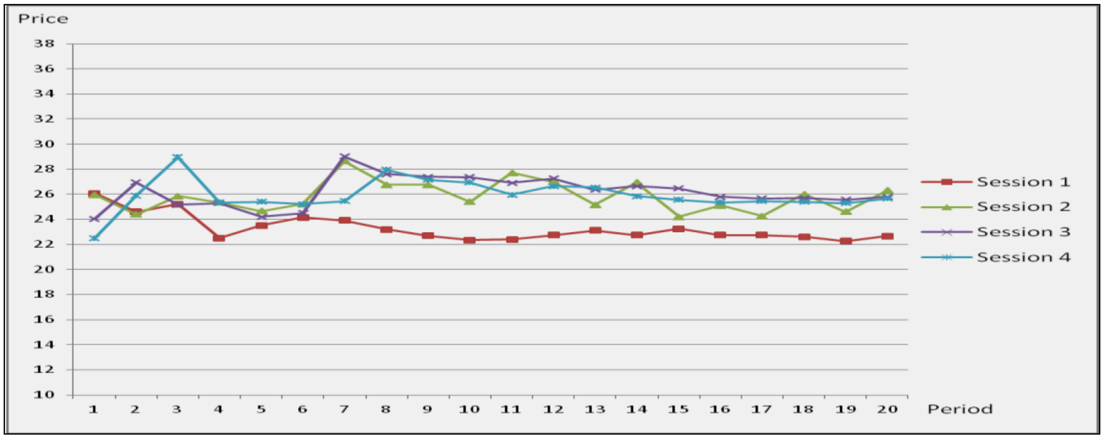


Figure 4: Average Winning Price in *Large-Diff* Sessions

