The Effect of Ambiguity on Price Dispersion in Duopoly Markets

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Abstract

Price dispersion remains a persistent feature of markets for many consumer goods. Theoretically, tension between competing for price-sensitive consumers and exploiting brand-loyal consumers yields mixed strategy pricing equilibria. This paper considers the implications on pricing levels and dispersion when there is ambiguity about a firm's share of the brand-loyal consumers. Said ambiguity forces firms to make pricing decisions without specific probabilities attached to consumer buying habits. The model reveals that ambiguity aversion forces relatively small firms to price higher on average while it causes relatively large firms to price more competitively on average. An experiment provides empirical support for this result, while also showing that individual ambiguity attitudes do not matter when in a market without ambiguity. Additionally, ambiguity significantly affects price dispersion in markets with a high fraction of price-sensitive consumers, while also increasing competition between firms. This effect is primarily driven by the firm with a larger share of brand-loyal consumers.

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1 Introduction

Firms, along with consumers, are regularly inundated with constant exposure to risk and ambiguity. Firms may change their behavior based on ambiguous events such as price changes, emerging competitors, donations to social causes, etc. This change takes into account the effect of said events on brand-loyal or price-sensitive consumers and what they will purchase in the future. Ellsberg (1961) stated that an individual will distinguish between decisions made under risk (known uncertainty) and those under ambiguity (unknown uncertainty). While the field has continually updated and incorporated new behavioral models, it has largely ignored the implications of ambiguity on firms' decisions in market environments.

The current model setup embeds the concept of ambiguity within a version of the Varian (1980) model, more specifically, the two-person asymmetric extension developed by Narasimhan (1988). We use theory and a lab experiment to study the effect of ambiguity on price levels and price dispersion in asymmetric duopoly markets, where the asymmetry stems from a firm's share of brand-loyal consumers. Brand-loyal consumers are defined as consumers who buy from one firm exclusively. Our analysis focuses on exogenous ambiguity within brand-loyal consumer shares; this is done under the assumption that price-sensitive consumers, or consumers who buy from the lowest priced firm, are less willing to be swayed by persuasive strategies and events. Our paper's main contribution to the literature is to show that a firm's aversion (or lovingness) to ambiguity has an effect on pricing markets. The model contains two types of firms that showcase the asymmetry: the firm with a greater number of brand-loyal consumers, denoted as Large firms, and the firm with a lower number of brand-loyal consumers referred to as Small firms. Theoretically, we find that Large (Small) firms that are ambiguity-averse are expected to price lower (higher) on average as compared to a similar firm that is ambiguity-loving. As a result, Large firms' prices shift down, while Small firms' prices shift up, leading to less dispersed prices. Large and Small firms' expected prices should not be influenced by varying ambiguity attitudes in unambiguous settings. Moreover, this provides theoretical support for the notion that a firm responds differently under an ambiguous setting.

Our experimental results provide empirical evidence for three parts of the theoretical analysis. First, we find that ambiguity attitudes significantly affect expected prices only in environments where ambiguity is present. Second, within these ambiguous environments, Large (Small) firms significantly decrease (increase) their expected price as they become more ambiguity-averse. These findings confirm that Large and Small firms' expected prices are moving in the correct direction of theory. Third, we find empirical evidence that prices are significantly less dispersed in treatments with a large number of price-sensitive consumers. Specifically, as we move from a certain to an ambiguous setting, we find evidence that ambiguity reduces Large firms' expected prices. In contrast, Small firms' expected prices remain constant, ultimately resulting in less dispersion.

Previous models using this consumer structure have always assumed that the breakdown of brand-loyal shares are common knowledge, however, in practice, that may not be accurate. More precisely, firms are never entirely confident of how many brand-loyal consumers will buy their products in the future. A firm may never know each consumer's individual preferences and only has a vague sense of how those preferences will aggregate. Therefore, firms need to make pricing decisions with imprecise knowledge of the underlying distribution of brand-loyal consumers, or in other words, they would need to make pricing decisions under conditions of ambiguity. This ambiguity is created when consumers constantly update and shift their purchasing preferences in response to events like company scandals, advertising campaigns, and the emergence of competitors. For example, one of these ambiguous events that would affect the preferences of consumers is PepsiCo's advertisement efforts at the Superbowl. It would be useful to see how these advertisements, which are seen by millions, affect the brand-loyal consumers of PepsiCo, as well as how they affect the brand-loyal consumers of competing firms like Coca-Cola, Redbull, or even a smaller firm like Dr. Pepper. This paper aims to model and experimentally investigate how firms with varying ambiguity attitudes respond to ambiguous consumer settings.

To model these ambiguity preferences, we use the multiple prior α-maxmin model developed and operationalized by Ghirardato, Maccheroni and Marinacci (2004) and Schmeidler (1989). α-maxmin preferences provide a natural way to differentiate between firms that are ambiguity-averse, neutral, and loving without a considerable jump from the EU model leading to a minor loss in terms of tractability. The parameter α corresponds to a firm's attitude towards ambiguity.

An optimistic firm ($\alpha = 1$), one that is ambiguity-loving, will price as though they will receive a higher, more favorable pick from the possible range of brand-loyal consumers. In comparison, a more pessimistic firm ($\alpha = 0$) will price as though they will receive a lower, less favorable pick. In our setting, brand-loyal shares are ambiguous, while price-sensitive shares are always unambiguous. The main reason for this feature is brand-loyal consumers are potentially more likely to be swayed by advertising, marketing, or emotional campaigns. In contrast, an price-sensitive consumer, a consumer who buys strictly from the lowest priced firm, may not be as easily swayed by dynamic strategies.

There are two prominent strands of literature that are especially relevant: ambiguity and markets. Knight (1921) and Ellsberg (1961) are essential to the foundation of ambiguity and its application. They provide a starting point for distinguishing between risk and ambiguity. Ellsberg (1961) makes a monumental leap in the distinction between risk and ambiguity by using the famous thought experiment using a pick from an urn with a known distribution of balls, versus one from an urn with an unknown distribution of balls. Relevant to the elicitation process within our experimental setting, Halevy (2007) takes that thought experiment and formalizes it to quantify an agent's attitude towards ambiguity. Similarly, Gilboa and Massimo (2016) provide a study on the comparison between ambiguity and Bayesian beliefs. We will not attempt to review all strands of ambiguity in either the experimental or theoretical setting, for a survey of the literature see Camerer and Weber (1992) and Keith and Ahner (2021). For a survey on decision making under uncertainty in natural economic settings, see Mukerji and Tallon (2004).

Turning to the literature on markets with price-sensitive and brand-loyal consumers, work has tended to focus on either symmetric or asymmetric firm sizes. Early symmetric models are explained in Salop and Stiglitz (1977), Shilony (1977), Rosenthal (1980), Varian (1980), and Baye and Morgan (2001). For example, Varian (1980) provides us with two relevant results from the symmetric world. First, there is no symmetric equilibrium that all firms charge the same price. Moreover, a comparative static result is derived thanks to this study: as the number of informed consumers rises (falls), the average expected market price paid by all consumers will fall (rise). Many papers since have extended these models to include features like automated price rules and price discrimination (e.g., Deck and Wilson (2000), Deck and Wilson (2003), and Deck and Wilson (2006)), consumer search rules (e.g., Seiler (2013)), and advertising (e.g., Villas-Boas (1995) and Chioveanu (2008)). Now moving from symmetric to asymmetric firm sizes, Narasimhan (1988) develops and derives a simple yet powerful asymmetric model. This straightforward asymmetric model is extended to include ambiguity in the current paper. Articles that have studied this asymmetric setting without ambiguity include Morgan, Orzen and Sefton (2006), Cason and Datta (2006), Chioveanu (2008), and Cason and Mago (2010). In these papers, asymmetry stems from advertising efforts, while in the current design, each firm is exogenously given a share of brand-loyal consumers. Asymmetry in firm structure lead to two types of firms; the first, are firms that price higher and rely more on their larger brand-loyal consumer share, while the second are firms that price lower and rely more on selling to the price-sensitive consumer share. This concept carries over to the equilibria in the asymmetric environment; Baye, Kovenock and De Vries (1992) characterize all mixed-strategy equilibria in the asymmetric setting. We use these equilibria to derive a pair of mixed strategy distributions according to an ambiguous brand-loyal consumer balance within a duopoly.

The remainder of this paper proceeds as follows. Section 2 describes our pricing model. We contribute to an asymmetric brand-loyal consumer environment by using the derived pricing distributions in a laboratory setting and implementing a pivotal piece to firms' pricing decisions, ambiguity. In Section 3, we describe the experimental design. Then, Section 4 presents our results, and Section 5 concludes.

2 Theory

2.1 Model

In this section, we describe the basic assumptions underlying the duopoly pricing model. The model contains two firms: Firm 1 and Firm 2. Both firms sell one homogeneous good and have a constant marginal cost normalized to 0. Each firm simultaneously moves by choosing a price for the good. After each firm has made a decision, a continuum of consumers, each who value the good at r, will demand at most one unit of the product based upon their preferences. The continuum of consumers contains two consumer types: informed and captive.[1] An informed consumer costlessly searches for the lowest priced firm and demands one unit of the good. The share of informed consumers is represented by the parameter ψ_0. A captive consumer will demand one unit of the good from one firm, exclusively. The share of consumers who exclusively buy from Firm 1 (Firm 2) is represented by the parameter ψ_1 (ψ_2). These three shares are connected by the constraints $\psi_0 + \psi_1 + \psi_2 = 1$ and $\psi_1 > \psi_2$. If firm i's price, denoted p_i, exceeds the reservation price, a captive consumer will opt-out and not purchase the good. An informed consumer will only opt-out if both firms' prices are above the reservation price, where the reservation price, r, is normalized to 1.

The expected profit function for firm i is:

$$E[\pi_i(p_i, p_{-i})] = \begin{cases} (\psi_i + \psi_0)p_i & \text{if } p_i < p_{-i} \leq 1 \\ (\psi_i + \frac{\psi_0}{2})p_i & \text{if } p_i = p_{-i} \leq 1 \\ (\psi_i)p_i & \text{if } p_{-i} < p_i \leq 1 \\ 0 & \text{if } p_i > 1 \end{cases}$$

$$i = 1, 2$$

The presence of informed consumers within the market incentivizes firms to undercut on price. Firms engage in this undercutting behavior to sell to both their captive and the informed consumer shares. Varian (1980) finds that this undercutting behavior, due to the presence of an informed consumer share, leads to the result that there are no symmetric pure strategy equilibria for the two-consumer standard model. Baye, Kovenock and De Vries (1992) used this result to characterize all mixed strategy equilibria for asymmetric shares of captive consumers.

