Behavioral Demand Effects When Buyers Anticipate Inventory Shortages*

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Abstract

Firms often worry about how buyers will react when there is an inventory shortage, but the *anticipation* of facing a shortage may also impact buyer behavior. In this paper we use a combination of theoretical modeling, computational methods, and laboratory experiments to understand buyers' search behavior in markets where there is potential for either a costly or costless inventory shortage. When inventory shortages are costly to buyers we find their equilibrium purchasing strategy generates a newsvendoresque problem among the firms. In turn, experimental data suggests buyer behavior can be explained by prospect theory better than by standard neoclassical theory, indicating that potential inventory shortages generate loss aversion among buyers, and there is systematic mis-identification of the probability with which they will be able to procure an item. Using computational methods, we find firms are able to extract more surplus from behavioral buyers via higher prices than would be predicted by the standard neoclassical model. On the other hand, when inventory shortages are not costly to buyers the effect of behavioral biases on the part of buyers is not relevant. But in this case there can exist a benefit to reducing inventory as in many cases it reduces price competition.

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Inventory shortages are problematic for firms as they represent missed sales opportunities. How buyers react to an inventory shortage has been of scholarly interest since at least Walter and Grabner (1975). What has received less attention, however, is how the anticipation of an inventory shortage may also be enough to discourage *potential* buyers. In this paper, we rely on the principles of prospect theory (Kahneman and Tversky 1979) to specify the behavioral demand effects on a product that creates costly shortages for buyers. We hypothesize that buyers will exhibit reference-dependent preferences over consumption outcomes and will systematically misinterpret the probability that they will face an inventory shortage. Specifically, prospect theory's *value function* predicts that when buyers fail to reach their reference level of consumption, the perceived loss in consumption leads to a larger absolute change in utility than a similarly sized gain in consumption would have provided them. Additionally, prospect theory's *probability weighting function* predicts that individuals overestimate the likelihood of small probability events and underestimate the likelihood of large probability events. If these responses exist among buyers who are anticipating inventory shortages, then the optimal inventory targets and prices of firms should respond accordingly.

The implications of behavioral biases have already been considered in a variety of operations relevant settings.[1] Moritz et al. (2013) compares an individual's cognitive reflection with their performance in a newsvendor experiment, finding this measure is a stronger performance predictor than years of experience or having a managerial position. Also with the use of laboratory experiments, Bostian et al. (2008) find a "pull-to-center" effect in which order quantities are too small when they should be larger and vice versa.[2] Prospect theory, particularly reference-dependent preferences, has been considered in many aspects of inventory management, such as among managers (Schweitzer and Cachon 2000; Ho et al. 2010; Wu and Chen 2013), pricing strategists (Fibich et al. 2003), and other members of the supply chain (Croson and Donohue 2006). However, there has not been a study demonstrating evidence of probability weighting by buyers and the resulting implications for optimal pricing and inventory decisions. Liu and van Ryzin (2010) show buyers learn to anticipate inventory shortages for seasonal items entering a markdown period by buying earlier. Similar results are reported in Mak et al. (2014). However neither study considers prospect theory as a potential explanation. Aviv and Pazgal (2008) use numerical analysis to identify a loss in revenue of up to 20% when firms mis-identify

[1]Gino and Pisano (2008) provide an overview of behavioral operations research on the newsvendor problem alongside many other considerations. Ovchinnikov et al. (2015) provides strategies on how to compete against a behavioral newsvendor.

[2]In a similar paper, Kremer et al. (2010) shows this effect can be explained context-sensitive decision strategies. Feng et al. (2011) reports differences in strategies across American and Chinese subjects.

buyers' myopic strategies for seasonal goods, although the effects of probability weighting are not directly considered.

In this paper, we apply prospect theory's value function and probability weighting function to examine the demand effects of potential inventory shortages. To do this we construct a theoretical model in which two firms offer vertically differentiated products (i.e. all buyers have a greater willingness to pay for a relatively higher quality product). The high quality firm is constrained to maintain an inventory level that cannot meet aggregate market demand, while for simplicity the low quality firm is not. Once inventory levels are determined, firms simultaneously post prices, and finally, after observing prices, buyers choose a firm and attempt to make purchases.

We consider this model under two search cost assumptions for buyers: one in which buyers can costlessly purchase from another firm in the event of an inventory shortage and one in which the cost of transacting with another firm is prohibitively large. In general, we see our framework applying to a situation where one firm offers personalization or some other costly value enhancement to the buyer. One example would be two bakeries where one offers basic pastries and the other offers labor intensive specialties to shoppers. On the weekend it may be a mild inconvenience to visit a second bakery, but one may not be able to do so when on the way to work during the week. This model can also represent competition between an online retailer offering a generic product and a brick and mortar store that offers a more tailored product. In this setting, the viability of purchasing from the online retailer after experiencing a stock-out at the brick and mortar store might depend on the timing of order fulfillment.

If it is costless to visit a second firm, then all buyers initially visit the firm offering the best deal (i.e. greatest consumer surplus). We find the behavioral responses of buyers become irrelevant in this case. Since buyers will collectively choose the firm with the larger surplus first, firms must use a mixed strategy over prices in equilibrium that creates a large degree of competition between them. The high quality firm can reduce this pricing competition, however, by reducing their inventory level. We find it is often in the high quality firm's best interest to offer the low quality firm a 'residual market,' so the benefit from undercutting the high quality firm's price is minimized.

However, if it is prohibitively costly for buyers to visit a second firm, then a variant of the newsvendor problem emerges and the stochastic demand for each product depends on the firms' respective inventory levels and consumer surplus offerings. In this situation, there is essentially a market entry game among buyers.[3] The tension in this game arises from a threshold number of entrants, below which one wants to enter and above which one does not. Hence, in equilibrium only some buyers should attempt to purchase the preferred product, but absent asymmetries, there is a coordination problem as to whom the entrants should be. This tension generates stochastic behavior as is often modeled in the newsvendor problem. In this case, increasing inventory may induce more buyers to buy from the high quality firm if they believe it is more likely they will be able to procure the product of interest. Alternatively, a firm could end up with excess inventory if behavioral buyers falsely anticipate an inventory shortage because they underestimate their probability of procuring the additional units. Many buyers avoiding a firm they believe will experience an inventory shortage is a variant of Yogi Berra's famous quip, "No one goes there anymore, it's too crowded." As a result, in some cases the standard models for managing inventory in the face of stochastic demand may be systematically mis-predicting buyers' choices.

The model we develop is in the vein of Deneckere and Peck (1995); however, in their model, firms offer a homogenous product and buyers are limited to visiting a single firm (see also Peters 1984). For markets with prohibitively high search costs, the problem our buyers face has no analytical solution in the symmetric equilibrium.[4] Therefore, we rely upon computational methods and controlled laboratory experiments to best understand market outcomes. Relative to theoretical and numerical predictions for standard neoclassical risk-averse expected utility maximizing agents, we find strong evidence that buyers experience both loss aversion and probability weighting when inventory shortages are costly. Using parameters estimated from the experimental data via maximum likelihood, we extrapolate the impact these behavioral preferences have on firms' pricing and inventory decisions in larger markets, and how those market outcomes differ in comparison to the case of standard neoclassical buyers.

The main contribution of this paper is to provide managers of inventory systems with a perspective on the behavioral demand effects of inventory shortages for products with varying degrees of search costs. Attention is given to how these effects should impact pricing and inventory decisions for the firm. Prospect theory's value function and probability weighting function would predict 1) through loss aversion, buyers will exaggerate the potential harm of

[3]In the traditional market entry game, players privately decide if they wish to take a sure payoff or enter a pool where payoffs are decreasing in the total number of entrants. This game is modeled on firms deciding to enter a market where a monopolist would earn more than a duopolist who in turn would earn more than a triopolist and so on.

[4]There are also asymmetric equilibria, such as exactly M buyers out of N follow a pure strategy to visit a particular firm. There are other equilibria where some buyers follow pure strategies of visiting the high quality firm or not while other buyers do so probabilistically.

choosing a firm's product that might be stocked out; 2) buyers will overestimate the likelihood they will procure a product with a relatively small inventory, and; 3) buyers will underestimate the likelihood they will procure a product with a relatively large inventory. As a result, it may be possible for a firm to increase demand by reducing inventory levels. This also suggests price becomes a double-edged sword for the firm. Lowering the price makes the firm more attractive, which should increase the quantity demanded; but, it also makes choosing this firm riskier for the buyer which could invoke loss aversion to an extent that ultimately reduces demand. Thus, a firm may find expected demand increases as the result of increasing the price. The experimental results presented in this paper demonstrate the extent to which buyers experience loss aversion and are capable of mis-identifying the probability of procuring a limited inventory product with high search costs. The relatively large degree of these two effects we estimate suggests there are meaningful deviations in behavior from what a manager might plan for in a standard (i.e. risk-averse expected utility maximizing buyer) setting, particularly when a firm is only able to serve a small fraction of the market.

1 Theoretical Model

Suppose there are N identical risk-neutral buyers seeking one of two vertically differentiated products over a fixed time interval. Among buyers, the higher quality product (H) has a common value V_H, while the lower quality product (L) has a common value of $V_L < V_H$. Let the surplus to the buyer from procuring product $i \in \{H, L\}$ at price P_i be defined as $S_i = V_i - P_i$.

To properly ground the theoretical investigation, we liken the firms' problems to that of a duopoly in which there is one internet-based firm (L) that provides a generic, low value product, and a brick-and-mortar-based firm (H) that offers a higher quality or more personalized service alternative. As a result, it is assumed H and L face differentiated inventory constraints. Due to the high quality firm's physical constraints, restrictions in inventory sourcing dictate that up to $\overline{C} < N$ units of H can be supplied over the fixed time interval.[5] Moreover, it is assumed H incurs an inventory cost of K_C for each unit it chooses to stock. Conversely, it is assumed L's inventory schedule and physical constraint is flexible enough to meet the demand of all N buyers, if necessary, and their inventory costs are normalized to zero.[6]

[5]Heterogeneous inventory constraints are common in markets with vertically differentiated products. As an alternative motivation, a firm with a high quality product may need to coordinate inputs with long-distance or international vendors that can rate-limit their output, whereas low quality firms may have multiple options for sourcing their inputs which reduces the likelihood of an inventory shortage within a fixed time interval.

[6]While not only being reflective of many market scenarios, the purpose for restricting inventory shortages at one

When choosing a product, each buyer has the pure strategy space $\{H, L\}$ which represents the buyer choosing product H or L, respectively.[7] Let $\lambda \in [0,1]$ denote the probability that a buyer independently chooses strategy H, and let M represent the number of other buyers who choose H. Our primary focus is on symmetric strategies over which any given buyer and the $Q = N - 1$ other buyers in the market use the same λ. As a result, $p(\lambda \mid C, Q)$ represents the probability a buyer procures H if they and all other buyers choose H with probability λ. In the event a buyer along with $M \geq C$ other buyers chooses H and an inventory shortage occurs, then the C units available are randomly allocated.[8]

We consider the two extreme cases of consequences to buyers impacted by an inventory shortage. In the first case, a buyer who chooses H and is unable to procure a unit faces no cost of then procuring L within the same fixed time interval. This case removes all risk from a buyer's choice to pursue H. In the second case, a buyer who chooses H and is unable to procure a unit finds it prohibitively costly to then procure L. Thus, in this case they receive a return of zero for that fixed time interval.

