Purchasing, Pricing, and Quick Response in the Presence of Strategic Consumers

Gérard P. Cachon
The Wharton School, University of Pennsylvania, Philadelphia, Pennsylvania 19104,
cachon@wharton.upenn.edu

Robert Swinney
Graduate School of Business, Stanford University, Stanford, California 94305,
swinney@stanford.edu

We consider a retailer that sells a product with uncertain demand over a finite selling season. The retailer sets an initial stocking quantity and, at some predetermined point in the season, optimally marks down remaining inventory. We modify this classic setting by introducing three types of consumers: myopic consumers, who always purchase at the initial full price; bargain-hunting consumers, who purchase only if the discounted price is sufficiently low; and strategic consumers, who strategically choose when to make their purchase. A strategic consumer chooses between a purchase at the initial full price and a later purchase at an uncertain markdown price. In equilibrium, strategic consumers and the retailer make optimal decisions given their rational expectations regarding future prices, availability of inventory, and the behavior of other consumers. We find that the retailer stocks less, takes smaller price discounts, and earns lower profit if strategic consumers are present than if there are no strategic consumers. We find that a retailer should generally avoid committing to a price path over the season (assuming such commitment is feasible)—committing to a markdown price (or to not mark down at all) is often too costly (inventory may remain unsold) even in the presence of strategic consumers; the better approach is to be cautious with the initial quantity and then mark down optimally. Furthermore, we discuss the value of quick response (the ability to procure additional inventory after obtaining updated demand information, albeit at a higher unit cost than the initial order). We find that the value of quick response to a retailer is generally much greater in the presence of strategic consumers than without them: on average 67% more valuable and as much as 558% more valuable in our sample. In other words, although it is well established in the literature that quick response provides value by allowing better matching of supply with demand, it provides more value, often substantially more value, by allowing a retailer to control the negative consequences of strategic consumer behavior.

Key words: strategic consumer behavior; quick response; dynamic pricing; game theory

1. Introduction

Retailers are increasingly cognizant of the fact that modern consumers are educated, sophisticated, and willing to go to extraordinary lengths to purchase goods at the lowest possible price (Silverstein and Butman 2006). One common and powerful tactic consumers use to achieve this goal is to wait to purchase items only when they are on sale or clearance, a strategy aided by the fact that many retailers have predictable seasonal markdown patterns and offer deep discounts (e.g., Warner and Barsky 1995 report an average markdown of 39% on men's sweaters over a four-month period). Customers who behave in this manner are referred to in the academic literature as strategic or rational consumers: they are nonmyopic utility maximizers who recognize that a desired prod-

uct is likely to be reduced in price at some point in time, and they take these future markdowns into account, along with the expected availability of the product, when timing their purchasing decisions. All too often, as a result, strategic consumers choose to wait for markdowns, thereby denying retailers full-price sales (Rozhon 2004).

O'Donnell (2006) suggests that retailers can employ the following two tactics to induce strategic consumers to purchase products at full price: limit quantities to avoid the need for deep markdowns and promote affordable full prices. Perhaps no firm is more successful at implementing these tactics than Zara, the Spanish fashion retailer. Since its inception, Zara has recognized the importance of minimizing the number and severity of markdowns in its retail out-

lets. As a result, Zara generated only 15%–20% of its sales at markdown prices as compared to 30%–40% for its European peers (Ghemawat and Nueno 2003). To execute this strategy, Zara monitors and replenishes inventory frequently in stores (as often as twice a week) and produces 85% of its in-house inventory during the fashion season in which it is sold, as compared to 0%–20% at most of its competitors (Ghemawat and Nueno 2003). This quick response capability comes with a price: Zara produces much of its merchandise in Europe, which has relatively expensive labor compared to outsourced production in Asia, and Zara frequently expedites shipments via expensive transportation methods such as air freight (Ferdows et al. 2004).