An asymmetric equilibrium involves mixed strategies where the firm with the larger share of captive consumers prices according to a continuous cumulative distribution H(p) and the firm with the smaller share pricing according to a continuous cumulative distribution G(p). Each of

[1] Previously denoted price-sensitive and brand-loyal

these types of firms uses the interval $[\underline{p}', 1]$, where the lower bound is presented below.

$$\underline{p}' = \frac{\psi_1}{\psi_0 + \psi_1} \tag{1}$$

Both firms use the same lower bound. Narasimhan (1988) shows that Firm 1 will never price below $\underline{p}'$ because it can guarantee itself a higher profit by simply pricing at 1. Firm 2 will never price below $\underline{p}'$ because by raising its price and coming arbitrarily close to $\underline{p}'$ it can capture the informed market and increase its profits by charging a higher price. Each firm's security profit is the maximum profit it can unilaterally guarantee itself. Firm 1, the firm with the larger share of captive consumers, obtains a security profit by charging 1 to its captive consumers. Firm 2, the firm with the smaller share of captive consumers, secures their security profit by setting a price slightly below the lower bound and selling to both captive and informed consumers. The smaller firm can always do strictly better by charging just below the lower bound than pricing at 1.

The addition of ambiguity on captive shares, ψ_1 and ψ_2, does not negate the value of the unambiguous informed consumer share, ψ_0, or more precisely the undercutting behavior. Therefore, there are still no symmetric pure strategy equilibria in the presence of ambiguity. We investigate an ambiguous captive consumer framework to see how firms' pricing strategies will change according to their ambiguity preferences. We use a value function and ambiguity preference parameter described below to analyze this behavior directly.

In each market, the informed consumer share is unambiguous and common knowledge to each firm. Each firm's captive consumer share is ambiguous to both firms when making pricing decisions. We implement ambiguity into our pricing model using α-maxmin preferences. Our model determines how a decision-maker will maximize its profit in the role of a firm, using both its and its opponent's captive consumer set. Crucial to the analysis, an ambiguity-seeking (ambiguity-averse) decision-maker will act as if they receive they highest (lowest) draw from the distribution while the other firm in the market receives the lowest (highest). This is done for two main reasons; first, to satisfy our constraint $\psi_0 + \psi_1 + \psi_2 = 1$, and second, it provides us the ability to assume our agents are acting naively when it comes to their opponents ambiguity attitude. Reiterating the idea that ambiguity is strictly coming from a decision-makers' own interval of captive consumers.

The duopoly pricing market contain a finite captive consumer set, A_i, and payoff function π_i for each firm. Suppose players have α-maximin expected utility preferences, where α_1 and α_2 denote firm 1's ambiguity attitude and firm 2's ambiguity attitude, respectively. α-maximin expected utility preferences represent an agent's weighted average of the best and worst-case scenarios, where $\overline{\psi}_i$ represents the largest possible pick from some interval of ψ_i, while $\underline{\psi}_i$ represents the smallest possible pick from the same interval of ψ_i, for i = 1, 2. Assuming $\psi_1 > \psi_2$, it must hold that $\overline{\psi}_1 > \overline{\psi}_2$ and $\underline{\psi}_1 > \underline{\psi}_2$. Also, under ambiguity, the lower bound of integration, $\underline{\text{p}}$, is subject to change based on an agent's level of optimism or pessimism towards their pick from the distribution, shown below.

$$\underline{p} = \frac{[\underline{\psi}_1, \overline{\psi}_1]}{\psi_0 + [\underline{\psi}_1, \overline{\psi}_1]} \tag{2}$$

Next, expected profits for all expected prices in the support of CDF H must equal $\pi_1(p) = \pi_1(1)$, for Firm 1. This equality holds because the profit Firm 1 will earn in equilibrium is equal to the term $\psi_1 * 1 = \psi_1$. This term represents Firm 1's payoff when charging a price of 1; the most Firm 1 can unilaterally guarantee itself. Moreover, since $\psi_1 > \psi_2$, expected profits for all expected prices in the support of CDF G must equal $\pi_2(p) = \pi_2(\underline{p})$, for Firm 2. This equality holds because the profit Firm 2 will earn in equilibrium is equal to the term $(\psi_2 + \psi_0) * \frac{\psi_1 1}{\psi_1 + \psi_0} = (\psi_2 + \psi_0) * \frac{\psi_1}{\psi_1 + \psi_0}$. This term represents Firm 2 charging just below Firm 1's lower bound, the largest payoff Firm 2 can unilaterally guarantee itself. The first equilibrium condition using α-maximin preferences and p $\in$ [$\underline{p}$, 1] can be expressed as

$$(\alpha_1 \overline{\psi}_1 + (1 - \alpha_1)\underline{\psi}_1)p + (1 - G(p))\psi_0 p = (\alpha_1 \overline{\psi}_1 + (1 - \alpha_1)\underline{\psi}_1) \tag{3}$$

Solving for G(p) implies

$$G(p) = 1 - [\frac{(\alpha_1 \overline{\psi}_1 + (1 - \alpha_1)\underline{\psi}_1)(1 - p)}{\psi_0 p}] \tag{4}$$

The second equilibrium condition using α-maximin preferences and p $\in$ [$\underline{p}$, 1] can be expressed as

$$(\alpha_2\overline{\psi}_2 + (1-\alpha_2)\underline{\psi}_2)p + (1 - H(p))\psi_0 p = ((\alpha_2\overline{\psi}_2 + (1-\alpha_2)\underline{\psi}_2 + \psi_0)\frac{(\alpha_2\underline{\psi}_1 + (1-\alpha_2)\overline{\psi}_1)}{(\alpha_2\underline{\psi}_1 + (1-\alpha_2)\overline{\psi}_1 + \psi_0)} \quad (5)$$

Solving for H(p) implies

$$H(p) = 1 + \frac{(\alpha_2\overline{\psi}_2 + (1-\alpha_2)\underline{\psi}_2)}{\psi_0} - \frac{(\alpha_2\underline{\psi}_1 + (1-\alpha_2)\overline{\psi}_1)((\alpha_2\overline{\psi}_2 + (1-\alpha_2)\underline{\psi}_2 + \psi_0)}{((\alpha_2\underline{\psi}_1 + (1-\alpha_2)\overline{\psi}_1 + \psi_0)\psi_0 p} \quad (6)$$

In this model, firms perceive ambiguity about their pick from the captive consumer share interval using neo-additive capacities. A neo-additive capacity is a convex combination of a probability measure and a special capacity. Neo-additive capacities allow for ambiguity-averse, -neutral and -loving firms, see Chateauneuf, Eichberger and Grant (2007) for further details. Given this, ambiguity for firm i is represented by a neo-additive capacity ν_i defined on the set of A_i. Therefore, firm i's α-maxmin preferences with a neo-additive capacity can be represented by the function:

$$V_i(p;\psi_i,\alpha_i,A_i) = \alpha_i[\underset{\psi_i\in A_i}{Max}\, E\pi_i(H(p),G(p),\psi_i)] + (1-\alpha_i)[\underset{\psi_i\in A_i}{Min}\, E\pi_i(H(p),G(p),\psi_i)] \quad (7)$$

For Firm 1, (7) can be rewritten as:

$$V_1(p_1;\psi_1,\alpha_1) = \alpha_1[\int_{\underline{p}}^{1}[\overline{\psi}_1 p_1 + (1-G(p_1))\psi_0 p_1]dH(p_1)] + (1-\alpha_1)[\int_{\underline{p}}^{1}[\underline{\psi}_1 p_1 + (1-G(p_1))\psi_0 p_1]dH(p_1)]$$
$$= \alpha_1[\overline{\psi}_1 \int_{\underline{p}}^{1} H'(p_1)dp_1] + (1-\alpha_1)[\underline{\psi}_1 \int_{\underline{p}}^{1} H'(p_1)dp_1] \quad (8)$$

Using $H(p_1)$, from Equation 6, we can find the expected price for Firm 1:

$$E(p_1) = \int_{\underline{p}}^{1} p_1 H'(p_1)dp_1 \quad (9)$$

For Firm 2, (7) can be rewritten as:

$$V_2(p_2;\psi_2,\alpha_2) = \alpha_2[\int_{\underline{p}}^{1}[\overline{\psi}_2 p_2+(1-H(p_2))\psi_0 p_2]dG(p_2)]+(1-\alpha_2)[\int_{\underline{p}}^{1}[\underline{\psi}_2 p_2+(1-H(p_2))\psi_0 p_2]dG(p_2)]$$

$$= \alpha_2[\frac{(\overline{\psi}_2+\psi_0)\underline{\psi}_1}{(\underline{\psi}_1+\psi_0)}\int_{\underline{p}}^{1} G'(p_2)dp_2] + (1-\alpha_2)[\frac{(\underline{\psi}_2+\psi_0)\overline{\psi}_1}{(\overline{\psi}_1+\psi_0)}\int_{\underline{p}}^{1} G'(p_2)dp_2] \quad (10)$$

Using $G(p_2)$, from Equation 4, we can also find the expected price for Firm 2:

$$E(p_2) = \int_{\underline{p}}^{1} p_2 G'(p_2)dp_2 \quad (11)$$

2.2 Comparative Statics

Using the pair of expected prices for firms 1 and 2, we derive two comparative statics. The first is the effect of a change in the informed consumer share, and the second is the impact of a change in the ambiguity parameter. The former follows from the notion that as the informed consumer share increases (decreases), we will see a decrease (increase) in expected prices for all consumers. Some intuition for this result is that as the share of informed consumers increases, decreasing one's price to obtain that share becomes relatively more attractive. As the informed consumer share rises, captive consumer shares must be decreasing. This reduces the cost on firms for lowering their price. The comparative static effects for a change in ψ_0 are presented below. See Appendix A for complete derivations.