We explore these two inventory shortage cases while assuming the stages of the game are as follows:

Stage 0: Nature chooses the number of buyers N, values V_H and V_L and the cost they face from an inventory shortage $\{\text{Costless}, \text{Costly}\}$, as well as the capacity $\overline{C}$ and constant marginal inventory cost of K_C to H.

Stage 1: H chooses its inventory level, $C \leq \overline{C}$.

Stage 2: H and L simultaneously choose prices which determine the surpluses S_H and S_L to offer buyers.

Stage 3: Buyers simultaneously attempt to purchase from H or L, or opt not to purchase from either.

Complete information of the outcomes of preceding stages is assumed in this model. In the following subsections we analyze this market for equilibria over buyer choice (λ^*) and firm choice (S_H^*, S_L^*, C^*) with a model that allows for behavioral tendencies (loss aversion and

firm is due to our primary interest in how it will affect buyer behavior. If inventory shortages are possible from both firms, then the risk of a shortage can be neutralized. Only allowing the high quality firm to face an inventory shortage creates the desired buyer tension between a safe option and a risky option with a higher potential payoff.

[7] It is assumed that at least one firm prices their product such that procuring it is strictly preferred to procuring nothing.

[8] This would be the case if arrival order was random and buyers were served on a first-come first-served basis. This assumption has no welfare effects in this model as all buyers' preferences are identical.

probability weighting) among buyers. For each assumption on the costs associated with an inventory shortage, analysis begins via backward induction with buyer behavior.

1.1 Case 1: Buyers Face A Costless Inventory Shortage

In the case where buyers face a costless inventory shortage, any buyer who chooses H and is unable to procure a unit will receive the same surplus as a buyer who chooses L, assuming both firms offer a positive surplus.[9] The condition to choose H with a pure strategy becomes $p(\lambda \mid C, Q)S_H + (1 - p(\lambda \mid C, Q))\, S_L > S_L$, which holds so long as $S_H \geq S_L$. Thus, there is a best response in which buyers choose H with probability $\lambda^* = 1$ or $\lambda^* = 0$. Moreover, due to the absence of risk or any salient trade-off to choosing the largest surplus first, there is also no opportunity for a behavioral response from buyers via prospect theory that could impact their decisions. This is basis of Buyer Hypothesis 1.

Buyer Hypothesis 1: When buyers are faced with the potential of a costless inventory shortage for H, there are two pure strategy Nash equilibria in which buyers pursue the largest surplus available such that

$$\lambda^* = \begin{cases} 1 & \text{if } S_H \geq S_L \\ 0 & \text{if } S_H < S_L. \end{cases} \tag{1}$$

Given Buyer Hypothesis 1, we can begin to backward induct Stage 2 strategies in which firms H and L simultaneously choose surpluses to offer buyers. To begin, equation (2) defines L's profit function in terms of their offered surplus,

$$\Pi_L(S_H, S_L \mid C) = \begin{cases} (N - C)(V_L - S_L) & \text{if } S_H \geq S_L \\ N(V_L - S_L) & \text{if } S_H < S_L \end{cases} \tag{2}$$

where $V_L - S_L$ is the price charged by L. The first case in equation (2) shows that when L offers a relatively low surplus it will receive the residual demand from H (i.e. those buyers who were unable to procure a unit from H). The second case expresses L's profit when it captures the entire market by providing a larger surplus than H.

Note that it is not always in the best interest for L to offer the larger surplus. The alternative is for L to accept the residual market of $N - C$ units and offer a consumer surplus of zero,

[9] In equilibrium firms will offer a non-negative surplus to buyers.

which can be relatively large for small C. Given S_H, the profit to L for offering the greater surplus exceeds than that from capturing the residual market when $N(V_L - S_H) > (N - C)V_L$ where $V_L - S_H$ represents the price L must set to equate the surpluses offered by the firms. Rearranging in terms of S_H we find that L will prefer offering a greater surplus than H when $S_H < \frac{C}{N}V_L$.

Likewise, H's profit can be defined in terms of its offered surplus as

$$\Pi_H(S_H, S_L \mid C) = \begin{cases} (V_H - S_H - K_C)C & \text{if } S_H \geq S_L \\ -CK_C & \text{if } S_H < S_L \end{cases} \tag{3}$$

where $V_H - S_H$ represents the price charged by H. In (3) we see when H offers a surplus greater than L they will sell all C units in its inventory. Conversely, if their surplus is less than L's then H sells nothing and still incurs the inventory costs of its C units. Thus, it is clear that H wants to offer the greater surplus and thus prevent L from capturing the entire market.

Given the nature of the firms' profit functions, it is relatively straight-forward to demonstrate there exists a mixed strategy equilibrium in surplus (i.e. pricing) for both H and L. For instance, if H offers a surplus of $S_H < \frac{C}{N}V_L$, then L's best response is to offer a surplus of $S_L^* = S_H + \epsilon$, giving H zero market share. This, in turn, generates a best response from H to offer a slightly greater surplus than L and so forth. If, instead, H offers a surplus of $S_H > \frac{C}{N}V_L$, then L's best response is to offer a surplus of $S_L^* = 0$ and accept the residual demand of $N - C$. The best response from H in this case is to decrease the consumer surplus its offering to $S_H^* = \epsilon$ without any loss in demand, in which case we arrive back to the conditions of the first scenario. Finally, if H offers a surplus of $S_H = \frac{C}{N}V_L$ then L is indifferent between offering a greater surplus than H and offering zero surplus to the residual demand.[10]

To define the mixed strategies over the consumer surplus offered, let S for $i \in \{H, L\}$ be drawn from the distribution F_i where $F_i(\underline{S}_i) = 0$ and $F_i(\overline{S}_i) = 1$. It is assumed that $F_i(\cdot)$ is differentiable everywhere and has density f_i. We begin by solving for H's mixed strategy over surplus by specifying L's expected profit equation as

$$E[\Pi_L] = F_H(S)(V_L - S)N + (1 - F_H(S))\,[N - C](V_L - S). \tag{4}$$

To generate indifference by L, we set (4) equal to the greatest profit L can unilaterally guarantee

[10]Since H cannot benefit from deviating, this constitutes the pure strategy Nash equilibrium of $S_H^* = S_L^* = \frac{C}{N}V_L$.

itself with a pure strategy. The 'security profit' that L can unilaterally guarantee itself is given by offering a surplus of $S_L = 0$ and selling $N - C$ units. Setting (4) equal to $(N - C)V_L$ and solving for $F_H(S)$ yields the mixed strategy over surplus of

$$F_H^*(S) = \frac{N - C}{C} \frac{S}{V_L - S}. \tag{5}$$

where $F(0) = 0$ and $F\left(\frac{C}{N}V_L\right) = 1$. The equilibrium mixed strategy for H demonstrates that as C increases, the expected surplus to buyers also increases. As a result, H faces a tradeoff between serving a larger share of the market and having to offer larger surpluses (i.e. charge lower prices).

In a similar manner, the expected profit to H for offering a surplus of S can be expressed as

$$\begin{aligned} E[\Pi_H] &= F_L(S)\left[(V_H - S)C - K_C C\right] + (1 - F_L(S))\left[-K_C C\right] \\ &= F_L(S)(V_H - S)C - K_C C. \end{aligned} \tag{6}$$

The security profit for H is determined by the lowest surplus H can offer and not incentive L to capture the entire market, which was previously determined to be $S_H = \frac{C}{N}V_L$. Using this surplus we find the security profit for H is $\left(V_H - \frac{C}{N}V_L - K_C\right)C$. Equating (6) to H's security profit and solving for $F_L(S)$ we find

$$F_L^*(S) = \frac{V_H - \frac{C}{N}V_L}{V_H - S} \tag{7}$$

where $F(0) = 0$ and $F\left(\frac{C}{N}V_L\right) = 1$.

Finally, in consideration of Stage 1 behavior we maximize H's expected profit according to its inventory level, C. Given that H's equilibrium strategy over consumer surplus is in mixed strategies, determining the optimal inventory level is equivalent to maximizing H's security profit of $\left(V_H - \frac{C}{N}V_L - K_C\right)C$. Therefore $C^* = \min\left\{\frac{N}{2}\frac{V_H - K_C}{V_L}, \overline{C}\right\}$. Under many parameter values, we see H benefits from reducing their inventory levels below $\overline{C}$, as it reduces the extent of pricing competition with L. The equilibrium analyses of Stage 1 and Stage 2 decisions are the basis of Firm Hypothesis 1.

Firm Hypothesis 1: When buyers face a potential inventory shortage that is costless, firms use a mixed strategy over the consumer surpluses they offer, and the high quality firm often finds it optimal to limit its inventory to reduce surplus (i.e. pricing) competition. Formally,

$$\begin{aligned} F_H^*(S) &= \frac{N-C}{C}\frac{S}{V_L - S} \\ F_L^*(S) &= \frac{V_H - \frac{C}{N}V_L}{V_H - S} \\ C^* &= \min\left\{\frac{N}{2}\frac{V_H - K_C}{V_L}, \overline{C}\right\}. \end{aligned} \tag{8}$$

1.2 Case 2: Buyers Face A Costly Inventory Shortage

When buyers face a costly inventory shortage, any buyer who unsuccessfully attempts to procure H cannot then choose L, and thus receives no surplus. As a result, if a buyer is to choose H with a pure strategy it is necessary they be offered an expected value from H that meets or exceeds the surplus they can obtain for certain from L. Mathematically, this is $p(\lambda \mid C, Q)S_H \geq S_L$. Given the buyer symmetry, if this buyer finds it optimal to choose H with a pure strategy then the $Q = N - 1$ other buyers will as well, in which case $p(\lambda = 1 \mid C, Q) = \frac{C}{N}$. This implies when $\lambda^* = 1$ it must be that the relative surplus is $\frac{S_L}{S_H} < \frac{C}{N}$. However, if instead $S_H \leq S_L$ then there is no benefit to choosing H. Therefore, the optimal choice among buyers is the pure strategy $\lambda^* = 0$ when $1 < \frac{S_L}{S_H}$.

What remains is the condition where $\frac{C}{N} \leq \frac{S_L}{S_H} \leq 1$, in which case there is no symmetric pure strategy equilibrium.[11] Instead, there exists a symmetric mixed strategy equilibrium, which generates a stochastic demand as in the newsvendor problem. To identify the mixed strategy equilibrium one must express the probability of procuring H as a function of λ, given C and Q, according to the following modified cumulative binomial distribution,

$$p(\lambda \mid C, Q) = \underbrace{\sum_{M=0}^{C-1}\binom{Q}{M}\lambda^M(1-\lambda)^{Q-M}}_{\substack{\Pr(M < C) \Rightarrow \\ \text{Receives Item at } H \text{ with Certainty}}} + \underbrace{\sum_{M=C}^{Q}\frac{C}{M+1}\binom{Q}{M}\lambda^M(1-\lambda)^{Q-M}}_{\substack{\Pr(M \geq C) \Rightarrow \\ \text{Randomly Receives Item at } H}}. \tag{9}$$

The first summation in (9) represents the probability there is no inventory shortage for H (i.e. $M < C$ other buyers choose H). The second summation in (9) represents the probability that the buyer is randomly allocated one of the C units of H when there is an inventory shortage (i.e. $M \geq C$ other buyers choose H). Since units of H are randomly allocated in the event of an inventory shortage, each term in the modified cumulative binomial distribution for which

[11] There are, however, $\binom{N}{C}$ asymmetric pure strategy equilibria in which C buyers choose H and $N - C$ buyers choose L. Due to the lack of heterogeneity assumed in the model, our analysis is restricted to the symmetric case.