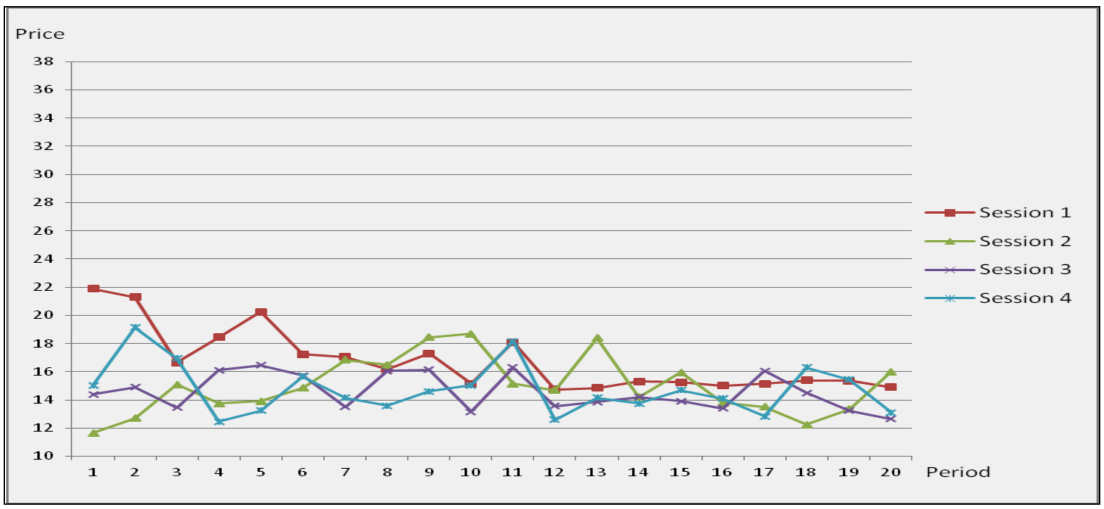
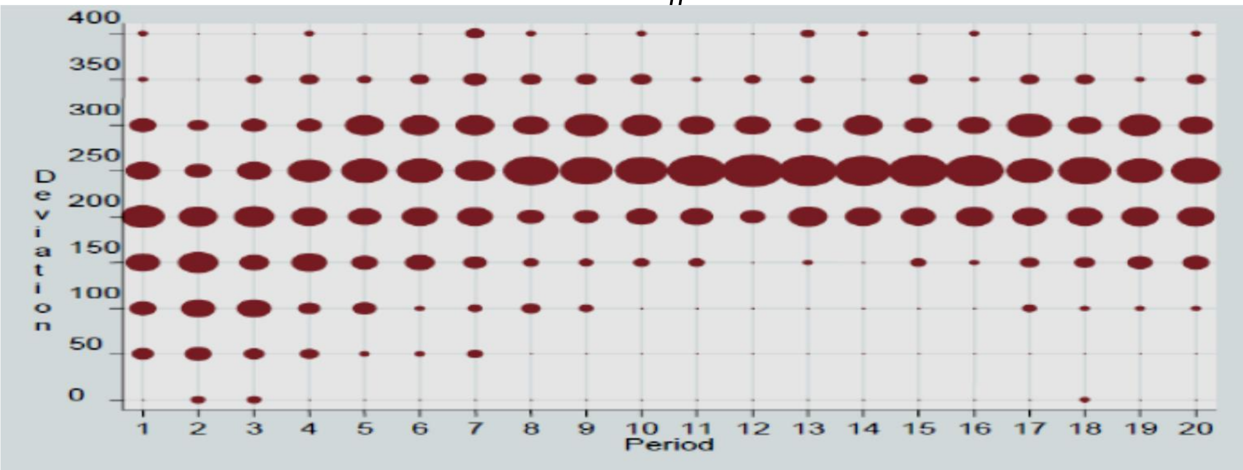
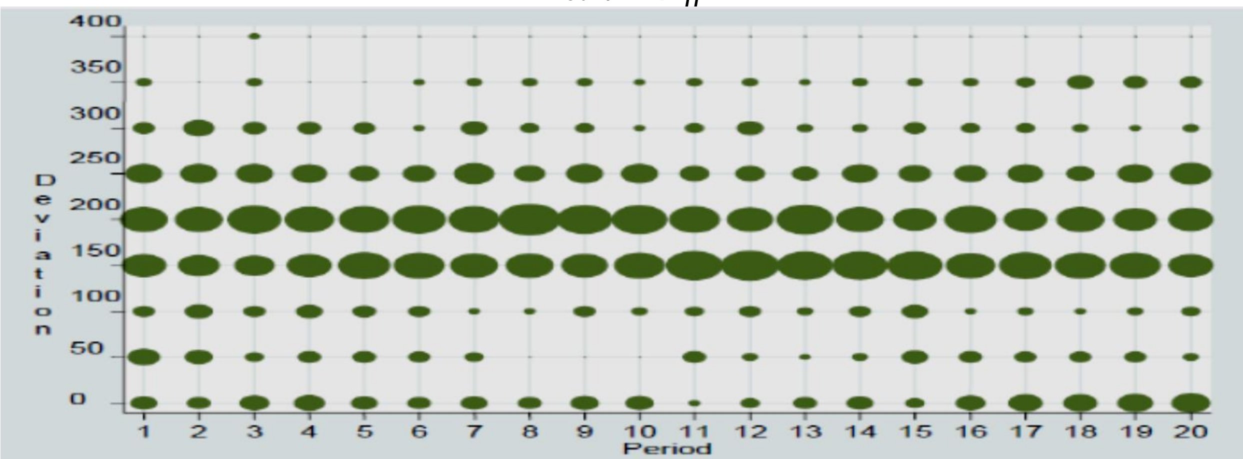