$$\frac{\partial E(p_1)}{\partial \psi_0} < 0 \quad (12)$$

$$\frac{\partial E(p_2)}{\partial \psi_0} < 0 \quad (13)$$

For a Small firm, the second comparative static, the impact of a change in the ambiguity parameter, follows from the fact that as the Small firm becomes more ambiguity-seeking, they believe their captive consumer share is rising while the Large firm's captive consumer share is shrinking, given the constraint $\psi_0 + \psi_1 + \psi_2 = 1$. Therefore, to stay below the Large firm's expected price, the Small firm must be decreasing in their expected price as ψ_2 increases. For the Large firm, as ψ_1 increases, they are increasing in their captive consumer share and therefore will price closer to 1 to extract as much profit as possible from their captive consumers. They do not need to be concerned, like the Small firm, about the other firm's price in the market. This is a perk of being a larger firm; they can rely on selling primarily to their captive consumers. The comparative static effects for a change in α_i are presented below. See Appendix A for complete derivations.

$$\frac{\partial E(p_1)}{\partial \alpha_1} > 0 \tag{14}$$

$$\frac{\partial E(p_2)}{\partial \alpha_2} < 0 \tag{15}$$

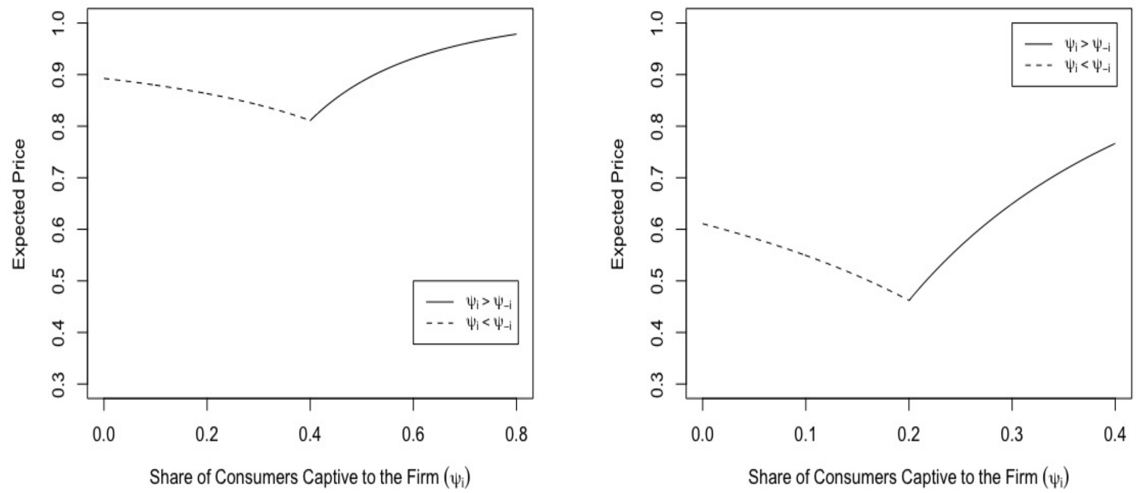
3 Experimental Design and Procedures

3.1 Experimental Design

In this section, we describe the design, parameters, and procedures used within the experiment. The experiment was run between subjects using a 2 × 2 design. The two dimensions of interest are the effect of a change in informed consumer share levels and the impact of ambiguity on firms' pricing strategies. First, We vary the number of informed consumers, ψ_0, at 20% and 60% of the total consumer continuum. We chose a high informed consumer share to represent a non-look-and-feel product industry, and a low informed consumer share to represent a look-and-feel product industry, Jung, Cho and Lee (2014). According to Jung, Cho and Lee (2014), non-look-and-feel product markets have been flooded with price comparison sites. Look-and-feel product markets are less susceptible to price comparison sites. Additionally, to examine the effect of ambiguity, we ran sessions at each informed consumer level with and without ambiguous captive consumer shares.

Figure 1: Expected Price for Captive Consumer Shares

Share of Informed Consumers set at 20% Share of Informed Consumers set at 60%



In Figure 1, the expected price is plotted in relation to firm i's captive consumer share. Firm i's captive consumer share curve is separated into a dashed and solid portion. A Large firm will price along the solid section of the curve, while a Small firm will price along the dashed section of the curve. Notice that the solid section of the curves has a steeper slope in absolute value than the dashed section. Chioveanu (2008) touched on this idea, distinguishing firms pricing strategies by their advertising limits. Chioveanu noted that firms who advertise more heavily would obtain a more significant portion of the captive consumers; this leads them to price higher and rely on predominantly selling to their captive consumers. Firms who advertise less tend to compete harder on prices to win the informed consumer share to make up for any missed profit from a lower captive consumer share. We see these patterns in the dashed and solid curves above; a Small firm will want to price slightly below the Large firm to win the informed consumer share.

In our experimental markets, without ambiguity, when ψ_0 is 20%, we set ψ_1 at 50% and ψ_2 at 30%. When ψ_1 is 50%, Firm 1's expected price is 88.7 in equilibrium, and when ψ_2 is 30%, Firm 2's expected price is 84.1 in equilibrium. In the markets where ψ_0 is 60% we set ψ_1 at 30% and ψ_2 at 10%. When ψ_1 is 30%, Firm 1's expected price is 65.0 in equilibrium, and when ψ_2 is 30%, Firm 2's expected price is 55.0 in equilibrium. Consistency is taken into account when deriving the firm i's expected price, in other words, the equality, $[\alpha_1\overline{\psi}_1 + (1-\alpha_1)\underline{\psi}_1] + [\alpha_2\overline{\psi}_2 + (1-\alpha_2)\underline{\psi}_2]$ = 1 - ψ_0, should hold.

The second dimension of interest is ambiguity. Ambiguity is imposed upon the captive consumer shares of the market. In an environment with ambiguity, firms are told that their true captive consumer share falls between an interval of captive consumers and that the underlying distribution of the share over that interval is unknown. In our experimental markets, with ambiguity, when ψ_0 is 20% of the continuum, we set the interval for ψ_1 between 40% and 60% and ψ_2 between 20% and 40%. In the markets where ψ_0 is 60%, we set the interval for ψ_1 between 20% and 40% and ψ_2 between 0% and 20%. Table 1 provides information on how firms should expect to price according to their given interval and ambiguity preferences.

With both dimensions of the design, there will be a total of four treatments. L(H) refers to treatments with a Low ψ_0 set at 20% (High ψ_0 set at 60%). N(Y) represents a treatment that has unambiguous(ambiguous) captive consumers. Throughout the remainder of the paper, an experimental treatment will be referred to by its two-letter combination. LN denotes the treatment when ψ_0 is 20%, L, and firms use an explicit captive consumer share, N. Table 1 includes all relevant parameters and dimensions for the 2 $\times$ 2 design.

Table 1: Treatments and Resulting Expected Price ($E(P_i)$) and Expected Price Dispersion (E(PD))

				$E(P_i)$ and E(PD)		
Treat.	ψ_0	Ambiguity	ψ_i	$\alpha_i = 0$	$\alpha_i = \frac{1}{2}$	$\alpha_i = 1$
			$\psi_1 = 0.50$		$E(P_1) = .887$	
LN	20%	No	$\psi_2 = 0.30$		$E(P_2) = .841$	
					E(PD) = .046	
			$\psi_1 \in [0.40, 0.60]$	$E(P_1) = .811$	$E(P_1) = .887$	$E(P_1) = .931$
LY	20%	Yes	$\psi_2 \in [0.20, 0.40]$	$E(P_2) = .863$	$E(P_2) = .841$	$E(P_2) = .811$
				E(PD) = .052	E(PD) = .046	E(PD) = .120
			$\psi_1 = 0.30$		$E(P_1) = .650$	
HN	60%	No	$\psi_2 = 0.10$		$E(P_2) = .550$	
					E(PD) = .100	
			$\psi_1 \in [0.20, 0.40]$	$E(P_1) = .462$	$E(P_1) = .650$	$E(P_1) = .767$
HY	60%	Yes	$\psi_2 \in [0.00, 0.20]$	$E(P_2) = .611$	$E(P_2) = .550$	$E(P_2) = .462$
				E(PD) = .149	E(PD) = .100	E(PD) = .305

Contained in Table 1, we have singular theoretical expected prices for the LN and HN treatments. For the LY and HY treatments, we have a range of expected prices, depending on an individual's ambiguity preference. $\alpha_i = 0$ represents a firm that is completely ambiguity-averse, $\alpha_i = \frac{1}{2}$ represents a firm that is neither ambiguity-seeking nor ambiguity-loving, and $\alpha_i = 1$ represents a firm that is completely ambiguity-loving, for $i = 1, 2$. According to the changing ambiguity preferences, one prediction we see in the ambiguous environment is how a sample of Large firm should price in expectation. They are expected to increase their expected price as they become more ambiguity-loving (as α moves from $0 \to 1$). A sample of Small firms are expected to increase their expected price as they become more ambiguity-averse (as α moves from $1 \to 0$). Table 1 and Figure 1 illustrates how expected prices for a Small and Large firm change as their ambiguity attitude changes. Given the constraint, $\psi_0 + \psi_1 + \psi_2 = 1$, when a firm's captive consumers share decreases, that implies that their rival firm's captive consumer share is increasing. Therefore, as a Small firm becomes more ambiguity-averse, they believe the Large firm must be gaining more captive consumers. So, a Small firm will raise its expected price to remain below the Large firm's rising expected price. Alternatively, as a Large firm becomes more ambiguity-loving, just like the Small firm, they believe they will recieve a better draw from their captive consumer interval. With this better draw, they will increase their expected price to take advantage of a larger amount of captive consumers. Large firms are less concerned with the Small firm's expected price; therefore, they disregard that a Small firm will decrease their expected price in equilibrium.