$M \geq C$ is multiplied by the random allocation probability $\frac{C}{M+1}$.

The mixed strategy equilibrium is a value for λ^* in which $p(\lambda^* \mid C, Q) = \frac{S_L}{S_H}$. While there is no analytical solution for λ^*, one can calculate its value numerically to an arbitrary degree of precision over a range of parameter values. The conditions under which there is a symmetric mixed strategy Nash equilibrium is the basis for Buyer Hypothesis 2.

Buyer Hypothesis 2: When buyers are faced with the potential of a costly inventory shortage, there exists a symmetric mixed strategy equilibrium in which buyers seek to procure the risky product, H, with the probability

$$\lambda^* = \begin{cases} 1 & \text{if } \frac{S_L}{S_H} \leq \frac{C}{N} \\ \underset{\lambda \in [0,1]}{\arg\min} \left| p(\lambda \mid C, Q) - \frac{S_L}{S_H} \right| & \text{if } \frac{C}{N} \leq \frac{S_L}{S_H} \leq 1 \\ 0 & \text{if } 1 \leq \frac{S_L}{S_H}. \end{cases} \tag{10}$$

In the interest of exploring potential behavioral reactions to costly inventory shortages, we adapt the buyer's problem according to prospect theory such that it includes a value function over consumption outcomes, $v(S \mid R)$, and a probability weighting function over the probability of procuring H, $w(p)$.[12] We assume these functions take the following forms.

$$\begin{aligned} v(S \mid R) &= \begin{cases} (S-R)^{\alpha} & \text{if } S \geq R \\ -\phi[-(S-R)]^{\beta} & \text{if } S < R \end{cases} \\ w(p) &= \frac{p^{\gamma}}{[p^{\gamma} + (1-p)^{\gamma}]^{\frac{1}{\gamma}}} \end{aligned} \tag{11}$$

In the value function, the determination of a buyer's utility depends on whether the surplus they receive, S, is greater than or less than their reference level of surplus, R. A curvature parameter, α, assumed to be less than or equal to one, mimics neoclassical risk aversion in the gain domain (when $S \geq R$). In the loss domain (when $S < R$), a curvature parameter, β, also assumed to be less than or equal to one, makes buyers risk-loving, as predicted by prospect theory. Finally, a loss parameter, ϕ, assumed to be greater than or equal to one, captures the

[12] We apply the weighting function to the probability given by equation (9) as this is the probability that concerns the buyer. Essentially, we are assuming that the buyer is inherently aware of the probability of procuring the item from H rather than being sufficiently sophisticated to carry through the calculations of equation (9) but still susceptible to probability weighting. An alternative approach is to apply the weighting function to the probability that another buyer opts to visit H inside of equation (9), λ, and then again to the overall probability p. Ultimately the two approaches yield qualitatively similar although numerically distinct patterns.

buyer's degree of loss aversion. The functional form we specify for the probability weighting function comes from Tversky and Kahneman (1992). While there are several variations of the probability weighting function (see Prelec 1998, Gonzalez and Wu 1996, Wu and Gonzalez 1999), this variation has shown to fit empirical observations well (Tversky and Kahneman 1992, Camerer and Ho 1994, Berns et al. 2008).[13]

Given that L offers a product with no inventory shortage potential, we argue that the risk free surplus of S_L is an appropriate reference point (i.e. $R = S_L$). The behavioral reactions in (11) adapt the equilibrium condition that balances the relative surpluses being offered for H and L with the *perceived* likelihood and value of procuring H such that

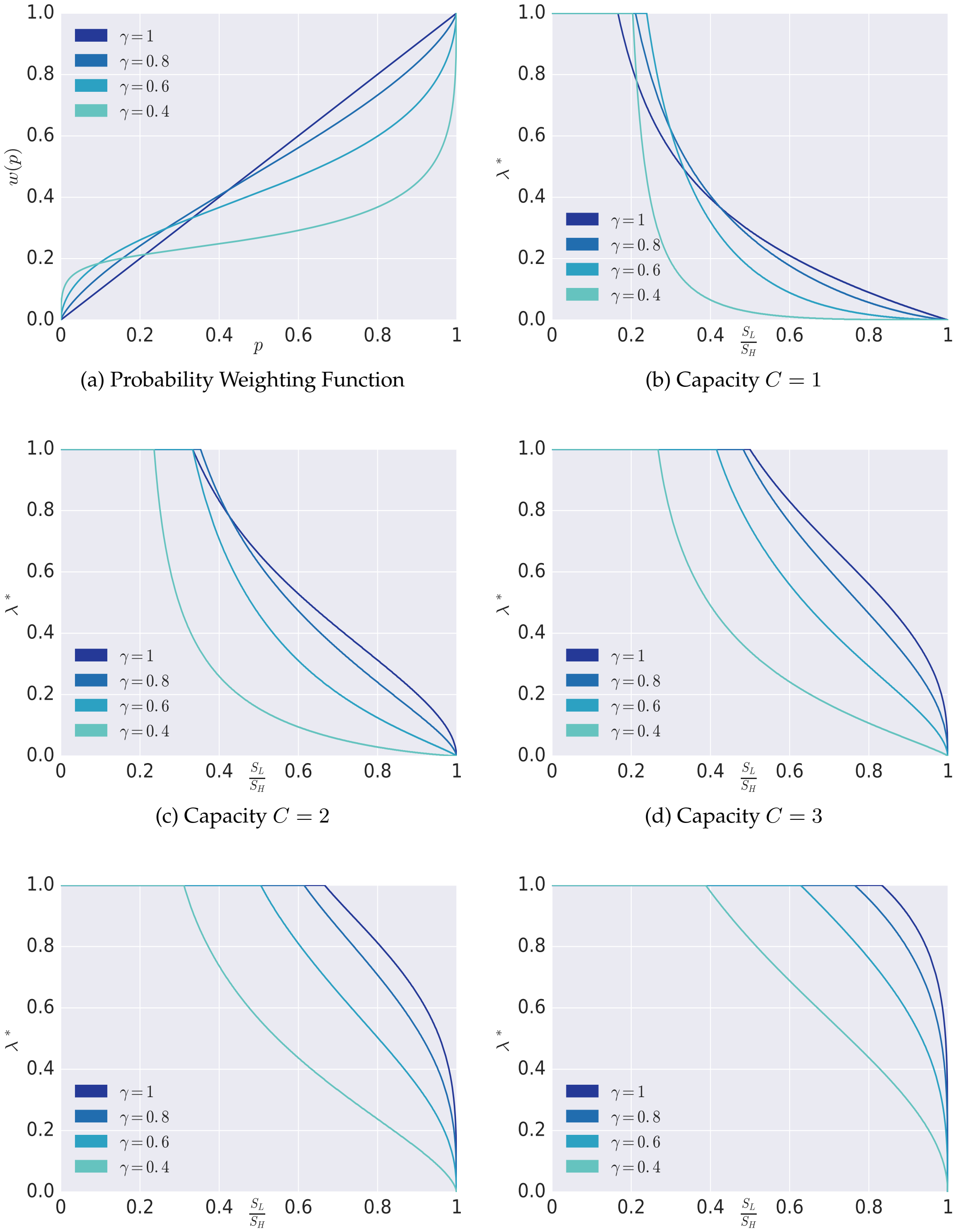
$$\begin{aligned} w(p)v(S_H \mid S_L) + [1 - w(p)]\, v(0 \mid S_L) &= v(S_L \mid S_L) \\ \Rightarrow w(p) &= \frac{\phi S_L^{\beta}}{(S_H - S_L)^{\alpha} + \phi S_L^{\beta}}. \end{aligned} \tag{12}$$

Note that when $\alpha = \beta = \gamma = \phi = 1$ the model reduces back to the standard risk-neutral expected utility maximizing predictions in Buyer Hypothesis 2. To explore one component of these behavioral effects on demand, the panels in Figure 1 illustrate the mixed strategy solution for λ^* using the condition expressed in (12). Here the probability weighting parameter (γ) is varied for $N = 6$ buyers (the number used in the experimental markets discussed below) while holding the other behavioral parameters fixed at their standard equivalents ($\alpha = \beta = \phi = 1$). In Figure 1(a) there are four probability weighting functions plotted for different values of γ. Note, for $\gamma = 1$ we see $w(p)$ sits on the 45 degree line (i.e. no probability weighting), and as γ decreases buyers increase the extent to which they over-estimate small probability events and under-estimate large probability events. Each of the five succeeding panels in Figure 1 illustrates the equilibrium values of λ^* with capacity constraints from $C = 1$ to $C = 5$. In these plots, buyers face a relative surplus in the range $\frac{S_L}{S_H} \in [0, 1]$, a natural range to consider as when $\frac{S_L}{S_H} \geq 1$ then buyers have a dominant strategy of $\lambda^* = 0$ and when $\frac{S_L}{S_H} \leq 0 < \frac{C}{N}$ then buyers have a dominant strategy of $\lambda^* = 1$.

The symmetric equilibrium mixed strategies in Figure 1 demonstrate that if the capacity constraint on H is relatively large compared to N then probability weighting buyers unambiguously reduce demand. For the simulations presented, when buyers face a capacity constraint of $C = 3$, $C = 4$, or $C = 5$, then decreasing the value of γ decreases the value of λ^* at any

[13]This specification for the weighting function is best suited to $\gamma \in [0.28, 1]$, where $\gamma = 1$ indicates zero probability weighting, and smaller values of γ indicate a greater degree of probability weighting. Ingersoll (2008) demonstrates that monotonicity is lost for values of $\gamma \lesssim 0.28$.

Figure 1: Equilibrium Mixing Strategies of $N = 6$ Buyers



(a) Probability Weighting Function

(b) Capacity $C = 1$

(c) Capacity $C = 2$

(d) Capacity $C = 3$

(e) Capacity $C = 4$

(f) Capacity $C = 5$

given relative surplus. Interestingly, however, as the capacity constraint on H reduces to $C = 2$ or $C = 1$, so that only a small fraction of the market can be served, the impact on demand for H depends on the value of γ and the relative surplus being offered. Under some conditions, demand for H will increase with probability weighting buyers as they overestimate the low probability of procuring the item from H.

Since λ^* does not have an analytical solution under these assumptions, it is not possible to analytically backward induct any of the firms' decisions. However, it is possible to continue the computational methods used on buyer behavior and solve for the stage 2 pure strategy Nash equilibria (S_H^*, S_L^*).[14] Specifically for Stage 2, given a specific parameterized model of buyer behavior for any (S_H, S_L) pair we can compute buyers' aggregate reaction, in expectation, and use the resulting λ^* to calculate the firms' expected profits. For H, the expected profit function is

$$E[\Pi_H] = (V_H - S_H)\min\{\lambda^* N, C\} - CK_C, \tag{13}$$

and for L the expected profit function is

$$E[\Pi_L] = (V_L - S_L)(1 - \lambda^*)N. \tag{14}$$

Using (13) and (14) to determine equilibrium choices at stage two, one can identify the choice of C that optimizes H's profit. In the next section we go through this numerical exercise for the specific parameter values used in our laboratory experiment. This process yields Firm Hypothesis 2.