In this paper, we study the interaction between a retailer's stocking decision and its markdown strategy in the presence of strategic consumers. Strategic consumers choose between buying an item early in the selling season at the full price and waiting until later in the season when the item may be marked down in price. Waiting for the potential deal has several drawbacks from the consumer's perspective: the strategic consumer values purchasing the item less at the end of the season than at the start of the season (e.g., a barbecue is more valuable at the start of summer than at the end of summer); the consumer does not know for sure whether the item will be marked down and, if so, by how much, i.e., the consumer faces pricing risk; and the item may not be available. Furthermore, availability and pricing are interconnected; if availability is high, the retailer is likely to offer a deep discount, whereas if inventory is limited (either because the retailer was conservative with her initial buy or because demand turns out to be greater than expected), the markdown will be modest, assuming the item is reduced in price at all. However, the potential benefit of waiting is clear: the markdown may indeed be substantial, thereby providing the consumer with a great value. For example, a strategic consumer may be willing to purchase a barbecue for $350 at the start of summer but may prefer the chance to purchase it at the end of summer for 50% off the initial price. Thus, in our model we seek to identify the set of equilibria with rational expectations: the retailer chooses an optimal order quantity and markdown price given her expectation of consumer behavior, and consumers choose an optimal purchasing strategy given their expectations of the behavior of the retailer and the other consumers.

Based on our model, we address several questions. Under what conditions is it optimal to restrict quantities when facing strategic consumers? How do strategic consumers influence a retailer's markdown strategy? Should a retailer commit to a price path

throughout the selling season (i.e., commit to a specific markdown price or to not mark down at all), or is the retailer better off with a dynamic pricing strategy that sets an optimal markdown given the available inventory and initial sales? What is the potential loss in profit if a retailer ignores strategic behavior? Finally, what is the value of quick response capabilities in the presence of strategic consumers? It is well known that quick response provides substantial value to a retailer when consumers are assumed to be entirely myopic (i.e., nonstrategic) because quick response allows a retailer to exploit updated information to better match supply with uncertain demand: with a quick response capability the retailer makes smaller inventory investments to mitigate the consequences of leftover inventory while using the ability to replenish to lessen the opportunity cost of lost sales. Is the incremental value of quick response greater or smaller in the presence of strategic consumers? The answer to this question is critical for understanding whether a firm should invest in quick response capabilities, such as Zara's investments in localized production and expedited shipments.

The remainder of this paper is organized as follows. Section 2 reviews the literature, and §3 describes the model. Section 4 analyzes the retailer's profit function, §5 addresses the consumer best response function, and §6 examines the equilibrium of the game. Section 7 considers the value of quick response inventory practices, §8 reports results from a numerical analysis, and §9 concludes with a summary of the answers to our research questions.

2. Related Literature

A wide variety of models characterized by supply-and-demand mismatches have recently emerged that explicitly incorporate consumer preferences or behavior. Examples include competing over price and service level for a random number of customers (Deneckere and Peck 1995), service level stimulating demand (Dana and Petruzzi 2001), capacity management via reservations in a restaurant facing uncertain demand (Alexandrov and Lariviere 2007), strategic joining of queues by arriving customers (Veeraraghavan and Debo 2008), and selling to rational consumers who learn about product value over time (Swinney 2008). The most relevant of these models to our analysis are those concerning multiperiod pricing.

Multiperiod pricing models are generally characterized by firms selling to consumers with unknown or heterogeneous valuations. Inventories are typically fixed, but the firm has the ability to change the price over time, exploiting this ability to price-discriminate between consumers or to discover information about

their valuations. For example, Lazear (1986) explains a variety of observed retail pricing phenomena via a fixed-inventory, two-period pricing framework with myopic consumers who purchase if their valuation of the product exceeds the price.

The addition of strategic consumers to the dynamic pricing problem is addressed by Besanko and Winston (1990), who model an uncapacitated, monopolistic retailer selling to a fixed number of heterogeneous, rational consumers over an arbitrary number of periods. The presence of strategic consumers leads to lower prices in each period than would be optimal with myopic consumers because the retailer competes intertemporally with itself (i.e., consumers have the option to wait until a later period to purchase). There is no uncertainty in the model; thus, there is no risk of stockouts or leftover inventory. More recently, several papers analyzed various aspects of the markdown problem with strategic consumers and fixed inventories, including multiunit customer demand (Elmaghraby et al. 2008), preannounced markdown policies with reservations (Elmaghraby et al. 2006), continuously declining consumer valuations (Aviv and Pazgal 2008), uncertain, evolving consumer valuations (Gallego and Şahin 2006), and heterogeneous consumer populations (Su 2007).