Figure 5: Percentage Deviation of Winning Price from the UE Price in Treatments

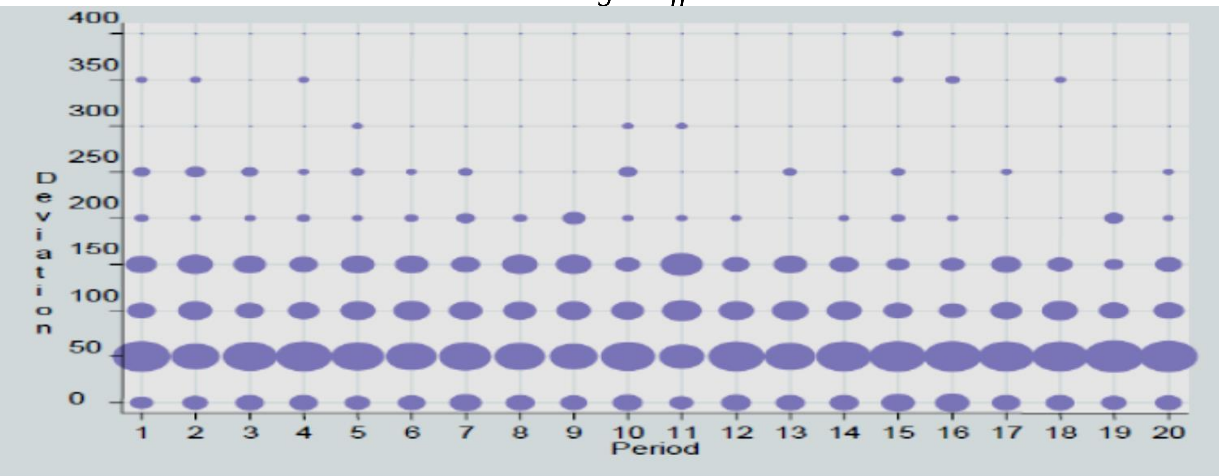
Small-Diff



Medium-Diff



Large-Diff



Note: The size of each scatter dot is proportional to the number of observations that fall in such category. Since the number of observations per period is 80 (across all treatments), the sum total of areas of the scatter dots for each period is constant.

Figure 6 (Panel A): Distribution of Posted Prices by Low-Cost Firm

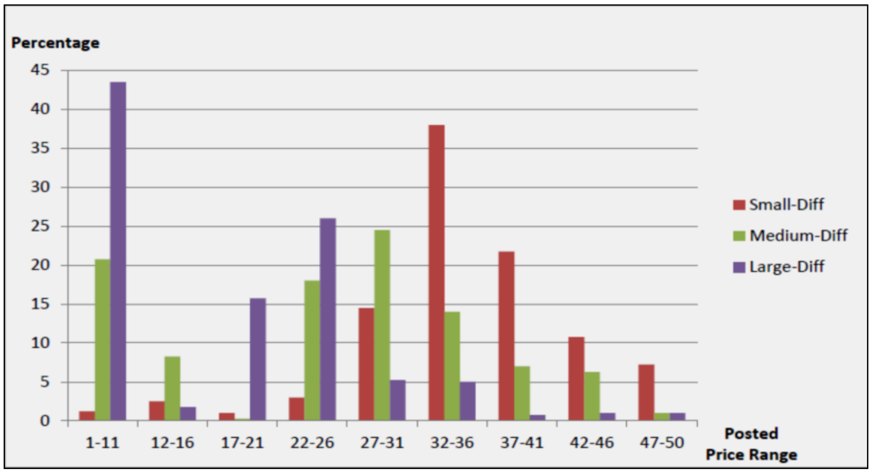


Figure 6 (Panel B): Distribution of Posted Prices by High-Cost Firm

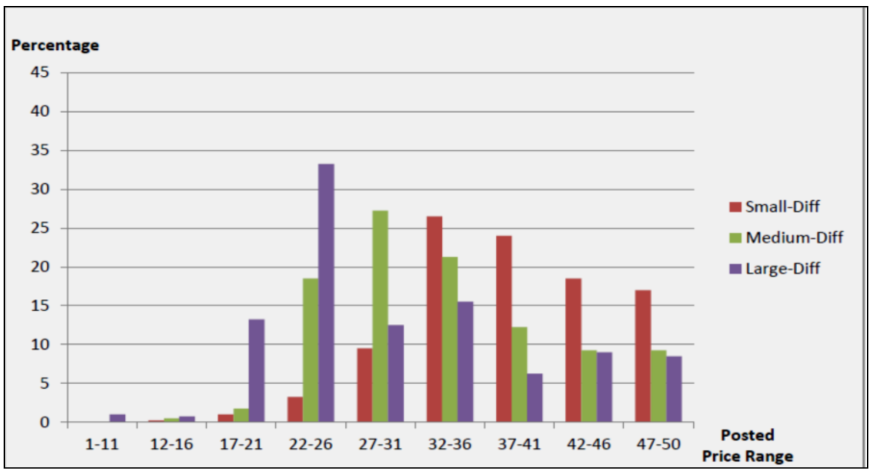


Figure 7: Distribution of Market Winning Prices