Firm Hypothesis 2: When buyers face a potential inventory shortage that makes procuring an alternative item impossible, firms will use a pure strategy over the consumer surpluses they offer, and the high quality firm optimizes its inventory level according to the following condi-

[14]The key distinction between this case and the case where visiting a second firm is not costly is that here demand is continuous in own surplus whereas in the other case demand has a discontinuity.

tions.

$$
\begin{aligned}
&\text{There exists a pure strategy equilibrium } (S_H^*, S_L^*) \in \mathbb{R}_+^2 \text{ such that} \\
&\qquad E[\Pi_i(S_i^*, S_j^* \mid C)] \;\geq\; E[\Pi_i(S_i, S_j^* \mid C)] \\
&\quad \text{for } S_i \in \mathbb{R}_+ \text{for } i, j \in \{H, L\}, i \neq j. \\
&\text{And, } H \text{ chooses } C \text{ according to} \\
&\qquad \underset{C \in \mathbb{C}}{\operatorname{argmax}} \;\; E[\Pi_H(S_H^*, S_L^* \mid C)] \\
&\quad \text{for } C \in \mathbb{C} = \{0, 1, ..., \overline{C}\}.
\end{aligned}
\tag{15}
$$

2 Experimental Design

To help identify the type of behavioral responses buyer may exhibit in markets with the potential for inventory shortages we rely upon controlled laboratory experiments. In the laboratory the assumptions of the model can be exogenously imposed and the behavioral reaction of buyers can be studied directly. Four experimental sessions were conducted, each with 24 subjects and lasting approximately ninety minutes. To invoke an organic market environment, roles for buyers and firms were randomly assigned to subjects, each of whom maintained the same role for the entire experiment. Subjects participated in a sequence of twenty vertically differentiated duopoly markets, each of which consisted of a firm selling H with a pure common value of $V_H = 15$, a firm selling L with a pure common value of $V_L = 9$, and $N = 6$ buyers. Thus, in any one of the twenty periods for a given session there were three concurrent and independent markets.[15]

Utilizing a within-subjects design, each subject was exposed to two treatments. In the *Costly* treatment, buyers face a costly inventory shortage where unsuccessfully seeking a unit of H results in no unit procurement and a return of zero. In the *Costless* treatment, buyers face a costless inventory shortage where procuring L is possible after unsuccessfully seeking H. In two of the four sessions, subjects first experienced the *Costly* treatment for ten periods and then the *Costless* treatment for the last ten periods. In the other two sessions, the treatment order was reversed. Thus, any treatment order effect was balanced across subjects. Given the stage 3 predictions discussed in the previous section, one might consider the *Costless* treatment behaviorally uninteresting; however, it serves the important purpose of verifying that the subject

[15]There was one experimental session with only 16 subjects, which ran two markets concurrently rather than three.

buyers understood the decision problem they faced and is thus a control for evaluating shopper behavior in the *Costly* treatment.

For both treatments, each of the market periods proceeded through stages 1 -3 of the game as described in the previous section. First, the H firm chose a inventory capacity of $C \leq \overline{C} = 5$ at a per unit cost of $K_C = 3$ for the period, which was then revealed to the L firm. Second, the H and L firms privately and simultaneously set their prices. Finally, after buyers observe the prices, which were also converted into surpluses for them, and inventory constraint on H in their market they privately and simultaneously decide which product to pursue, if any. In the *Costless* treatment, any buyer who experienced an inventory shortage for H was subsequently allowed to decide whether or not to buy from the L firm. This last step was omitted in the *Costly* treatment. Subjects saw the outcomes of their market (and only their market) at the end of the period. Once a market period concluded, all subjects were reshuffled and the next market period began. Since no identifying information was present, subjects did not know if or when they might interact with another subject again, which aided in reducing repeated play dynamics. The model parameters, along with theoretical predictions for standard risk-neutral expected utility maximizing buyers, are outlined in Table 1.

Table 1: Parameter Values and Predicted Outcomes by Treatment

	Parameters		
	$V_H = 15$	$K_C = 3$	$N = 6$
	$V_L = 9$		$\overline{C} = 5$

	Costless Treatment	*Costly Treatment*
Optimal Capacity	4	5
High Quality Price	E[10.9]	6
Low Quality Price	E[7.6]	1
High Quality Profit	E[24]	E[15]
Low Quality Profit	E[18]	E[0.5]
Individual Shopper Surplus	E[4.3]	E[8.9]

Note: treatment predictions are made assuming risk-neutral expected utility maximizing buyers. E[·] indicates the prediction is an expected value.

The experiments were run with the use of z-Tree (Fischbacher 2007) at a research laboratory at a large American university. The subjects were undergraduates at that institution and were drawn from a standing database of study volunteers, a majority of whom were students in the business school. None of the subjects had previously participated in any related studies. Upon entering the laboratory, subjects were seated at individual workstations separated by privacy dividers. Subjects then read the computerized instructions and answered a series of comprehension questions.[16] Once everyone had finished the instructions, answered the comprehension questions, and had any remaining questions answered, the computerized experiment began. After the 10$^{\text{th}}$ market period, a second set of directions and comprehension questions were administered, which described the second treatment. Participants did not know the number of market periods nor did they know in advance that there would be a second treatment.

At the conclusion of the experiment, subjects were paid in private based upon their cumulative earnings, which were denoted in Experimental Dollars ($E). The conversion rate into $US was $E 20=$US 1 for firms and $E 10=$US 1 for buyers. In addition to the salient payment based upon earnings in the market, which averaged $13.57, subjects also received a $5 participation payment. After receiving their payment, subjects were dismissed from the study.

3 Experimental Results

The results are presented by treatment. We begin by describing firm and buyer strategies for *Costless* inventory shortages.

3.1 Case 1: The *Costless* Inventory Shortage Treatment

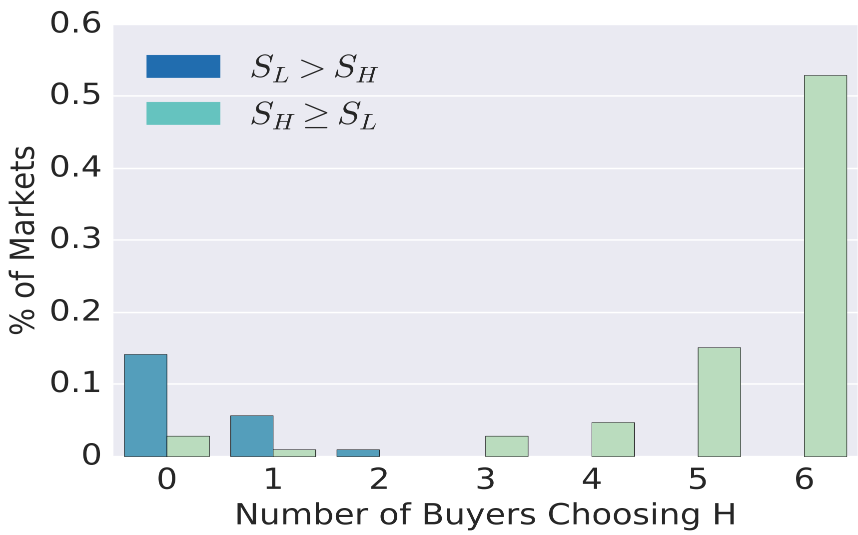
When inventory shortages are costless, buyers should choose the product with the greater surplus according to Buyer Hypothesis 1, regardless of the capacity constraint. Figure 2 reveals that subject buyers overwhelmingly follow this strategy. The blue bars indicate markets in which $S_L < S_H$, while the green bars indicates markets in which $S_H \geq S_L$. 92% of the time shoppers visited the high quality firm when it offered the relatively larger surplus, and 97% of the time shoppers visited the low quality firm when it offered the relatively larger surplus. Proportions confidence intervals at the 95% level for λ^* when $S_L > S_H$ and $S_H \geq S_L$ yield $[0, 0.07]$ and $[0.90, 0.94]$, respectively. This finding is the basis for Buyer Result 1.

Buyer Result 1: When faced with a costless inventory shortage, buyers overwhelmingly follow their dominant strategy according to Buyer Hypothesis 1.

Given that buyers behave optimally, firms' Stage 2 equilibrium strategies over surpluses are outlined in Firm Hypothesis 1, which states that surpluses are offered according to mixed

[16]The text of the directions and the questions are included in the appendix.

Figure 2: Buyers Choosing H When Inventory Shortages are Costless



strategies over the range $S \in [0, \frac{C}{N}V_L]$. Figure 3 plots the theoretical CDF distributions over pricing along with the observed CDF distributions for each capacity level. Results of the K-S tests corresponding to each theoretical-observed distribution pair are reported in each subfigure. The observed distributions indicate that firms were generally reluctant to offer a low surplus (charge a high price). This conclusion is also supported by regression results with standard errors clustered at the subject level as reported in Table 2. The dependent variable is the difference between the observed and expected price, conditional on capacity level. While the coefficient on firm type is insignificant, there is some evidence that underpricing is reduced in markets where H has a larger inventory.

Firm Hypothesis 1 also suggests there are benefits to constraining H's capacity to $C = 4$ as a method of reducing price competition. The average inventory choice was 4.17, which is not statistically different from 4 (two tailed t-test p-value = 0.71). But in the vast majority of markets H chose the maximum inventory level of $C = 5$. Because the degree of price competition in the experimental markets exceeds the stage 2 predictions for all inventory capacity levels, particularly for smaller inventory capacities, the incentive for H to restrict inventory is weakened. The average profits earned by H when $C = 5$ were 13.16 experimental currency dollars, whereas the next best inventory level ($C = 4$) earned H 10.8 experimental currency dollars on average. Though this difference is not statistically significant (p-value = 0.55), it is a 30% increase in profit for H, which helps explain their capacity decisions. These results lead to Firm Result 1.