Several recent papers study how a retailer's initial stocking level is affected by strategic consumers. In each case the price path over the selling season is fixed (either exogenously set or chosen by the retailer at the start of the selling season). Yin et al. (2007) compare the efficacy of two different in-store display formats to manipulate consumer expectations regarding the availability of inventory. (In our model the retailer can influence consumer expectations only via its order quantity decision.) Liu and van Ryzin (2008) find that if consumers are risk averse, even if demand is deterministic, it is optimal for the retailer to create a rationing risk by understocking initially to induce consumers to purchase early. (In our model consumers are risk neutral.) Su and Zhang (2008b) conclude that several types of contracts can coordinate the supply chain when consumers are strategic, including, surprisingly, wholesale price contracts.

Our model is distinct along several key dimensions. In our model the retailer chooses both an initial stocking level and its markdown price dynamically. In other words, an optimal markdown is chosen given initial season sales and remaining inventory: a greater discount is offered if initial sales are weak or if there is a substantial amount of inventory remaining. (Cachon and Kök 2007 study a similar model of optimal dynamic markdowns, but they do not consider the presence of strategic consumers.) Consequently, in our model consumers face price risk: they do not know for certain how deep a future markdown may be. Furthermore, our results do not depend on the presence

of rationing/availability risk–even if consumers know in our model that a unit will be available in the markdown period, they still face a trade-off between purchasing now at the full price and waiting for the uncertain markdown. Yin et al. (2007), Liu and van Ryzin (2008), and Su and Zhang (2008b) assume a fixed price path, so consumers in their models do not face price risk. Instead, the interesting dynamics in their models are generated exclusively via rationing risk: a strategic consumer makes a trade-off between buying for sure at the full price now and buying later at the markdown price if the product is available.

Our model allows us to study the value of using dynamic pricing relative to committing to a fixed price path. Besanko and Winston (1990) find, in their model, that a retailer does benefit from a commitment to a price path. Aviv and Pazgal (2008) numerically evaluate whether a retailer is better off committing to a price path or choosing an optimal markdown price (given the initial fixed quantity of inventory) and find that commitment is generally better for the retailer. Dasu and Tong (2005) find that posted pricing schemes perform nearly optimally with fixed quantities and are usually preferred to contingent pricing schemes. Our results are different: when a retailer is able to choose the initial stocking quantity and its markdown price, the retailer is generally better off dynamically pricing rather than committing to a markdown price. As a result, in our setting, even if a retailer could commit to a price path (e.g., because of repeated game dynamics, as assumed by Liu and van Ryzin 2008), the retailer is generally better off not doing so.

Another important distinction of our analysis is that we investigate the value of quick response capabilities in the presence of strategic consumers. There is a broad literature documenting the large benefit of quick response in a supply chain (e.g., Barnes-Schuster et al. 2002, Eppen and Iyer 1997, Fisher and Raman 1996, Fisher et al. 2001, Iyer and Bergen 1997, Jones et al. 2001, Petruzzi and Dada 2001). However, to the best of our knowledge, the influence of strategic consumer behavior on the value of quick response has not been addressed.

3. Model Description

We model a single firm (the retailer) selling a single product over two periods. In the first period, the retailer sells the product at a fixed, exogenous full price p.[1] In the second period, the product is sold for

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[1] See the online appendix (provided in the electronic companion to this paper, which is available as part of the online version that can be found at http://mansci.journal.informs.org/) for a discussion of the initial pricing decision. Roughly speaking, we find that

Table 1   Characteristics of the Three Consumer Segments

Segment	Number	Period-1 valuation	Period-2 valuation
Myopic	$(1-\alpha)D$	v_M	n/a
Strategic	αD	v_M	$U[\underline{v}, \overline{v}]$
Bargain-hunting	∞	n/a	v_B

the markdown price s. We refer to the first period as the "full-price" period and the second period as the "sale" or "salvage" period.