Along with these expected prices, we can find the resulting price dispersion for individuals who are ambiguity-averse, -loving, or neither. For the purpose of simplicity we theoretically compare ambiguity-averse individuals to other ambiguity-averse individuals for expected price dispersion, this same pattern follows for -seeking individuals. Table 1 also shows expected price dispersion resulting for each treatment. The price dispersion metric is measured as the expectation of the absolute difference between the two firm's prices.[2]

3.2 Procedures

The experiment consists of 24 sessions conducted at the University of Alabama TIDE Lab in the Spring of 2021. Each session consisted of six subjects, divided randomly into the roles of Firm 1 or Firm 2.[3] At the beginning of a session, subjects were seated at a computer and read the instructions individually (a full breakdown of each treatment's instructions are presented in Appendix C). After all the subjects completed the instructions, they saw four practice pricing markets where they were informed that the other firm was a computer and that the computer priced randomly. After the practice markets, subjects participated in 25 pricing rounds with

[2]In each round, two firms both enter a probability distribution over prices 5 through 100. The prices are in increments of 5, giving a firm a total of 20 prices to place probabilities on (5, 10, 15, ..., 95, 100). We take the difference of each price combination and then the expectation of those 400 combinations (20 price/probability combinations for Firm 1 $\times$ 20 price/probability combinations for Firm 2). For example, say Firm 1 puts 50% weight on price 95 and 50% weight on price 100, and Firm 2 puts 50% weight on price 5 and 50% weight on price 10. The only price combinations that matter (result in dispersion) are $|95-5|, |95-10|, |100-5|$, and $|100-10|$. The rest of the combinations will have a dispersion of 0 and have no impact on the metric. Next, we multiply each difference by the probability of it happening, $50\% \times 50\% = 25\%$. We then sum those resulting four numbers to find expected price dispersion for each round. Note that we are not looking at the absolute difference in expected prices because absolute values are not linear operators.

[3]The role of Firm 1 and Firm 2 is retained by the respective subject for the entire study.

random rematching of firms each round.[4] No subject appeared in more than one session, and all choices and information were entered into the z-Tree program, Fischbacher (2007).

Given the model only generates mixed strategy equilibria, we decided to have the subjects put in a pricing distribution instead of a singular price. This new technique was used to see how firms' strategies appeared and changed. In the experiment, subjects put weights, which added to 100, on prices 5 through 100. The prices were in increments of 5 and all prices were scaled up by a factor of 100 from the theory. For example, If a subject put a weight of 20 on the price of 95 and a weight of 80 on the price of 30, there was a 20% chance the price of 95 would be selected and an 80% chance the price of 30 would be selected.[5]

In the decision stage, a subject was able to see which round they were in and how the captive and informed consumer shares were broken down. Within the experimental sessions, captive consumers were denoted loyal consumers, and informed consumers were labeled price-sensitive consumers. After a pricing distribution was entered for both subjects, subjects were then shown a results page where 35 period realizations occurred simultaneously. In each period realization, a 1000 consumers bought the homogeneous good based upon pre-set preferences. Informed consumers purchased from the lowest priced firm.[6] Captive consumers purchased from one firm exclusively. In the markets without ambiguity, subjects were informed of their explicit profit. In ambiguous markets, subjects were told the upper and lower limits on potential profit to ensure continued ambiguity. If subjects were informed of the actual profit realizations, ambiguity about the share of captive consumers would diminish throughout multiple rounds.

Figure 2 displays what the results page looked like to a subject. On the left-hand side of Figure 2, they saw 35 period realizations. In each period realization, they were told their firm's price, the other firm's price, whom the informed consumers purchased from, and their firm's profit range. On the right-hand side, they were shown frequencies of price draws for themselves and the other firm, and they were also shown a profit range by period figure. This results page comes from

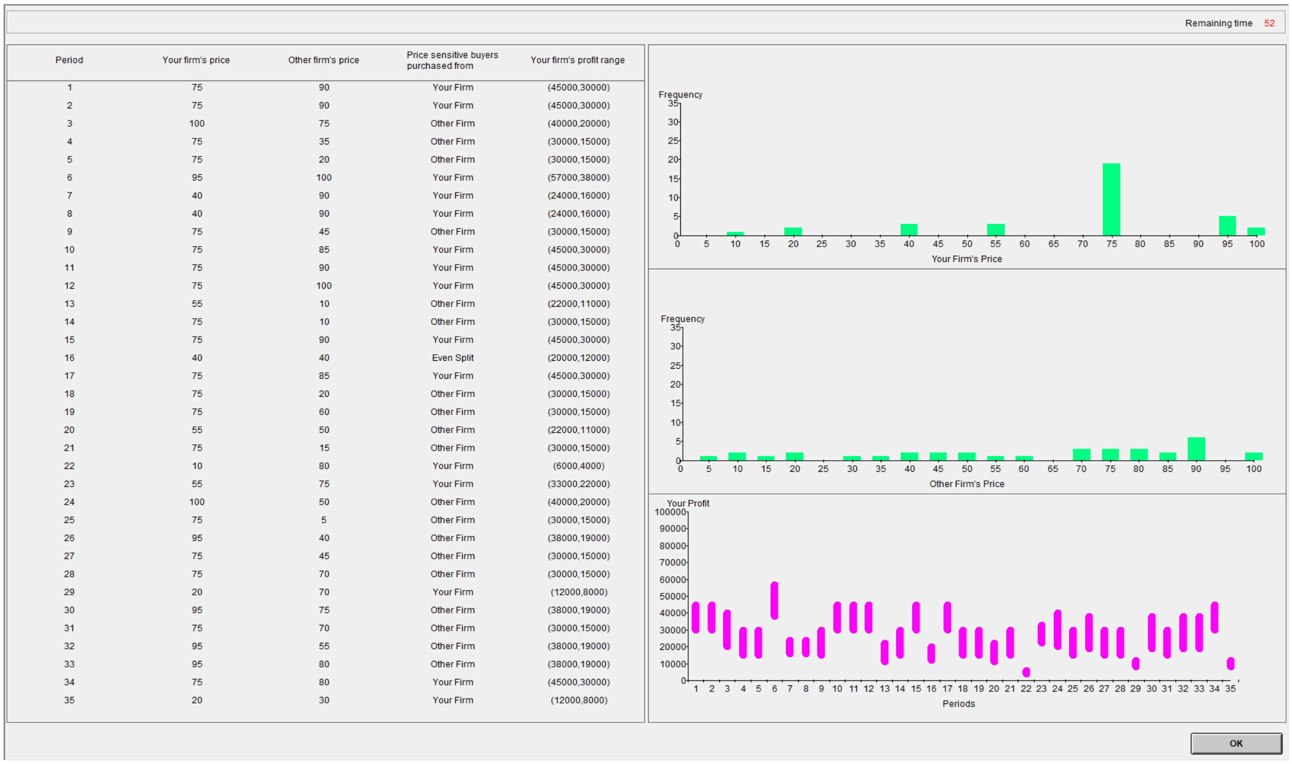
[4]We anonymously and randomly rematched subjects after each market and prevented communication among subjects. This is a standard technique to prevent the players from developing a reputation and limiting repeated play issues.

[5]During and after this process, the firm could verify its percentages all add to 100% using the probability sum section located at the bottom of the decision page.

[6]If both firms priced equally, half of the informed consumer would buy from each firm.

an ambiguous treatment. Subjects in an unambiguous treatment would see explicit profits and dots rather than lines for the profit figure.

Figure 2: z-Tree Program: Result Stage



Subjects were recruited from the TIDE lab's distribution list comprised of undergraduate students from across the entire university who had indicated a willingness to be paid volunteers in decision-making experiments. This pool of undergrads is primarily comprised of business school undergrads, and none of the participants had previously participated in any related studies. For this experiment, subjects were sent an e-mail invitation to participate in a session lasting approximately 60 minutes. Subjects were informed they would receive a \$5 show-up payment plus any salient earnings made during the study. After the 25 markets were complete, the subjects were paid for ten random periods in one random market. We paid the subjects at a conversion of 25,000 Lab Dollars = \$1 US Dollar for the Low treatments ($\psi_0 = 20\%$) and a conversion of 20,000 Lab Dollars = \$1 US Dollar for the High treatments ($\psi_0 = 60\%$). These conversions were used to balance earnings across treatments. Conversion rates were defined in the instructions and were known to subjects before pricing decisions were made. The average earnings in the study were \$20.39.

4 Results

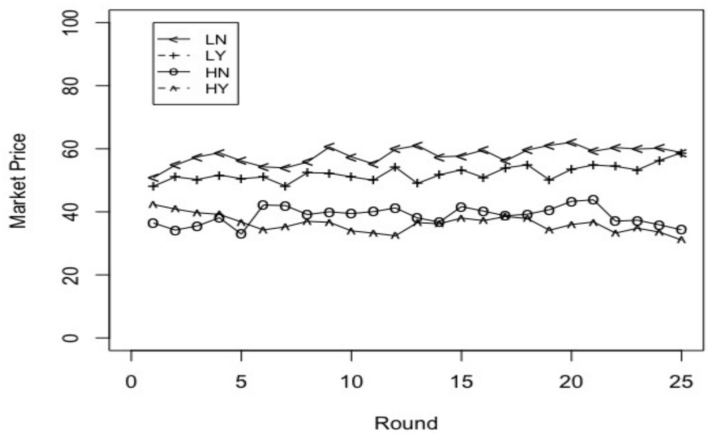
The data consists of 1800 pricing markets. Each session contained three duopoly markets that ran for 25 rounds for a total of 24 sessions. We report the analysis in four subsections. The first examines price level behavior across treatments, and the following two subsections discuss price dispersion behavior by firm size for the High and Low treatments, respectively. Lastly, we investigate the effects of individual ambiguity attitudes.

4.1 Comparing Behavior Across Treatments

4.1.1 Expected Price Analysis

Figure 3 displays average treatment-level data over the 25 rounds. Market price is defined as the price a consumer would expect to pay given both informed and captive consumers' prices and market shares. Recall that the expected market price paid by captive consumers should, in theory, decrease as the share of informed consumers rises. Figure 3 shows a decrease in market price as we move from the Low informed consumer markets to the High informed consumer markets. The data supports the comparative static result that as the informed consumer share increases, more consumers value the cheapest priced good; thus, all firms lower their price to sell to the rising informed consumer share. This result is borne out in the regression analysis presented in Table 2 specification (1).