Figure 3: Theoretical and Experimental Mixed Strategies Over Surpluses Offered

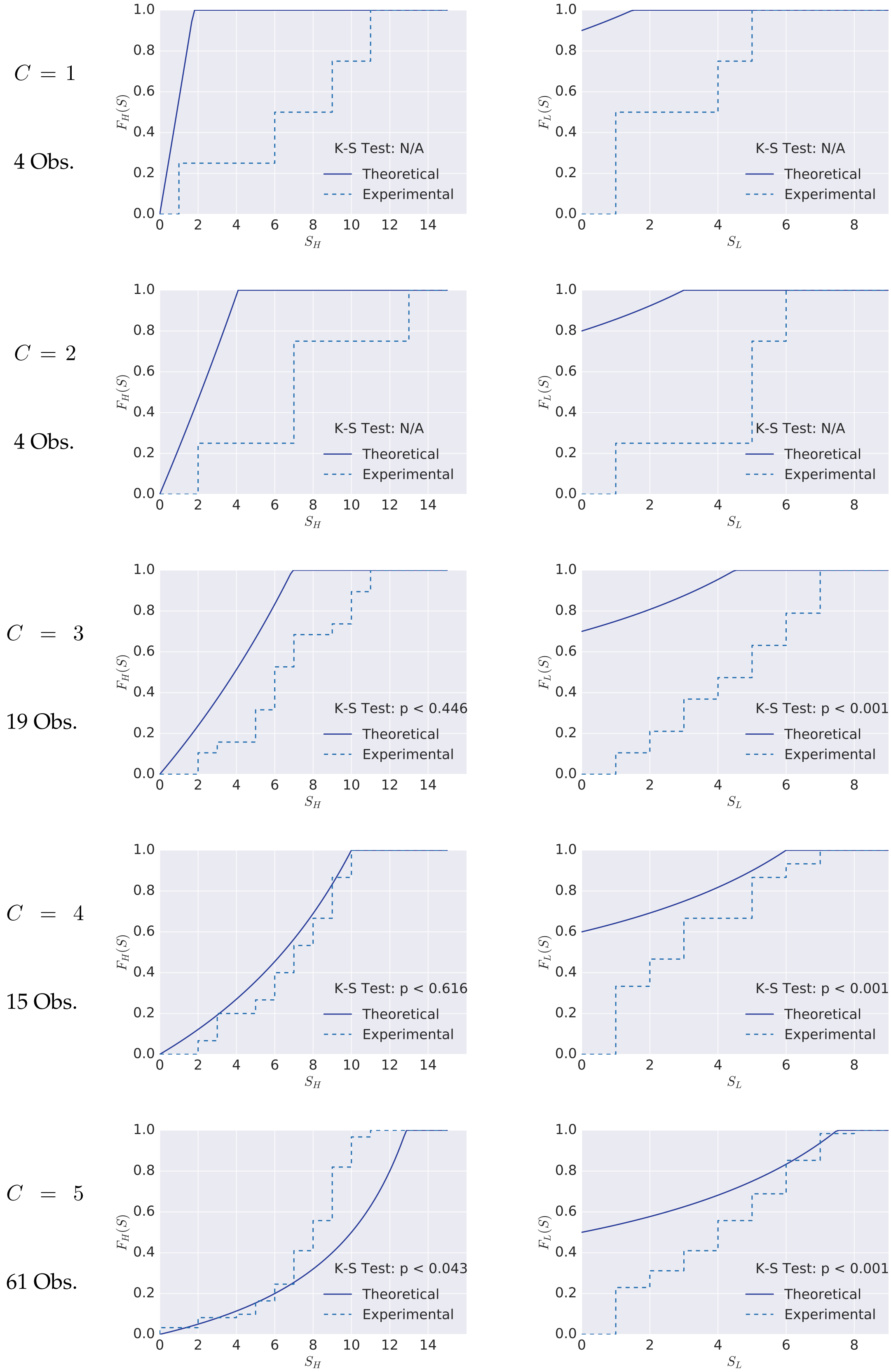


Table 2: Stage 2 Pricing in *Costless* Treatments

Dependent Variable: *Observed Price - Predicted Price*		
	Coefficient	Std. Error
High Firm (H)	-2.49*	1.34
Capacity (C)	0.64***	0.22
Capacity × High Firm	0.49	0.31
Treatment Order	0.17	0.38
Constant	-5.01***	0.64
Observations	206	

Notes: ***, **, and * indicate significance at the 1%, 5% and 10% level, respectively.

Firm Result 1: When faced with a costless inventory shortage, firms follow a pricing strategy that offers larger surpluses to buyers than predicted by theory. This weakens the incentive for H to reduce inventory capacity as a method of reducing price competition, and as a result the majority of markets are such that C exceeds the equilibrium level.

3.2 Case 2: The *Costly* Inventory Shortage Treatment

We now turn to situation where behavioral biases of buyers would be expected to impact shopping behavior. When a buyer cannot visit a second firm after experiencing a shortage a tension emerges if the high quality firm offers a larger surplus than the low quality firm. As a result buyers follow a mixed strategy as described in Buyer Hypothesis 2. Importantly, the specific probability that buyers visit H given the choices of the firms depends on the degree to which buyers exhibit behavioral biases. Thus our analysis begins with two maximum likelihood estimations (MLE) of equation (12), the buyers' willingness to choose H, with robust standard errors clustered at the subject level.[17] These estimations are reported in Table 3.[18] The first MLE uses typical assumptions on the tradeoffs of choosing H or L, (i.e. buyers are expected utility maximizers but may not be risk-neutral).[19] In this case, the MLE is done for the param-

[17]The maximum likelihood estimations in Table 3 were calculated by modifying STATA code in Harrison (2008).

[18]Some observations were lost because subjects chose not to buy anything in a given period, at least one firm offered a negative surplus, or because the H firm offered zero surplus making the relative surplus undefined.

[19]This is equivalent to applying prospect theory when the reference point is 0 and no losses are possible.

eter α, which captures the curvature in the utility function. The second MLE uses prospect theory assumptions in the evaluation of tradeoffs buyers face between H and L. As mentioned previously, the reference point in this context is the 'safe' surplus a buyer can procure from L. Thus, the potential of choosing H and not procuring an item induces a loss aversion response among buyers. Moreover, prospect theory predicts that buyers will systematically mis-predict the likelihood with which they will procure an item, be risk averse over gains, and risk seeking over losses.

Table 3: Maximum Likelihood Estimation of Buyer Utility Parameters

Dependent Variable: *Buyer Decision* (Choose $H = 1$)		
	Neoclassical Theory	Prospect Theory
α	0.873***	0.812***
	(0.050)	(0.054)
β		0.240***
		(0.158)
ϕ		1.425**
		(0.215)
γ		0.616***
		(0.059)
Observations	592	592
AIC	610.135	566.997
BIC	614.519	584.531

Notes: ***, **, and * indicate significance at the 1%, 5% and 10% level, respectively, from the null hypothesis that each parameter equals one (i.e. standard buyers). Robust standard errors are reported in parentheses.

The null hypotheses for both MLE specifications is based on the standard risk-neutral expected utility maximizing model. Therefore, the curvature parameters (α in gains, β in losses), the loss aversion parameter (ϕ) and the probability weighting parameter (γ) are each hypothesized to equal one. Additionally, the parameters estimated represent the average response of buyers, which makes the estimated parameters reflective of the market's representative buyer.

The MLE for neoclassical assumptions on buyer preferences suggests that the curvature parameter is statistically significantly less than one at 0.873, which suggests that the average buyer's revealed risk preferences are consistent with risk aversion in an expected utility setting. However, the estimation results provide stronger evidence for prospect theory. First, each of the four parameters in the second specification are statistically significantly different than those of the null hypotheses, and each estimated parameter value falls on the side of the null predicted by prospect theory. Both curvature parameters are less than one, which suggests risk averse preference in gains and risk loving preferences in losses. The loss aversion parameter is estimated to be greater than one, which suggests buyers avoid choosing H due to loss aversion created by the potential inventory shortage. The probability weighting parameter is less than one, which suggests buyers are overly optimistic that they will be able to procure H when it is likely to be in high demand, and that they are pessimistic about their chances when H is not likely to be in high demand. A second result serving as evidence in support of the behavioral model over the standard model, both the AIC and BIC, which are criteria used to balance goodness of fit with parsimony, are lower for the second specification. This is the basis of Buyer Result 2.

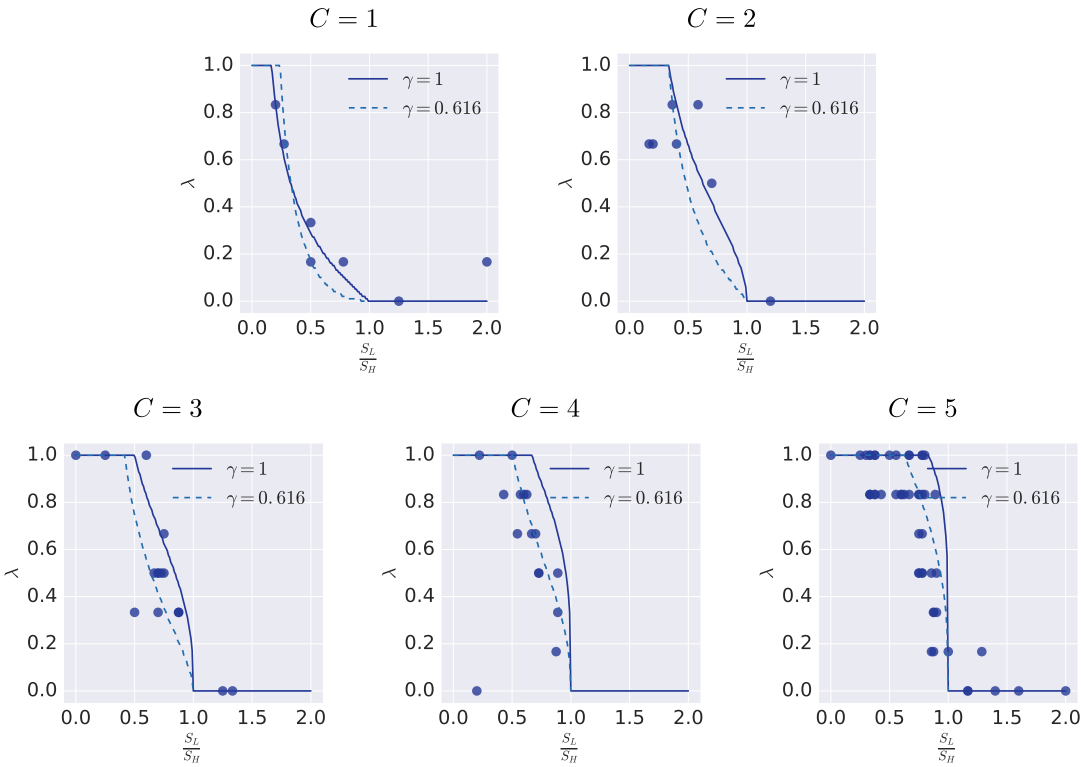
Buyer Result 2: When faced with a costly inventory shortage, buyers respond to the potential of not procuring a unit at H in a way that exhibits loss aversion, risk aversion over gains, risk seeking over losses, and probability weighting as predicted by prospect theory.

To demonstrate the effects behavioral buyers have on aggregate demand as compared to risk neutral expected utility maximizers, Figure 4 fits the probability weighting parameter value of $\gamma = 1$ as in the standard model and $\gamma = 0.616$ as suggested by the MLE results to the experimental data from the *Costly* treatment.[20] A full comparison of the risk neutral expected utility model and the prospect theory model would involve plotting three dimensional demand 'surfaces' as the absolute values of S_L and S_H matter for loss aversion, however such figures are difficult to convey on paper. Thus, we abstract from the effects of the value function by setting $\alpha = \beta = \phi = 1$ because doing so allows surpluses to be compared in relative terms of $\frac{S_L}{S_H}$. This allows the demand for H to be plotted in two dimensions in Figure 4. The experimental markets are plotted as points distributed across five panels according to H's capacity choice, C. For the experimental data the relative surplus for a market was determined by prices chosen by the H and L type subjects, and λ is the resulting percentage of the six buyers who chose H. The predictions for the fraction of buyers that should demand H under the standard model are

[20]The fitted value of $\gamma = 0.616$ is similar to previous estimates from Tversky and Kahneman (1992), Camerer and Ho (1994), Wu and Gonzalez (1996), and Berns et al. (2008) which range from 0.56 to 0.71.

shown as solid lines, while the (modified) behavioral predictions are represented by dashed lines. The figure shows that probability weighting generally leads to a lower expected number of buyers visiting H as compared to the standard model, which is the behavior we observe. However, the Figure also shows that when H can only serve a small fraction of the market (i.e. $C = 1$ in the experiment) probability weighting can actually increase expected demand for H in situations where L is offering relatively little surplus.