The retailer has two decisions: sale price and initial stocking quantity. The sale price is chosen at the start of the second period to maximize revenue, $R(s, I)$, where I is the inventory available at the beginning of the second period. Prior to the first period, the stocking level q is chosen to maximize total expected profit, $\pi(q)$. We assume initially that production lead times are long enough that there is only one purchasing opportunity (this assumption is relaxed in §7).

The unit procurement cost to the retailer is c. Any inventory remaining at the end of the second period has zero value. The total number of customers that may purchase in the first period is a random variable $D \geq 0$ with distribution $F(\cdot)$, complementary cdf $\overline{F}(\cdot) = 1 - F(\cdot)$, and density $f(\cdot)$. We assume that D satisfies the following property.

DEFINITION 1. A continuous, nonnegative random variable X with density f satisfies the *monotone scaled likelihood ratio* (MSLR) property if, for all $\lambda \leq 1$ and x in the support of X, $f(\lambda x)/f(x)$ is monotonic in x.

This property is satisfied by many commonly used nonnegative distributions, including the gamma, Weibull, uniform, exponential, power, beta, chi, and chi-squared distributions (see the online appendix).[2] It is related to the monotone likelihood ratio (MLR) property (Karlin and Rubin 1956). In fact, if the distribution in question can be characterized by a scale parameter and satisfies the MLR property, then the distribution satisfies the MSLR property. In addition, for expositional purposes we assume $F(0) = 0$; i.e., the demand distribution has no mass at zero.

The population of consumers is divided into three distinct segments with the following characteristics (summarized in Table 1):

Bargain-Hunting Consumers. Bargain-hunting consumers purchase the product only when it is on sale.

These consumers do not even consider the product in the full-price period, possibly because they do not physically visit the retailer, because their valuation is less than p in the first period, or because they derive some utility from getting a good deal. Best Buy, for example, has famously labeled these customers as "devils," in contrast with Best Buy's favorite customers, referred to as "angels," who purchase at the full price (McWilliams 2004). In the sale period, each bargain hunter has value v_B for the item, and so their surplus from purchasing an item is $v_B - s$. There are an unlimited number of bargain hunters, and they purchase, like the other segments, whenever their surplus is nonnegative.[3] These consumers are analogous to the salvage market in a newsvendor formulation; as such, we make the usual assumption that $v_B < c$.

Myopic Consumers. Myopic consumers are the opposite of bargain hunters in the sense that they purchase only in the first period. The first period valuation of each myopic consumer is $v_M \geq p$, and these consumers comprise a fraction $(1 - \alpha)$ of the initial (first-period) demand. Thus, there are a total of $(1 - \alpha)D$ myopic consumers that visit the retailer in the first period, where $\alpha \in [0, 1]$ and D is a random variable. Myopic consumers purchase only in the first period (and at the full price) because they are unwilling to return to the retailer in the second period, because their value for the item in the second period is low (e.g., if their value is v_B or lower they clearly always prefer to purchase in the first period), or because they are simply shortsighted.[4]

Strategic Consumers. Both myopic and bargain-hunting consumers have only one decision: to purchase or not to purchase. The final group of consumers have an additional decision: *when* to purchase. Thus, these consumers are the "strategic segment" the sense that they are nonmyopic. They consider their surplus from purchasing the product at the full price and their surplus from purchasing the product on sale, choosing between the two to maximize their expected surplus. There are αD strategic consumers, and, like myopic consumers, they each have value v_M for the item in the first period. Consequently, variation in α alters the degree of sophistication in the consumer population without altering the underlying valuations or the number of consumers (i.e., there are always D consumers in the first period with value v_M, and a fraction α of these are strategic).

In the sale period, strategic consumers' values for the item are uniformly distributed in the interval

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the presence of strategic consumers lowers the optimal first-period price because the firm needs to offer those consumers an incentive to buy in the early period. Consequently, markdowns become less deep relative to the initial full price.

[2] The only result dependent on this assumption is the equilibrium existence result, for which the MSLR property is a sufficient, but not a necessary, condition. We have numerically observed that an equilibrium exists for many distributions that do not satisfy the MSLR assumption, such as the truncated normal.