Figure 3: Average Market Price by Treatment



The change in expected market price as we move from Low informed consumer shares to High informed consumer shares from Figure 3 can be statistically shown. Specifically, we estimate the following regression with standard errors clustered at the session level, where the dependent variable is expected market price. *MarketPrice* is a numerical variable that represents the expected price a consumer would pay in each market. *HighInformed* is an indicator variable that takes on the value of 1 if the observation is from an HY or HN treatment and zero otherwise. *Ambiguity* is an indicator variable that takes on the value of 1 if the observation is from a treatment with ambiguous captive consumers (Y) and zero otherwise. *Round* is a time indicator variable that captures rounds (1-25). The specification is denoted in Equation (16) and the results from this regression are displayed in Table 2 specification (1).

$$Market\hat{P}rice = \beta_0 + \beta_1 Round + \beta_2 HighInformed + \beta_3 Ambiguity + \beta_4 HighInformed \times Ambiguity \quad (16)$$

In Table 2 specification (1), we observe that the High informed consumer treatments lead to a lower expected market price than the Low informed consumer treatments. For the no ambiguity treatments, this result can be seen from the negative and highly significant value on β_2. As we move from informed consumers shares at 20% of the market, LN, to 60% of the market,

Table 2: Regression Analysis of Treatment Effects on Expected Market Price and Price Dispersion

Coefficient	(1)	(2)
Constant (β_0)	56.76***	31.60***
	(4.85)	(1.65)
Round (β_1)	0.09	0.10
	(0.10)	(0.08)
HighInformed (β_2)	-19.19***	2.69
	(5.76)	(3.14)
Ambiguity (β_3)	-5.69	2.43
	(7.10)	(4.07)
HighInformed × Ambiguity (β_4)	3.18	-12.76**
	(9.07)	(5.96)
R^2	0.19	0.04
Observations	3600	1800
Hypothesis Test	p-value	
$H_0 : \beta_3 + \beta_4 = 0$	0.657	
$H_0 : \beta_2 + \beta_4 = 0$	0.022	
$H_0 : \beta_0 = 86.4$	< 0.001	
$H_0 : \beta_0 + \beta_3 = 86.4$	< 0.001	
$H_0 : \beta_0 + \beta_3 + \beta_4 = 58$	0.597	
$H_0 : \beta_0 + \beta_2 + \beta_4 = 58$	0.039	
$H_0 : \beta_3 + \beta_4 = 0$		0.018
$H_0 : \beta_0 = 4.6$		< 0.001
$H_0 : \beta_0 + \beta_3 = 4.6$		< 0.001
$H_0 : \beta_0 + \beta_3 + \beta_4 = 10$		0.016
$H_0 : \beta_0 + \beta_2 + \beta_4 = 10$		0.036

The dependent variable for specification (1) is Expected market Price and for specification (2) it is Price Dispersion. The results are based on a panel regression with random effects for each session. The dependent variable is Expected Price. Standard errors are in parenthesis and are clustered at the session level. Significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

HN, the expected market price drops by a little over 19 dollars or about 34%. We expect to see the same effect as we move from LY to HY. We confirm this result from testing the hypothesis, $H_0 : \beta_2 + \beta_4 = 0$, at the bottom of Table 2 specification (1), with a p-value of 0.022.

Next, as we move from the LN to the LY treatment, we see no significant effect on expected market price. We see this result from the non-significant value on β_3. If we do the same analysis in a High informed consumer treatment, we end up with the same result. The hypothesis, $H_0 : \beta_3 + \beta_4 = 0$, tells us the effect from moving from treatment HN to HY. Again, we see no significant difference in expected market price, as shown in the lower portion of Table 2 under specification (1).

Furthermore, using Table 2 specification (1), we can compare behavior in each treatment to its theoretical expected market price. The expected market price in Low informed consumer treatments, LN and LY, is 86.4. The observed expected market prices for LN and LY are captured in terms β_0 and $\beta_0 + \beta_3$, respectively. In both treatments, firms are significantly pricing below 86.4 (p-values < 0.001). In High informed consumer treatments, HN and HY, the expected market price is 58. The observed expected market prices for HN and HY are captured in terms $\beta_0 + \beta_3 + \beta_4$ and $\beta_0 + \beta_2 + \beta_4$, respectively. In the HN treatment, firms are not pricing significantly different from 58 (p-value $= 0.597$). In the HY treatment, firms are pricing significantly lower than 58 (p-value $= 0.039$).

4.1.2 Price Dispersion Analysis

From Table 2 specification (1), we saw that price levels were not significantly different when moving from the LN (HN) to LY (HY) treatment. Next, we examine price dispersion in each market. The price dispersion metric is measured as the expectation of the absolute difference between the two firm's prices. Using the same specification as Equation (16), we now run a regression with the price dispersion metric as the dependent variable. Table 2 specification (2), reports the analysis.

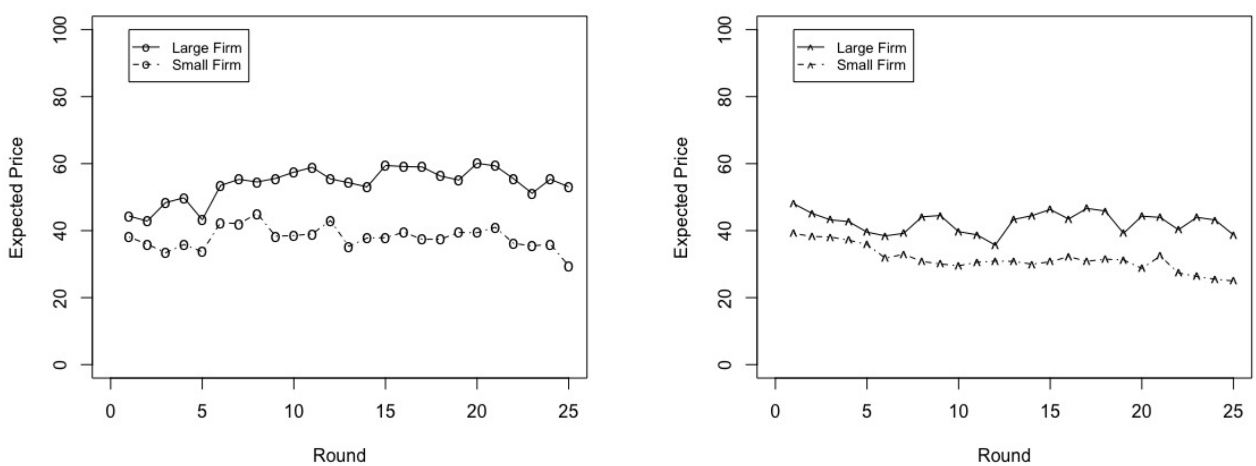
Looking at β_3 in Table 2 specification (2), we observe an insignificant change in price dispersion when moving from LN to LY. However, we see a significant change when moving from HN to HY, which can be seen from testing the hypothesis, $H_0 : \beta_3 + \beta_4 = 0$. With a p-value of 0.018, this result shows support for the central claim of the paper that ambiguity significantly affects price dispersion. From this result, we conclude that ambiguity mainly plays a significant role in price dispersion when markets are composed of many informed consumers.

Moreover, using Table 2 specification (2), we can compare behavior in each treatment to its theoretical expected price dispersion. In Low informed consumer treatments, LN and LY, the expected price dispersion is 4.6 (from Table 1). The observed price dispersion for LN and LY are captured in terms β_0 and $\beta_0 + \beta_3$, respectively. In both treatments, expected price dispersion for firms is above 4.6 (p-values < 0.001). In high informed consumer treatments, HN and HY, the expected price dispersion is 10 (from Table 1). The observed expected price dispersion for HN and HY are captured in terms $\beta_0 + \beta_3 + \beta_4$ and $\beta_0 + \beta_2 + \beta_4$, respectively. In both treatments, expected price dispersion for firms is above 10 (p-value $= 0.016$ and p-value $= 0.036$, respectively). As a result of this significant change in price dispersion, next, we break down firm types to see where this price dispersion is rooted. By separating firm types for each treatment, we can see how each firms type affects behavior under ambiguity.

4.2 Behavior in High Informed Consumer Treatments

Figure 4: Expected Prices in High Informed markets by Firm Size

High Informed No Ambiguity Treatment (HN) | High Informed Ambiguity Treatment (HY)



This section analyzes how expected price responds to ambiguity given firm size. Recall that firm size represents how many captive consumers a firm has - we denote a firm with more captive consumers as the Large firm and a firm with fewer captive consumers as the Small firm. Here, the terms more and fewer are in relation to the other firm's number of captive consumers. On the left, in Figure 4, we have the High informed consumer treatment without ambiguity, HN. On the right, we have a High informed consumer treatment with ambiguity, HY. Notice, in Figure 4, Large firms are pricing higher than Small firms on average. Below, Table 3, contains average theoretical and observed expected prices. This pattern of Large firms pricing higher than Small firms can be seen in Table 3 where the Large firm in treatment HN has an average observed expected price of 54.0, while the Small firm has an average observed expected price of 37.9. In treatment HY, the Large firm has an average observed expected price of 42.5, while the Small firm has an average observed expected price of 31.5.

Table 3: Average Theoretical and Observed Expected Prices in High Informed Consumer Treatments

Treatment	$\alpha = 0$	$\alpha = \frac{1}{2}$	$\alpha = 1$	Observed Average
HN	$E(P_1) = 65.0$	$E(P_1) = 65.0$	$E(P_1) = 65.0$	$P_1 = 54.0$
	$E(P_2) = 55.0$	$E(P_2) = 55.0$	$E(P_2) = 55.0$	$P_2 = 37.9$
HY	$E(P_1) = 46.2$	$\text{E}(P_1) = 65.0$	$\text{E}(P_1) = 76.7$	$P_1 = 42.5$
	$E(P_2) = 61.1$	$E(P_2) = 55.0$	$E(P_2) = 46.2$	$P_2 = 31.5$

In the previous section, we compared HN to HY across average consumer expected price; now, we compare a Large (Small) firms' expected price in HN to a Large (Small) firms' expected price in HY. Examining Table 3, we see that the Small firms' expected prices, for both treatments, have a smaller differential than the Large firms' expected prices. We can see if this relationship is statistical using regression analysis.