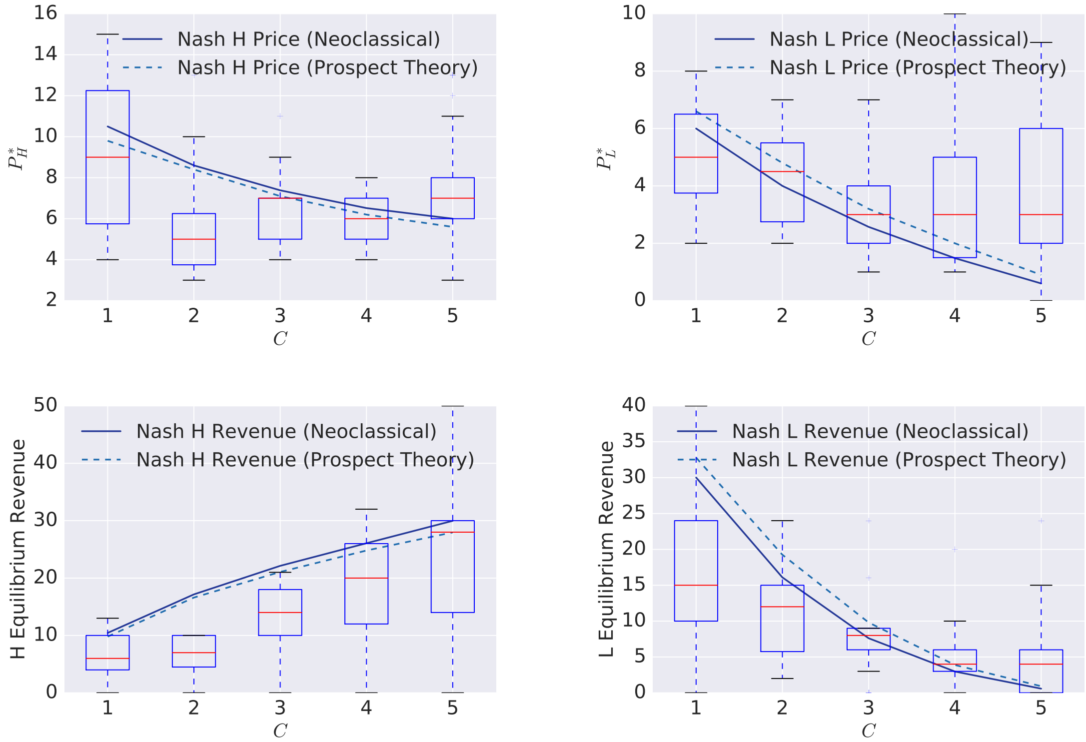
Figure 4: Demand for H when $\gamma = 1$ (Neoclassical) and $\gamma = 0.616$ (Estimated)



Given the strong evidence that buyers behaviorally adjust their search for H according to prospect theory, we now turn to the pricing (i.e. surplus) strategies of H and L, as well as the inventory strategy of H. While it is possible that firms in general, and our subject firms in particular, exhibit behavioral biases, our goal is to study the optimal (expected payoff maximizing) strategic choices of firms under the assumption that this is the objective most firms want to pursue rather than studying what market outcomes behavioral firms would pursue. Figure 5 plots the equilibrium prices and revenues for the experimental markets ($N = 6$). The solid lines are constructed with standard assumption of buyer behavior while the dashed lines

Figure 5: Equilibrium Pricing with Standard or Behavioral Buyers

For $N = 6$ (with Experimental Results)



were constructed for behavioral buyers. In both cases, the equilibrium is as described by Firm Hypothesis 2.

The box plots in Figure 5 map the experimental results on pricing and revenue for both standard and behavioral buyers. While firms tend to decrease their prices on average as capacity increases, it is difficult to determine if our firms are responding in a way that anticipates the behavioral response from buyers because the two sets of predictions are very similar and there is considerable noise in firm pricing (as opposed to the predicted pure strategy equilibrium price). Table 4 compares observed and predicted prices in a similar fashion to that done for the Costless treatment in Table 2. Optimal prices in the first specification are calculated based on standard assumptions of buyer behavior while the second specification calculates optimal prices based on the behavioral model with the specific parameter values estimated in the second specification in Table 3. Given the similar equilibrium point predictions between the two specifications for when $N = 6$, the estimates are very similar for both models. In both cases,

H is found to charge statistically higher prices when the capacity is small, however this difference decreases as the capacity increases. L does not differ statistically from either model's predicted prices, nor are there differences by capacity level. Finally, the inclusion of a dummy variable on the order in which subjects experienced the treatments shows no impact on the pricing strategies of H or L.

Table 4: Stage 2 Pricing in *Costly* Treatments

Dependent Variable: *Observed Price - Predicted Price*		
	Neoclassical	Prospect Theory
High Firm (H)	5.776**	4.79**
	(2.206)	(2.283)
Capacity (C)	0.053	0.028
	(0.268)	(0.282)
Capacity $\times$ High Firm	-1.043**	-1.002*
	(0.499)	(0.514)
Treatment Order	-0.121	-0.133
	(0.675)	(0.691)
Constant	-1.954	-1.388
	(1.409)	(1.455)
Observations	206	

Notes: ***, **, and * indicate significance at the 1%, 5% and 10% level, respectively.

Regarding capacity decisions, under the standard model H should have an inventory of $C = 5$. Assuming firms set optimal prices and that buyers exhibit behavioral preferences, the optimal inventory choice for H remains to be $C = 5$. Given the observed pricing patterns and buyer reactions, the average profit returns to H also suggest the optimal inventory level for H in the experiment is $C = 5$. However, the average observed inventory is this treatment is $C = 3.86$, which is statistically significantly different than each of the predictions above.

The two preceding paragraphs lead to Firm Result 2.

Firm Result 2: There is some evidence that average prices fall for both H and L type firms with the inventory level of H. However, there is considerable variation in pricing behavior, contrary to the equilibrium predictions, and L type firms tend to over price when H has a relatively large inventory. With respect to H's inventory decision, firms tend to set inventory levels below what is optimal according to both neoclassical and prospect theory models of buyers.

One feature of our experimental markets is that the number of buyers is small ($N = 6$). In such small markets, extremely low or extremely high probabilities, where the probability weighting function has the greatest distortionary effect, do not arise. But, we can easily identify what should happen in larger markets. Figure 6 repeats Figure 5 for the case of $N = 100$ buyers. The general patterns are the same for L, with prices and revenues are higher in both markets when buyers exhibit behavioral biases. Alternatively, H sees higher prices and revenues with behavioral biases when $N = 100$, rather than lower prices and revenues with similar buyers when $N = 6$.[21] Further, this pattern reveals that firms may be 'leaving money on the table' if these biases are ignored. For the case of $N = 100$ Figure 7 reports the percentage loss in H's revenue when the firms ignore the tendencies of behavioral buyers - that is when firms price as if buyers have standard preferences when in fact they have behavioral preferences. For inventory capacities of $\overline{C} < 10$ we find H's revenue falls by more than 25% from this error, and for $\overline{C} < 50$ we find revenue falls by more than 10%.

4 Conclusion

This paper provides managers of inventory systems with a perspective on how the behavioral tendencies of buyers can affect demand for a firm with a limited capacity. While other studies have considered the issue of what buyers do after failing to procure a desired item, this study focuses on the impact that anticipation of being shut out of the market has on buyers. We find the presence of a potentially costly inventory shortage yields a stochastic demand akin to that assumed in the newsvendor problem. Essentially, buyers in such a setting are engaged in a coordination game. Under standard assumptions, a firm offering a better deal and having a larger inventory would attract more buyers. However, this is not necessarily the case if buyers experience loss aversion and systematically mis-characterize the probability of inventory shortages, as is predicted in prospect theory. With loss averse and probability weighting buyers, a better deal and a larger inventory may not yield the anticipated increase in demand as buyers fixate on the perceived heightened chance of not being able to procure an item.

Using controlled laboratory experiments, we verify buyer behavior in the presence of po-

[21]Computational methods suggest the comparative statics between neoclassical and behavioral buyers found in the $N = 100$ case hold for H when $N \geq 8$.

Figure 6: Equilibrium Pricing with Standard or Behavioral Buyers

When $N = 100$

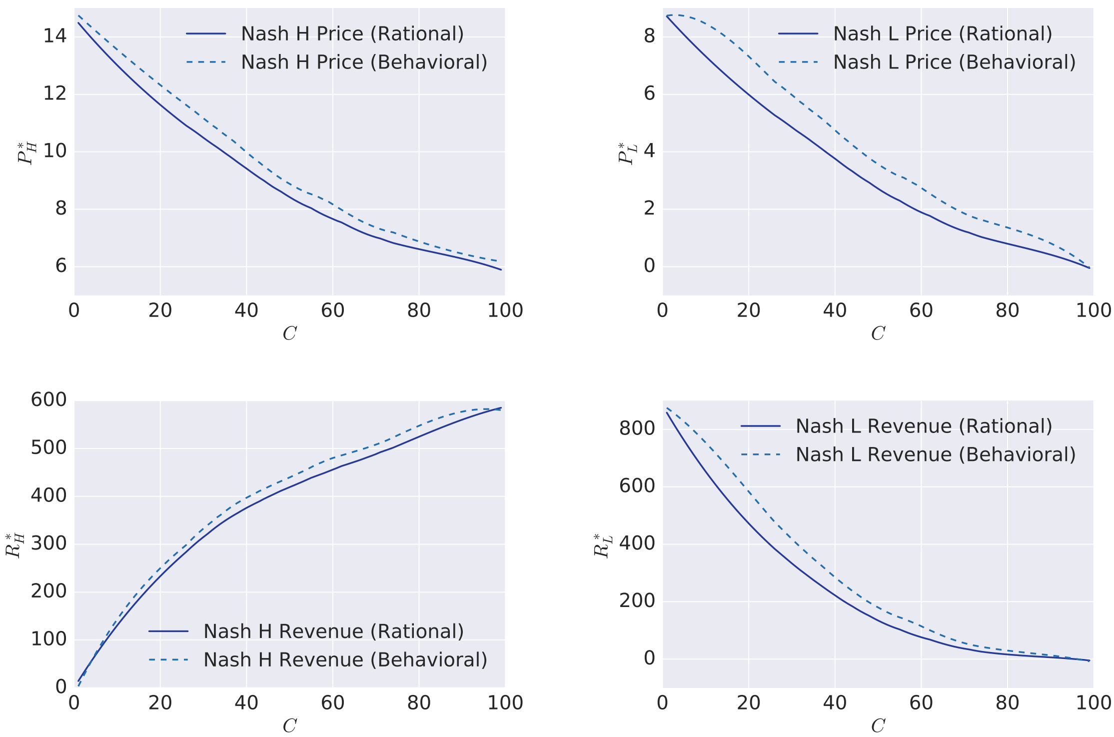
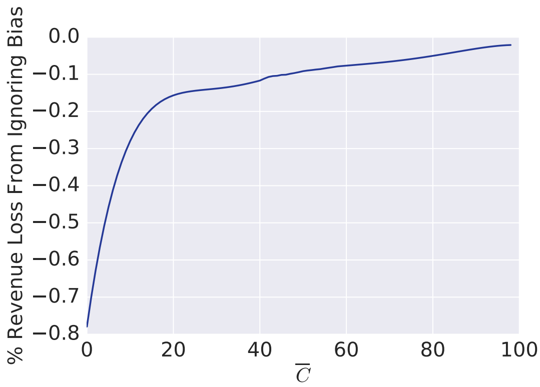


Figure 7: H's Revenue Loss from Ignoring Behavioral Buyers When $N = 100$



tentially costly inventory shortages is consistent with prospect theory. The results also affirm that buyer subjects understood the salient trade offs in the experiment, as they respond rationally to market conditions when the costs of inventory shortages are removed. Extending the experimental results to market simulations reveals that the demand effects due to probability weighting can have substantial results. An important takeaway from these results for inventory systems managers is that the negative demand effects due to potential inventory shortages may be reduced for many firms due to probability weighting buyers. While our work is suggestive, we believe that further theoretical, empirical, and behavioral research is needed to better understand how a firms' inventory and pricing strategies and customers' expectations affect market outcomes in competitive settings.

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5 Appendix

5.1 Subject Directions and Comprehension Questions

Items in italics were not observed by the subjects. Items in brackets were role specific.

Subject Instructions

Instructions, Page 1

In this experiment some people will be in the role of a firm and others will be in the role of a buyer. Buyers and firms will have the opportunity to buy and sell fictitious products with each other via their computers in a market. Firms earn money when they sell these items for more than their costs and buyers earn money when they purchase items at prices below their values. At the end of the experiment you will be paid based upon your earnings. Since you are paid based upon your decisions, it is important that you understand the directions completely. If you have any questions, please raise your hand and someone will come to your desk.

Instructions, Page 2 for Sellers

This experiment will last for several market periods. In each period you will be randomly matched with other people in the experiment.

In each market there are 2 Firms, A and B, and 6 buyers.

You will be Firm [A/B] and will retain the same role throughout the experiment. However, it is very important to understand how all the roles work.

All of the buyers value Firm A's product at $15.
All of the buyers value Firm B's product at $9.
A buyer can only purchase one unit in each period.

Each market period has three phases.

Phase 1: Firm A makes an inventory decision.
Phase 2: Firms A and B set their prices.
Phase 3: Buyers decide what to buy.

We will next describe each phase in detail.

Instructions, Page 2 for Buyers

This experiment will last for several market periods. In each period you will be randomly matched with other people in the experiment.

In each market there are 2 Firms, A and B, and 6 buyers.

You will be a buyer and will retain the same role throughout the experiment. However, it is very important to understand how all the roles work.

All of the buyers value Firm A's product at $15.
All of the buyers value Firm B's product at $9.
A buyer can only purchase one unit in each period.

Each market period has three phases.

Phase 1: Firm A makes an inventory decision.
Phase 2: Firms A and B set their prices.
Phase 3: Buyers decide what to buy.

We will next describe each phase in detail.

Instructions, Page 3

During Phase 1, Firm A will decide what quantity to order. This is the maximum amount that Firm A can sell in the market. Firm A can order between 0 and 5 units. Notice that this means Firm A cannot order enough units to serve all 6 buyers. Each unit Firm A orders costs Firm A $9 regardless of whether or not Firm A ultimately sells the unit or not. Units cannot be carried forward from one market period to the next.

Instructions, Page 4

During Phase 2, Firm B will learn how many units Firm A ordered. Firm B always has 6 units of available to sell each period and does not incur any cost for these units. Firm A and Firm B will both set their price for the current period. Both firms will set their prices in private, but both firms will learn of the other firm's price after both prices are set.

Instructions, Page 5 for Costly Treatment

During Phase 3, each buyer chooses to go to Firm A, Firm B, or neither.

Any buyer who goes to Firm B will buy a unit from Firm B at Firm B's price. These buyers' earnings will be $9 minus Firm B's price. Recall that Firm B always has enough units to serve all buyers.

If the total number of buyers who go to Firm A is less than or equal to the number of units that Firm A ordered, each of the buyers who goes to Firm A will buy a unit from Firm A at Firm A's price. These buyers' earnings will be $15 minus Firm A's price.

If the total number of buyers who go to Firm A is greater than the number of units that Firm A ordered, then Firm A experiences a stock out and the computer will randomly pick which buyers actually get to purchase Firm A's units.

The buyers who get to buy from Firm A will earn $15 minus Firm A's price.

The buyers who are not randomly selected to buy units from Firm A will earn $0.

Any buyer who chooses to go to neither firm will not buy a unit and will earn $0 for the period.

Instructions, Page 5 for Costless Treatment

During Phase 3, each buyer chooses to go to Firm A, Firm B, or neither.

Any buyer who goes to Firm B will buy a unit from Firm B at Firm B's price. These buyers' earnings will be $9 minus Firm B's price. Recall that Firm B always has enough units to serve all buyers.

If the total number of buyers who go to Firm A is less than or equal to the number of units that Firm A ordered, each of the buyers who goes to Firm A will buy a unit from Firm A at Firm A's price. These buyers' earnings will be $15 minus Firm A's price.

If the total number of buyers who go to Firm A is greater than the number of units that Firm A ordered, then Firm A experiences a stock out and the computer will randomly pick which buyers actually get to purchase Firm A's units. The buyers who get to buy from Firm A will earn $15 minus Firm A's price.

The buyers who are not randomly selected to buy units from Firm A will then have the option to either go to Firm B or not. If these buyers choose to go to Firm B they will earn $10 minus Firm B's price. If these buyers choose not to go to Firm B they will earn $0.

Any buyer who chooses to go to neither firm will not buy a unit and will earn $0 for the period.

Instructions, Page 6 for Sellers

Firm A's earnings for the period equal (Firm A's price × number of units Firm A sold) - ($9 × number of units Firm A ordered).

Firm B's earnings for the period equal (Firm B's price × number of units Firm B sold).

After each period, a table on the right-hand side of your screen will be updated with information about how many units Firm A ordered, the prices of both firms, and the number of units that each firm sold. Buyers' summary tables also record their own choice of which firm to visit. Keep in mind that all of the other people in your market are determined randomly each period.

At the end of the experiment, the amount you earned will be divided by 20 to determine your payment in US dollars. If you have any questions, please raise your hand. Remember that you are paid based upon your decisions so it is important that you understand the directions completely.

Instructions, Page 6 for Buyers

Firm A's earnings for the period equal (Firm A's price × number of units Firm A sold) - ($9 × number of units Firm A ordered).

Firm B's earnings for the period equal (Firm B's price × number of units Firm B sold).

After each period, a table on the right-hand side of your screen will be updated with information about how many units Firm A ordered, the prices of both firms, and the number of units that each firm sold. Buyers' summary tables also record their own choice of which firm to visit. Keep in mind that all of the other people in your market are determined randomly each period.

At the end of the experiment, the amount you earned will be divided by 10 to determine your payment in US dollars. If you have any questions, please raise your hand. Remember that you are paid based upon your decisions so it is important that you understand the directions completely.

Comprehension Questions

Subjects were presented with a scenario and had to answer a series of questions on the computer. The feedback depended on the answers given. In the scenario, X, Y and Z are all discrete uniform random variables in an attempt not to bias subsequent behavior.

X was equally likely to be 2, 3, 4 or 5.
Y was equally likely to be 9, 10, 11, 12, 13, 14 or 15.
Z was equally likely to be 1, 2, 3, 4, 5, 6, 7, 8 or 9.

The version below is for the Costly treatment. The version for the Costless treatment omits this.

Comprehension Questions, Page 1

Let's work through a few questions to make sure you understand the way the experiment will work. The following questions will not impact your payoff in any way. Instead, these questions are designed to ensure that everyone understands exactly how this experiment is structured and exactly how your payment will be calculated when the study is over. Please feel free to raise your hand at any point if you have any questions.

Comprehension Questions, Page 2

Suppose Firm A orders <X> unit(s) and sets a price of $<Y> while Firm B sets a price of $<Z>.

  If <X - 1> buyer(s) visit Firm A,

    ...how many units will Firm A sell?

Comprehension Questions, Page 3a (screen shown when subject's answer was correct)

Suppose Firm A orders <X> unit(s) and sets a price of $<Y> while Firm B sets a price of $<Z>.

If <X-1> buyer(s) visit Firm A,

...how many units will Firm A sell? You said: [subject's input]

That is correct.

Comprehension Questions, Page 3b (screen shown when subject's answer was incorrect)

Suppose Firm A orders <X> unit(s) and sets a price of $<Y> while Firm B sets a price of $<Z>.

If <X-1> buyer(s) visit Firm A,

...how many units will Firm A sell? You said: [subject's input]

That is incorrect. The correct answer is <X-1>. If Firm A orders at least as many units as it has customers visit, then it will always sell to whomever visits. Since Firm A ordered <X> unit(s) and only <X-1> buyers visited, Firm A would have been able to sell to each customer.

Comprehension Questions, Page 4

Suppose Firm A orders <X> unit(s) and sets a price of $<Y> while Firm B sets a price of $<Z>.

If <X-1> buyer(s) visit Firm A,

...how many units will Firm A sell? You said: [subject's input]

...The correct answer was <X-1>.

...how much profit will Firm A earn? Recall that profit is equal to (Firm A's price × number of units Firm A sold) - ($9 × number of units Firm A ordered).

Comprehension Questions, Page 5a (screen shown when subject's answer was correct)

Suppose Firm A orders <X> unit(s) and sets a price of $<Y> while Firm B sets a price of $<Z>.

If <X-1> buyer(s) visit Firm A,

...how many units will Firm A sell? You said: [subject's input]

...The correct answer was <X-1>.

...how much profit will Firm A earn? Recall that profit is equal to (Firm A's price × number of units Firm A sold) - ($9 × number of units Firm A ordered). You said: [subject's input]

That is correct.

Comprehension Questions, Page 5b (screen shown when subject's answer was incorrect)

Suppose Firm A orders <X> unit(s) and sets a price of $<Y> while Firm B sets a price of $<Z>.

If <X-1> buyer(s) visit Firm A,

...how many units will Firm A sell? You said: [subject's input]

...The correct answer was <X-1>.

...how much profit will Firm A earn? Recall that profit is equal to (Firm A's price × number of units Firm A sold) - ($9 × number of units Firm A ordered). You said: [subject's input]

That is incorrect. The correct answer is <(Y*(X-1) -9*(X))>. To find Firm A's profit, we multiply the price it charges, <Y>, by the number of units sold, <X-1>, and then subtract the costs that Firm A incurs for ordering units. Since Firm A is charged $9 for each unit it orders, and since Firm A ordered <X> units, these costs are 9 x <X>, or <9*X>. Therefore, the total earnings of Firm A is <Y> x <X-1> - 9 x <X> = <(Y*(X-1) - 9*(X))>.

Comprehension Questions, Page 6

Suppose Firm A orders <X> unit(s) and sets a price of $<Y> while Firm B sets a price of $<Z>.