This subsection's regression analysis is based on data from HN and HY treatments. We estimate the following regression with standard errors clustered at the session level, where the dependent variable is expected price. *LargeFirm* is an indicator variable that takes on the value of 1 if the observation is from a Large firm and zero otherwise. The specification is denoted in Equation (17) and the results from this regression are presented in Table 4 specification (1).

$$Expect\hat{e}dPrice = \beta_0 + \beta_1 Round + \beta_2 Ambiguity + \beta_3 LargeFirm + \beta_4 LargeFirm \times Ambiguity \tag{17}$$

Table 4: Regression Analysis of Firm Size Effects on Expected Price in each Treatment

Coefficient	(1)	(2)
Constant (β_0)	38.32***	49.09***
	(4.23)	(4.41)
Round (β_1)	-0.03	0.26**
	(0.18)	(0.11)
LargeFirm (β_2)	16.09***	13.86***
	(3.02)	(3.50)
Ambiguity (β_3)	-6.40	1.44
	(5.56)	(6.57)
Ambiguity $\times$ LargeFirm (β_4)	-5.09	-11.74
	(4.28)	(8.58)
R^2	0.10	0.05
Observations	1800	1800
Two-Sided p-value		
$H_0 : \beta_3 + \beta_4 = 0$	0.073	0.281
$H_0 : \beta_2 + \beta_4 = 0$	0.000	0.786
$H_0 : \beta_0 = 55$	0.000	
$H_0 : \beta_0 + \beta_3 = 55$	0.000	
$H_0 : \beta_0 + \beta_3 + \beta_4 = 65$	0.000	
$H_0 : \beta_0 + \beta_2 + \beta_4 = 65$	0.000	
$H_0 : \beta_0 = 84.1$		0.000
$H_0 : \beta_0 + \beta_3 = 84.1$		0.000
$H_0 : \beta_0 + \beta_3 + \beta_4 = 88.7$		0.000
$H_0 : \beta_0 + \beta_2 + \beta_4 = 88.7$		0.000

The dependent variable for specification (1) is Expected Price for HN and HY treatments and for specification (2) it is Expected Price for LN and LY treatments. The results are based on a panel regression with random effects for each session. The dependent variable is Expected Price. Standard errors are in parenthesis and are clustered at the session level. Significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

In Table 4 specification (1), we observe that the Large firms have higher expected prices on average than the Small firms for both HN and HY. This result can be seen from the positive and highly significant value of β_2 for HN and the highly significant p-value on $H_0 : \beta_2 + \beta_4 = 0$ for HY. As we move from a Small firm to a Large firm, expected price increases by a little over 16 dollars if ambiguity is not present.

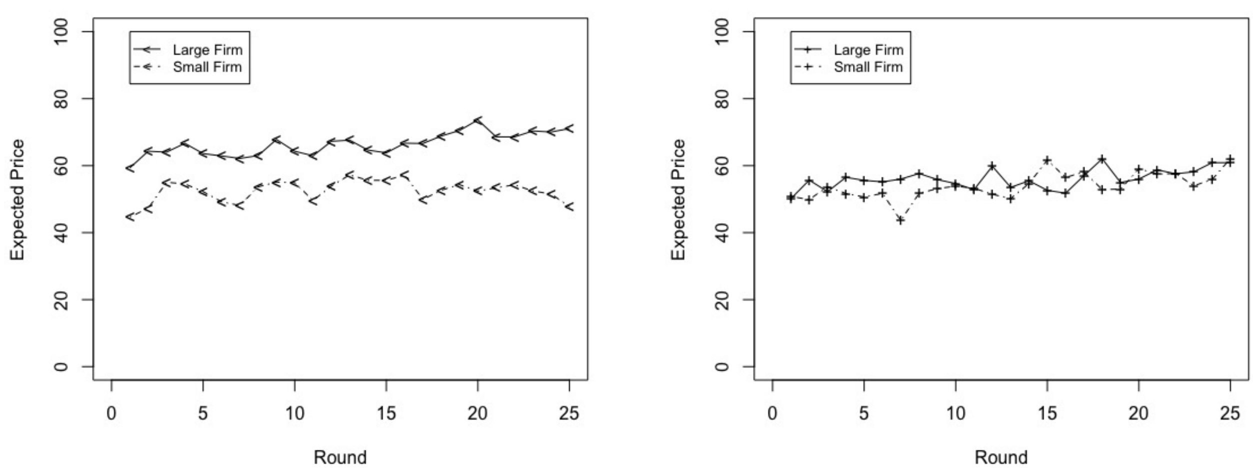
Next, as we move from an environment with ambiguity to one without ambiguity, we see no significant effect on expected price for a Small firm. We see this result from the non-significant value on β_3. If we do the same analysis for Large firms, we get a different result. Testing the hypothesis, $H_0 : \beta_3 + \beta_4 = 0$, tells us the effect of moving from a Large firm in HN to a Large firm in HY. The difference in expected prices is marginally significant. Concluding that the significant price dispersion from treatment HN to HY results primarily from the difference in the Large firms' expected prices.

Lastly, using Table 4 specification (1), we can compare behavior in each treatment to its theoretical expected price. For Small firms, the theoretical expected price is 55. The observed average expected price for Small firms in HN and HY is captured in terms β_0 and $\beta_0 + \beta_3$, respectively. In both treatments, Small firms are significantly pricing below 55 (both have p-value $<$ 0.001). For Large firms, the theoretical expected price is 65. The observed average expected price for Large firms in HN and HY is captured in terms $\beta_0 + \beta_3 + \beta_4$ and $\beta_0 + \beta_2 + \beta_4$, respectively. In both treatments, Large firms are significantly pricing below the expected price 65 (both have p-value < 0.001).

4.3 Behavior in Low Informed Consumer Treatments

Figure 5: Expected Prices in Low Informed markets by Firm Size

Low Informed No Ambiguity Treatment (LN) | Low Informed Ambiguity Treatment (LY)



This section will now focus our attention on Low informed consumer treatments. Similar to the last section, we will distinguish between Large and Small captive consumer share firms. On the left, in Figure 5, we have the Low informed consumer treatment without ambiguity, LN. On the right, we have Low informed consumer treatment with ambiguity, LY. A pattern that continues to hold for the Low informed treatments is that Large firms are pricing higher than Small firms, on average. This pattern is expected regardless of informed consumer share size. Below, Table 5, contains average theoretical and observed expected prices. In Table 5, we observe the Large firm in treatment LN has an average observed expected price of 66.4, while the Small firm has an average observed expected price of 52.5. In treatment LY, the Large firm has an average observed expected price of 56.1, while the Small firm has an average observed expected price of 54.0. The Small(Large) firms in each treatment have similar(dissimilar) observed mean expected prices, similar to the High informed consumer treatments. In the Low informed consumer treatments, we see that the firms are less competitive on price because unlike the High informed consumer treatments, there is a smaller incentive to win the informed consumer share. Firms in the Low informed consumer treatments rely more on captive consumer shares and price closer to the reservation price, r.

Table 5: Average Theoretical and Observed Expected Prices in Low Informed Consumer Treatments

Treatment	$\alpha = 0$	$\alpha = \frac{1}{2}$	$\alpha = 1$	Observed Average
LN	$E(P_1) = 88.7$	$E(P_1) = 88.7$	$E(P_1) = 88.7$	$P_1 = 66.4$
	$E(P_2) = 84.1$	$E(P_2) = 84.1$	$E(P_2) = 84.1$	$P_2 = 52.5$
LY	$E(P_1) = 81.1$	$E(P_1) = 88.7$	$E(P_1) = 93.1$	$P_1 = 56.1$
	$E(P_2) = 86.3$	$E(P_2) = 84.1$	$E(P_2) = 81.1$	$P_2 = 54.0$

Previously we compared Large(Small) firms in HN to Large(Small) firms in HY; now, we want to do the same for LN and LY. This subsection's regression analysis is based on data from LN and LY treatments. We estimate the following regression with standard errors clustered at the session level, where the dependent variable is expected price. The specification is denoted in Equation (18) and the results from this regression are presented in Table 4 specification (2).

$$\hat{ExpectedPrice} = \beta_0 + \beta_1 Round + \beta_2 Ambiguity + \beta_3 LargeFirm + \beta_4 LargeFirm \times Ambiguity \tag{18}$$

In Table 4 specification (2) we observe that the Large firms have higher expected prices on average than the Small firms for treatment LN. This result can be seen from the positive and highly significant value of β_2. As we move from a Small firm to a Large firm, expected price increases by a little under 14 dollars if there is no ambiguity. This result does not hold for treatment LY; Large and Small firms do not have significantly different expected prices. We get this result from testing the hypothesis, $H_0 : \beta_2 + \beta_4 = 0$, located at the bottom of Table 4.

Next, as we move from an environment with ambiguity to one without ambiguity, we see no significant effect on expected price for Small firms. We see this result from the non-significant value on β_3. If we do the same analysis for Large firms, we get a similar result. The hypothesis at the bottom of Table 4 specification (2), $H_0 : \beta_3 + \beta_4 = 0$, tells us the effect from moving from a Large firm in LN to LY. Testing the hypothesis provides us a p-value of 0.281. Therefore, we cannot conclude that Large firms have different expected prices when moving from LN to LY. This provides evidence that ambiguity does not play a significant role when informed consumer share is Low. Given that the Low informed consumer markets are full of firms with a larger amount of captive consumer shares than informed consumer shares, we hypothesize that firms rely more on their captive consumer shares to establish the majority of their profit.

Lastly, using Table 4 specification (2), we can compare behavior in each treatment to its theoretical expected price. For Small firms, the theoretical expected price is 84.1. The observed expected price for Small firms in LN and LY is captured in terms β_0 and $\beta_0 + \beta_3$, respectively. In both treatments, firms are significantly pricing below 84.1 (both have p-value < 0.001). For Large firms, the theoretical expected price is 88.7. The observed expected price for Large firms in LN and LY is captured in terms $\beta_0 + \beta_3 + \beta_4$ and $\beta_0 + \beta_2 + \beta_4$, respectively. In both treatments, firms are significantly pricing below 88.7 (both have p-value < 0.001).

4.4 Individual Ambiguity Attitudes

This section analyzes the effect individual ambiguity attitudes had on Large and Small firm behavior. Comparative statics showed that as a Large firm moves from ambiguity-averse to -loving, they will increase their expected price. As a Small firm moves from ambiguity-averse to -loving, they will decrease their expected price. Therefore, we want to take elicited ambiguity attitudes and test them against these theoretical findings.