If <X-1> buyer(s) visit Firm A,

...how many units will Firm A sell? You said: [subject's input]

...The correct answer was <X-1>.

...how much profit will Firm A earn? Recall that profit is equal to (Firm A's price × number of units Firm A sold) - ($9 × number of units Firm A ordered). You said: [subject's input]

...The correct answer was <(Y*(X-1) - 9*(X))>.

...how much profit will a buyer who visits Firm A earn?

Comprehension Questions, Page 7a (screen shown when subject's answer was correct)

Suppose Firm A orders <X> unit(s) and sets a price of $<Y> while Firm B sets a price of $<Z>.

If <X-1> buyer(s) visit Firm A,

...how many units will Firm A sell? You said: [subject's input]

...The correct answer was <X-1>.

...how much profit will Firm A earn? Recall that profit is equal to (Firm A's price × number of units Firm A sold) - ($9 × number of units Firm A ordered). You said: [subject's input]

...The correct answer was <(Y*(X-1) - 9*(X))>.

...how much profit will a buyer who visits Firm A earn? You said: [subject's input]

That is correct.

Comprehension Questions, Page 7b (screen shown when subject's answer was incorrect)

Suppose Firm A orders <X> unit(s) and sets a price of $<Y> while Firm B sets a price of $<Z>.

If <X-1> buyer(s) visit Firm A,

...how many units will Firm A sell? You said: [subject's input]

...The correct answer was <X-1>.

...how much profit will Firm A earn? Recall that profit is equal to (Firm A's price × number of units Firm A sold) - ($9 × number of units Firm A ordered). You said: [subject's input]

...The correct answer was <(Y*(X-1) - 9*(X))>.

...how much profit will a buyer who visits Firm A earn? You said: [subject's input]

This is incorrect. The correct answer is <15 - Y>. To calculate how much an individual will profit from purchasing a unit we take how much they value the good and subtract the price that is charged. In this case, the buyer values Firm A's product at $15 and Firm A decided to set a price of $<Y>. Therefore the profit to a buyer who buys from Firm A is the difference between these two values: 15 - <Y>, or <15 - Y>.

Comprehension Questions, Page 8

Suppose Firm A orders <X> unit(s) and sets a price of $<Y> while Firm B sets a price of $<Z>.

If <X + 1> buyers visit Firm A,

...how many units will Firm A sell?

Comprehension Questions, Page 9a (screen shown when subject's answer was correct)

Suppose Firm A orders <X> unit(s) and sets a price of $<Y> while Firm B sets a price of $<Z>.

If <X + 1> buyers visit Firm A,

...how many units will Firm A sell? You said: [subject's input]

That is correct.

Comprehension Questions, Page 9b (screen shown when subject's answer was incorrect)

Suppose Firm A orders <X> unit(s) and sets a price of $<Y> while Firm B sets a price of $<Z>.

If <X + 1> buyers visit Firm A,

...how many units will Firm A sell? You said: [subject's input]

That is incorrect. The correct answer is <X>. If Firm A orders fewer units than it has buyers visit then it will sell all the units it ordered. Since Firm A ordered <X> unit(s) and <X + 1> buyers visited, Firm A would have been able to sell all <X> of its units.

Comprehension Questions, Page 10

Suppose Firm A orders <X> unit(s) and sets a price of $<Y> while Firm B sets a price of $<Z>.

If <X + 1> buyers visit Firm A,

...how many units will Firm A sell? You said: [subject's input]

The correct answer was <X>.

...how much profit will Firm A earn?

Comprehension Questions, Page 11a (screen shown when subject's answer was correct)

Suppose Firm A orders <X> unit(s) and sets a price of $<Y> while Firm B sets a price of $<Z>.

If <X + 1> buyers visit Firm A,

...how many units will Firm A sell? You said: [subject's input]

The correct answer was <X>.

...how much profit will Firm A earn? You said: [subject's input]

That is correct.

Comprehension Questions, Page 11b (screen shown when subject's answer was incorrect)

Suppose Firm A orders <X> unit(s) and sets a price of $<Y> while Firm B sets a price of $<Z>.

If <X + 1> buyers visit Firm A,

...how many units will Firm A sell? You said: [subject's input]

The correct answer was <X>.

...how much profit will Firm A earn? You said: [subject's input]

That is incorrect. The correct answer is <(Y*X - 9*X)>. To find Firm A's profit, we multiply the price it charges, <Y>, by the number of buyers who visit the store and can purchase, <X>, and then subtract the costs that Firm A incurs for ordering units. Since Firm A is charged $9 for each unit it orders, and since Firm A ordered <X> units, these costs are 9 x <X>, or <9*X>. Therefore, the total earnings of Firm A is <Y> x <X> - 9 x <X> = <(Y*(X) - 9*(X))>.

Comprehension Questions, Page 12

Suppose Firm A orders <X> unit(s) and sets a price of $<Y> while Firm B sets a price of $<Z>.

If <X + 1> buyers visit Firm A,

...how many units will Firm A sell? You said: [subject's input]

The correct answer was <X>.

...how much profit will Firm A earn? You said: [subject's input]

...The correct answer was <(Y*X - 9*X)>.

...how much profit will a buyer who actually buys a unit from Firm A earn?

Comprehension Questions, Page 13a (screen shown when subject's answer was correct)

Suppose Firm A orders <X> unit(s) and sets a price of $<Y> while Firm B sets a price of $<Z>.

If <X + 1> buyers visit Firm A,

...how many units will Firm A sell? You said: [subject's input]

The correct answer was <X>.

...how much profit will Firm A earn? You said: [subject's input]

...The correct answer was <(Y*X - 9*X)>.

...how much profit will a buyer who actually buys a unit from Firm A earn?

You said: [subject's input]

That is correct.

Comprehension Questions, Page 13b (screen shown when subject's answer was incorrect)

Suppose Firm A orders <X> unit(s) and sets a price of $<Y> while Firm B sets a price of $<Z>.

If <X + 1> buyers visit Firm A,

...how many units will Firm A sell? You said: [subject's input]

The correct answer was <X>.

...how much profit will Firm A earn? You said: [subject's input]

...The correct answer was <(Y*X - 9*X)>.

...how much profit will a buyer who actually buys a unit from Firm A earn?

You said: [subject's input]

That is incorrect. The correct answer is <15 - Y>. To calculate a buyer's profit we take the value the buyer has for the good and subtract how much the buyer paid for the good. Since this buyer bought from Firm A, the value of the good is 15, and the price was <Y>. Therefore the buyer's profit is 15 - <Y>, or <15 - Y>.

Comprehension Questions, Page 14

Suppose Firm A orders <X> unit(s) and sets a price of $<Y> while Firm B sets a price of $<Z>.

If <X + 1> buyers visit Firm A,

...how many units will Firm A sell? You said: [subject's input]

The correct answer was <X>.

...how much profit will Firm A earn? You said: [subject's input]

...The correct answer was <(Y*X - 9*X)>.

...how much profit will a buyer who actually buys a unit from Firm A earn?

You said: [subject's input]

...The correct answer was <15 - Y>.

...what happens to a buyer who visits Firm A but is unable to purchase a unit?

Button: {"Has the option to visit Firm B"; "Is unable to purchase in this period"}

Comprehension Questions, Page 15a (screen shown when subject's answer was correct)

Suppose Firm A orders <X> unit(s) and sets a price of $<Y> while Firm B sets a price of $<Z>.

If <X + 1> buyers visit Firm A,

...how many units will Firm A sell? You said: [subject's input]

The correct answer was <X>.

...how much profit will Firm A earn? You said: [subject's input]

...The correct answer was <(Y*X - 9*X)>.

...how much profit will a buyer who actually buys a unit from Firm A earn?

You said: [subject's input]

...The correct answer was <15 - Y>.

...what happens to a buyer who visits Firm A but is unable to purchase a unit?

You said: [subject's input]

That is correct.

Comprehension Questions, Page 15b (screen shown when subject's answer was incorrect)

Suppose Firm A orders <X> unit(s) and sets a price of $<Y> while Firm B sets a price of $<Z>.

If <X + 1> buyers visit Firm A,

...how many units will Firm A sell? You said: [subject's input]

The correct answer was <X>.

...how much profit will Firm A earn? You said: [subject's input]

...The correct answer was <(Y*X - 9*X)>.

...how much profit will a buyer who actually buys a unit from Firm A earn?

You said: [subject's input]

...The correct answer was <15 - Y>.

...what happens to a buyer who visits Firm A but is unable to purchase a unit?

You said: [subject's input]

That is incorrect. If a buyer is unable to buy a unit from Firm A it will not have the opportunity to visit Firm B in the same period.

Comprehension Questions, Page 16

Suppose Firm A orders <X> unit(s) and sets a price of $<Y> while Firm B sets a price of $<Z>.

If <6 - X + 1> buyers visit Firm B,

...how much profit will Firm B earn?

Comprehension Questions, Page 17a (screen shown when subject's answer was correct)

Suppose Firm A orders <X> unit(s) and sets a price of $<Y> while Firm B sets a price of $<Z>.

If <6 - X + 1> buyers visit Firm B,

...how much profit will Firm B earn? You said: [subject's input]

That is correct.

Comprehension Questions, Page 17b (screen shown when subject's answer was incorrect)

Suppose Firm A orders <X> unit(s) and sets a price of $<Y> while Firm B sets a price of $<Z>.

If <6 - X + 1> buyers visit Firm B,

...how much profit will Firm B earn? You said: [subject's input]

That is incorrect. The correct answer is <(6 - X + 1)*Z>. To calculate Firm B's profit, we multiply how many buyers visit Firm B, <6 - X + 1> by the price that Firm B set, <Z>. This gives us <6 - X + 1> x <Z>, or <(6 - X + 1)*Z>.

Comprehension Questions, Page 18

Suppose Firm A orders <X> unit(s) and sets a price of $<Y> while Firm B sets a price of $<Z>.

If <6 - X + 1> buyers visit Firm B,

...how much profit will Firm B earn? You said: [subject's input]

...The correct answer was <(6 - X + 1)*Z>.

...how much profit will a buyer who visits Firm B earn?

Comprehension Questions, Page 19a (screen shown when subject's answer was correct)

Suppose Firm A orders <X> unit(s) and sets a price of $<Y> while Firm B sets a price of $<Z>.

If <6 - X + 1> buyers visit Firm B,

...how much profit will Firm B earn? You said: [subject's input]

...The correct answer was <(6 - X + 1)*Z>.

...how much profit will a buyer who visits Firm B earn? You said: [subject's input]

That is correct.

Comprehension Questions, Page 19b (screen shown when subject's answer was incorrect)

Suppose Firm A orders <X> unit(s) and sets a price of $<Y> while Firm B sets a price of $<Z>.

If <6 - X + 1> buyers visit Firm B,

...how much profit will Firm B earn? You said: [subject's input]

...The correct answer was <(6 - X + 1)*Z>.

...how much profit will a buyer who visits Firm B earn? You said: [subject's input]

That is incorrect. To calculate how much profit a buyer will earn from visiting Firm B take the value of Firm B's product, 9 and subtract the price charged by Firm B, <Z>. Therefore, the profit earned by the buyer would be 9 - <Z>, or <9 - Z>.

Comprehension Questions, Page 20

We are now ready to begin the experiment. If you do not have any questions, please click the BEGIN button below.