The standard approach to measuring a subject's ambiguity attitude is by testing the theories of the original Ellsberg experiments. The application of the Ellsberg theories elicits a willingness to bet on a "risky" urn and a willingness to bet on an "ambiguous" urn, Halevy (2007). The risky urn contains a known distribution of red and black balls, while the ambiguous urn contains an unknown distribution of red and black balls. A subject's ambiguity attitude can be extracted by taking the difference between the ambiguous and risky urn bets. By subtracting the ambiguous urn price from the risky urn price, we can see whether that subject is ambiguity-seeking, -neutral, or -averse and the "premium" or magnitude of their view towards ambiguity.

After the main portion of the experiment, subjects were prompted to answer a non-incentivized survey. The survey first asked a risky and ambiguous urn question. The risky urn task detailed an urn containing 50 red balls and 50 black balls. If a red ball were selected, the subject would earn $100, and if a black ball were selected, they would earn $0. They were then asked how much they would bet for the chance to draw a red ball from this first urn. The ambiguous urn task detailed an urn containing an unknown combination of red and black balls, summing to 100. If a red ball were selected, they would earn $100, and if a black ball were selected, they would earn $0. They were then asked how much they would bet for the chance to draw a red ball from this second urn. A subject's ambiguity attitude was then computed by taking the difference between the subject's ambiguous and risky urn bets. We can see that subject's ambiguity attitudes by subtracting the ambiguous urn price from the risky urn price. For example, if a subject were willing to bet $75 on the ambiguous bet and $50 on the risky bet, they would be ambiguity-seeking with a premium of 25. Next, the survey elicited a CRT score using the standard seven Cognitive Reflection Test (CRT) questions (See Appendix C for the seven questions). The

Cognitive Reflection Test(CRT) is designed to measure a subject's reflection process. The CRT questions measure cognitive activity by having an intuitive wrong answer and a more pensive, reflective correct answer. The CRT has been shown to have a moderate positive correlation with measures of intelligence[7] and high correlation with various measures of mental heuristics.[8] Lastly, the survey asked the subjects their gender (male, female, other).

Next, we compare elicited ambiguity attitudes and CRT to expected prices. The first subsection describes the Large firms' behavior, followed by the Small firms' behavior.

4.4.1 Large Firm's Behavior

This section describes the Large firm's behavior. Table 6 specification (1) and (2) contain data that comes strictly from Large firms. We estimate the following regressions with standard errors clustered at the session level, where the dependent variable is expected price. The specification is denoted in Equation (19) and the results from this regression for the no ambiguity treatments are presented in specification (1) in Table 6 and the results from this regression for the ambiguity treatments are presented in specification (2) in Table 6. The variable *CRT* is based on a subject's elicited CRT score. The variable *AmbiguityAttitude* is based on a subject's elicited ambiguity attitude.

$$\hat{ExpectedPrice} = \beta_0 + \beta_1 Round + \beta_2 CRT + \beta_3 AmbiguityAttitude \tag{19}$$

Specification (1) in Table 6 shows the regression analysis results from Equation 19 for Large firms in treatments without ambiguity. The first result we find is that the coefficient on *CRT* is highly significant. A significant coefficient on *CRT* shows that a person with a higher CRT score will have a higher expected price. This is congruent with the idea that a subject with a higher reflection process will price closer to theoretical predictions. Previously, Table 4 showed that subjects' observed expected prices were significantly lower than the theoretical expected price.

[7] A measure such as the Intelligence Quotient test.

[8] Measures such as the gambler's fallacy, understanding of regression to the mean, the sunk cost fallacy, and others.

Table 6: Regression Analysis of CRT and Ambiguity Attitude on Expected Price for Large Firms

Coefficent	(1)	(2)	(3)	(4)
Constant (β_0)	27.70***	32.13***	43.98***	38.03***
	(8.02)	(4.04)	(4.84)	(5.18)
Round (β_1)	0.39***	0.10	0.01	-0.04
	(0.12)	(0.18)	(0.11)	(0.24)
CRT (β_2)	7.99***	4.38**	2.38**	2.58*
	(2.13)	(1.82)	(1.14)	(1.46)
AmbiguityAttitude (β_3)	24.53	31.13***	-48.88	-21.63*
	(32.09)	(11.92)	(30.07)	(12.43)
R^2	0.39	0.22	0.10	0.10
Observations	900	900	900	900

The dependent variable for specification (1) is Expected Price for Large firms in no ambiguity treatments, and for specification (2) is Expected Price for Large firms in ambiguity treatments, and for specification (3) is Expected Price for Small firms in no ambiguity treatments, and for specification (4) is Expected Price for Small firms in ambiguity treatments. The results are based on a panel regression with random effects for each session. The dependent variable is Expected Price. Standard errors are in parenthesis and are clustered at the session level. Significance levels: * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Therefore, a subject that raises their expected price would price closer to the theoretical predictions from the model. The second result we find is that the coefficient on *AmbiguityAttitude* is not significant. We expect this result because ambiguity should not matter in the treatments without ambiguity present. Furthermore, a subject's price distribution should not shift according to a changing ambiguity attitude for explicit captive consumer shares.

Specification (2) in Table 6 shows the regression analysis results from Equation 19 for Large firms in ambiguity treatments. Again, we find that the coefficient on *CRT* is significant. A significant coefficient on *CRT* shows that a person with a higher CRT score will have a higher expected price. The second result we find is that the coefficient on *AmbiguityAttitude* is highly significant. This result is expected because a subject's ambiguity attitude could affect their expected price in the ambiguity treatments. If a subject is ambiguity-neutral, ambiguity will not shift their price distribution. If a subject is ambiguity-seeking(ambiguity-averse), the presence of ambiguous captive consumers will shift their price distribution upwards(downwards) for Large firms. Furthermore, the coefficient is moving in the direction of theory. As a Large firm becomes more ambiguity-seeking, they will raise their expected price.

4.4.2 Small Firm's Behavior

This section describes the Small firm's behavior. Table 6 specification (3) and (4) contain data that comes strictly from Small firms. We estimate the following regressions with standard errors clustered at the session level, where the dependent variable is expected price. The specification is denoted in Equation (20) and the results from this regression for the no ambiguity treatments are presented in specification (3) in Table 6 and the results from this regression for the ambiguity treatments are presented in specification (4) in Table 6.

$$\widehat{ExpectedPrice} = \beta_0 + \beta_1 Round + \beta_2 CRT + \beta_3 AmbiguityAttitude \tag{20}$$

Specification (3) in Table 6 shows the regression analysis results from Equation 20 for Small firms in no ambiguity treatments. The first result we find is that the coefficient on *CRT* is significant. A significant coefficient on *CRT* shows that a person with a higher CRT score will have a higher expected price. The second result we find is that the coefficient on *AmbiguityAttitude* is not significant. We would expect to see this result because ambiguity should not affect the treatments without ambiguity present.

Specification (4) in Table 6 shows the regression analysis results from Equation 20 for Small firms in ambiguity treatments. Again, we find that the coefficient on *CRT* is marginally significant. A significant coefficient on *CRT* shows that a person with a higher CRT score will have a higher expected price. The second result we find is that the coefficient on *AmbiguityAttitude* is marginally significant. This result is expected because a subject's ambiguity attitude could affect their expected price in the ambiguity treatments. If a subject is ambiguity-neutral, ambiguity will not shift their price distribution. If a subject is ambiguity-seeking(ambiguity-averse), the presence of ambiguous captive consumers will shift their price distribution downwards(upwards) for Small firms. Moreover, the coefficient is moving in the direction of theory. As a Small firm becomes more ambiguity-seeking, they will lower their expected price.

5 Discussion

In practice, the breakdown of informed and captive consumers is never known with certainty, regardless of the type of market or market power. In the literature, this precise breakdown has always been explicitly given. In markets where this breakdown is unknown for captive consumers, we find that ambiguity will increase price competition and ultimately lower price dispersion. This result is increasingly relevant as more informed consumers enter the market, as shown by the paper's experimental results, where ambiguity is found to significantly lower price dispersion.

The theoretical findings initially supported that ambiguity on captive consumer shares would decrease price dispersion. Using a series of controlled laboratory experiments, as we move from an environment with a High level of informed consumers with certain captive consumer shares to an environment with a High level of informed consumers with ambiguous captive consumer shares, there is a significant decrease in price dispersion. We found that only the Large firms', firms with the greater fraction of captive consumers, expected price decreased for these treatments. Driving the Large firms' expected prices closer to Small firms', ultimately causing significantly less dispersed prices.

One possible explanation is that ambiguity creates smaller price dispersion by forcing Large firms to act more like Small firms. Without that exact larger security profit, the introduced ambiguity could cause the Large firms to grow concerned and lower their expected price to fight for the informed consumer share, increasing price competition. Small firms do not share the luxury of a large security profit in an ambiguous or unambiguous market and have to compete on price consistently. This leads to the possible explanation of why ambiguity significantly affected Large firms' expected price but had little to no effect on Small firms' expected price.

Additionally, we find that a firm's ambiguity attitude matters in an asymmetric framework relative to the direction and magnitude of their expected price. The results support the finding that as Large firms become more ambiguity-seeking, they will significantly increase their expected price. As Small firms become more ambiguity-seeking, they will significantly decrease their expected price. This shows support for the claim that Large firms rely more on their safety net of captive consumers. When Large firms believe they will receive a larger draw of captive consumers, they increase their expected price to take advantage of this. When Small firms think they will receive a larger draw of captive consumers, they decrease their expected price to stay below the Large firms' expected price to continue to compete for the informed consumer base—also supporting the other claim that Small firms continually face price competition.

This paper is a starting point for understanding how ambiguity affects firms' decisions within a simple pricing model. Future directions of research are to implement ambiguity on the informed consumer share or both the captive and informed consumer share. Both paths seem promising, but the latter is more parallel with markets in practice.

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Appendix A

Comparative Statics

The first comparative statics in this appendix identify the effects of changes in ψ_0 for both firms in a non-ambiguity setting. Given: $\psi_1 > \psi_2$, $\psi_0 + \psi_1 + \psi 2 = 1$, and $r = 1$.

For Firm 1 (Equation 12):

$$\frac{\partial E(p_1)}{\partial \psi_0} = \int_{\underline{p}'}^{1} pH'(p)\, d\psi_0 = \int_{\underline{p}'}^{1} \frac{\psi_1(\psi_2 + \psi_0)}{(\psi_1 + \psi_0)\psi_0 p}\, d\psi_0 = -\frac{\psi_1(\psi_1\psi_2 + \psi_0(2\psi_2 + \psi_0))}{\psi_0^2(\psi_1 + \psi_0)^2}[ln(1) - ln(\underline{p})] = (-)(+) < 0 \tag{21}$$

For Firm 2 (Equation 13):

$$\frac{\partial E(p_2)}{\partial \psi_0} = \int_{\underline{p}'}^{1} pG'(p)\, d\psi_0 = \int_{\underline{p}'}^{1} \frac{\psi_1}{\psi_0 p_2}\, d\psi_0 = -\frac{\psi_1}{\psi_0^2}[ln(1) - ln(\underline{p})] = (-)(+) < 0 \tag{22}$$

For Firm 1 (Equation 14):

$$\frac{\partial E(p_1)}{\partial \alpha_1} = \int_{\underline{p}}^{1} pH'(p)\, d\alpha_1 = [\frac{\partial}{\partial \alpha_1} \frac{(\alpha_1\underline{\psi}_1 + (1-\alpha_1)\overline{\psi}_1)(1 - (\alpha_1\underline{\psi}_1 + (1-\alpha_1)\overline{\psi}_1))}{(\alpha_1\underline{\psi}_1 + (1-\alpha_1)\overline{\psi}_1 + \psi_0)\psi_0}][ln(1) - ln(\underline{p})] = (+)(+) > 0 \tag{23}$$

For Firm 2 (Equation 15):

$$\frac{\partial E(p_2)}{\partial \alpha_2} = \int_{\underline{p}}^{1} pG'(p)\, d\alpha_2 = \int_{\underline{p}}^{1} \frac{\alpha_2\underline{\psi}_2 + (1-\alpha_2)\overline{\psi}_2}{\psi_0 p_2} = \frac{\underline{\psi}_2 - \overline{\psi}_2}{\psi_0}[ln(1) - ln(\underline{p})] = (-)(+) < 0 \tag{24}$$

Appendix B

All subjects observed the instructions for Part 1 and then participated in four unpaid practice rounds played against the computer. Next, subjects read treatment-specific instructions for Part 2 of the study. Note, terms in [ ] next to section headings and < > in body of text were not shown to the subjects. They are provided to distinguish which treatment the instructions were shown.

Part 1

Introduction

This is a study on economic decision making. You will be paid at the end of the study based upon the decisions you and others make in this study, so it is important that you understand these instructions fully. If you have a question at any point, please raise your hand. Also, please make sure you have turned off and put away all personal electronic devices at this time.

In this study you will participate in several market rounds with each round lasting for several periods. You will be in the role of a firm as a seller of a fictitious good. Your payoff will be based on the profit your firm earns. The computer will serve as the consumers. This set of instructions will first explain how pricing in these markets will work. Then you will have the opportunity to go through four practice rounds. The practice markets will not affect your payment in any way; rather, the practice rounds are meant to help you understand how these markets will function.

There are 6 people in your group equally split into two sub-groups: Blue and Yellow. Color assignment is random and everyone retains the same color throughout the study. Your color is _____.

How the basic duopoly will function

Each round your firm will be matched with another firm. In each market, there will always be one firm from the Blue group and one firm from the Yellow group. There will always be 1000 consumers in the market each period. Each consumer values the good at $100. There are

3 types of consumers in each market: price-sensitive, those brand-loyal to the Blue firm and those brand-loyal to the Yellow firm. Price-sensitive consumers will buy from the lowest priced firm, while brand-loyal consumers will buy from the firm to which they are brand-loyal.

Rather than charging a single price you will specify a price strategy. At the start of each round you will be able to specify the probability you charge on each price between 5 and 100. For every period in the round, the computer will determine your price randomly based upon the probability you specify. The probabilities you assign to each price must add up to 100. Putting a higher probability will give that price a greater chance of being charged. Prices with a 0 probability will be selected 0% of the time. Prices with a 50 probability will be selected on average 50% of the time. For example, if you want to charge a price of 45 with certainty, you would put a probability of 100 on a price of 45. Or if you want to randomly pick between 15 and 95, you would put a probability of 50 on those two prices.

Each round lasts 35 periods. All 35 periods in each round will occur simultaneously. Each period, the computer will randomly determine a price for each firm based upon the firm's pricing strategy. The Yellow firm will sell to all consumers that are loyal to the Yellow firm at its selected price. The Blue firm will sell to all consumers that are loyal to the Blue firm at its selected price. The price-sensitive consumers will purchase from the firm offering the lowest price. Note, loyal and price-sensitive consumers pay the same price if they buy from the same firm.

Therefore, the profit a firm earns each period depends on its price relative to the price of the other firm:

If your price is greater than the other firm's price in the market, then your profit in a given period will be your selected price times your number of brand-loyal consumers.

If you price is equal to the other firm's price in the market, then your profit in a given period will be your selected price times your number of brand-loyal consumers plus your selected price times half the price sensitive consumers.

If you price is less than the other firm's price in the market, then your profit in a given period will be your selected price times your number of brand-loyal consumers plus your selected price times all the price sensitive consumers.

<Shown in Unambiguous Treatments>

You will now go through four unpaid practice rounds. During the practice rounds, the computer will serve as the other firm in the market. The computer is programmed to put random probabilities on each price for the other firm. There will be 400 price-sensitive consumers and 400 brand-loyal consumers to your firm and 200 brand-loyal consumers to the other firm (which is played by the computer).

After the pricing decisions are made in a round, results for the 35 periods in the round will be displayed. Your screen will display 35 pairs of price draws and your resulting profit.

<Shown in Ambiguous Treatments>

You will now go through four unpaid practice rounds. During the practice rounds, the computer will serve as the other firm in the market. The computer is programmed to put random probabilities on each price for the other firm. There will be 1000 consumers, 400 of whom are price-sensitive, but the number of consumers who are brand-loyal to Yellow and the number of consumers who are brand-loyal to Blue is not known. The only thing that you and the other firm know about the number of brand-loyal customers is that there are somewhere between 300 to 500 brand-loyal consumers for your firm and somewhere between 100 to 300 brand-loyal consumers for the other firm (which is played by the computer in the practice round). The actual number of brand-loyal consumers will not be revealed. Note, that the number of brand-loyal consumers for your firm plus the number of brand-loyal consumers for the other firm must be 600 since there 1000 total customers and 400 are price sensitive. For example, if your firm has 500 brand-loyal consumers, the other firm would have to have 100 brand-loyal consumers. Similarly, if your firm has 300 brand-loyal consumers then the other firm must have 300 brand-loyal consumers since 400 consumers are price-sensitive.

After the pricing decisions are made in a round, results for the 35 periods in the round will be displayed. Your screen will display 35 pairs of price draws and the range of profit you could have earned. There is a range for your profit because there is a range for the possible number of consumers who are brand-loyal to your firm. Your actual number of brand-loyal consumers will not be shown.

Part 2

Main portion of study

The main portion of the study is similar to the practice rounds, except that the other seller will be another person in this study, and some of the values will change as described below.

In the main portion of the study you will complete several rounds of markets. With each round lasting 35 periods. Like the practice rounds, after each firm inputs their price strategy, the 35 periods will occur simultaneously. This completes one round. After each round, you will be randomly and anonymously re-matched with another firm.

Consumers [Unambiguous Treatments]

<Shown in the Low ψ_0 Treatments>

The only changes from the practice rounds will be that the market will now include:

200 price-sensitive consumers

300 brand-loyal consumers to the Blue firm

500 brand-loyal consumers to the Yellow firm

<Shown in the High ψ_0 Treatments>

The only changes from the practice rounds will be that the market will now include:

600 price-sensitive consumers

100 brand-loyal consumers to the Blue firm

300 brand-loyal consumers to the Yellow firm

Consumers [Ambiguous Treatments]

<Shown in the Low ψ_0 Treatments>

The only changes from the practice rounds will be that the market will now include:

200 price-sensitive consumers

A range of 200 to 400 brand-loyal consumers to the Blue firm

A range of 400 to 600 brand-loyal consumers to the Yellow firm

<Shown in the High ψ_0 Treatments>

The only changes from the practice rounds will be that the market will now include:

600 price-sensitive consumers

A range of 0 to 200 brand-loyal consumers to the Blue firm

A range of 200 to 400 brand-loyal consumers to the Yellow firm

Your Payment [Low ψ_0 Treatments]

After the study is complete, one round will be randomly selected by the computer. 10 periods will be randomly drawn from the selected round. Your payment will be based on the summation of your earnings in the 10 random periods. Your earnings from the randomly selected round will be converted to US at the rate 25,000 Lab Dollars = $1 US Dollar.

You have now completed the instructions. If you have any questions please raise your hand.

Your Payment [High ψ_0 Treatments]

After the study is complete, one round will be randomly selected by the computer. 10 periods will be randomly drawn from the selected round. Your payment will be based on the summation of your earnings in the 10 random periods. Your earnings from the randomly selected round will be converted to US at the rate 20,000 Lab Dollars = $1 US Dollar.

You have now completed the instructions. If you have any questions please raise your hand.

Appendix C

The seven CRT questions used within the experiment:

1) A bat and a ball cost $1.10 in total. The bat costs a dollar more than the ball. How much does the ball cost? $_____.

2) If it takes 5 machines 5 minutes to make 5 widgets, how long would it take 100 machines to make 100 widgets? _____ minutes.

3) In a lake, there is a patch of lily pads. Every day, the patch doubles in size. If it takes 48 days for the patch to cover the entire lake, how long would it take for the patch to cover half of the lake? _____ days.

4) If John can drink one barrel of water in 6 days, and Mary can drink one barrel of water in 12 days, how long would it take them to drink one barrel of water together? _____ days.

5) Jerry received both the 15th highest and the 15th lowest mark in the class. How many students are in the class? _____ students.

6) A man buys a pig for $60, sells it for $70, buys it back for $80, and sells it finally for $90. How much has he made? $_____.

7) Simon decided to invest $8,000 in the stock market one day early in 2008. Six months after he invested, on July 17th, the stocks he had purchased were down 50%. Fortunately for Simon, from July 17th to October 17th, the stocks he had purchased went up by 75%. At this point Simon has:

A) Broken even in the stock market.

B) Is ahead of where he began.

C) Has lost money.