[3] We have results for the comparable model with a finite number of bargain hunters. This change does not alter the qualitative results but does complicate the analysis of equilibrium.
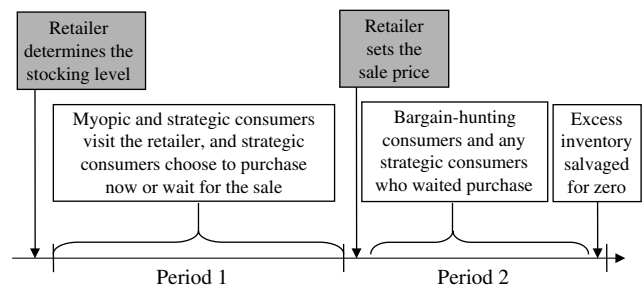
[4] Su (2008a, b) explores in detail how bounded rationality can influence the dynamics of a market.

$[\underline{v}, \bar{v}]$, where $\bar{v} \leq p$.[5] The upper bound on $\bar{v}$ ensures that markups are never optimal and that all consumer values weakly decline over time (because $p \leq v_M$), reflective of either seasonality in the product or discounting of future consumption.[6] For notational convenience, we define $G(\cdot)$ and $g(\cdot)$ to be, respectively, the distribution and density functions of strategic consumer valuations, with $\bar{G}(\cdot) = 1 - G(\cdot)$.

An alternative interpretation of our model is that strategic consumers are heterogeneous in their cost to delay their purchase or their discount factor: their period-2 value for the item is δv, where the discount factor, δ, is uniformly distributed on the interval $[\underline{v}/v, \bar{v}/v]$. Consumers with period-2 value $\bar{v}$ are the most patient (i.e., a delay in consumption is least costly to them), so they are the most likely to wait for a potential sale.[7]

The retailer and all consumers know the values of v_B, v_M, $\underline{v}$, $\bar{v}$, and α.[8] Each strategic consumer has private knowledge of his own second-period valuation at the start of the game. All strategic consumers arrive in the first period and, should they find the product in stock, decide to either purchase the product at that time or wait for the sale, whichever gives them the highest expected surplus, which is defined to be the difference between the consumer's valuation

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[5] Uniform values lead to a linear demand curve in the sale period. In addition, much of the consumer behavior and multiperiod pricing literature assumes uniformly distributed valuations (e.g., Desai et al. 2007, Lazear 1986). Although we have not established the existence of an equilibrium for more general distributions, we have observed numerically that an equilibrium exists with any increasing generalized failure rate distribution (see Lariviere 2006). Our subsequent results continue to hold analytically for more general distributions, conditional on the existence of an equilibrium.

[6] The model can also be solved with $\bar{v} \leq v_M$, so long as markups are not allowed (i.e., $s \leq p$). This case is notationally cumbersome and so is omitted for ease of exposition.

[7] An alternative model has consumer heterogeneity in their period-1 value for the item, $v \in [\underline{v}, \bar{v}]$, and a common discount factor, δ, so that their period-2 value is δv. In that model the consumers with the highest initial value have the most to lose from delayed consumption so they are the most likely to purchase in period 1. There are also some similarities to the model we consider. For example, the firm's period-2 discount still depends on period-1 inventory, and the strategic consumers are still more likely to wait as the expected sale price decreases (possibly because more inventory is purchased). However, that model may yield different qualitative insights.

[8] This is more restrictive than necessary, so we make this assumption for convenience. For example, a consumer needs to know her own valuation and needs to form an expectation that there will be a deep discount in the second period. We then require that the expectation is consistent with practice; e.g., if the consumer expects a deep discount 50% of the time, then in fact a deep discount is offered 50% of the time. We do not discuss how these expectations are formed, but see Liu and van Ryzin (2007) and Gans (2002) for models in which consumers learn about their environment.

Figure 1   Sequence of Events in Base Model

and the purchase price.[9] If the product is not available, the consumer receives zero surplus, and we assume that consumers purchase the product if their surplus is greater than or equal to zero. The surplus to a strategic consumer when purchasing in the first period is $v_M - p$, and we denote the expected surplus from purchasing in the sale period by $\psi(v)$, where v is a strategic consumer's second-period valuation.

The sequence of events is depicted in Figure 1. We model the game between the retailer and the strategic consumers as simultaneous. In other words, the retailer is incapable of credibly committing to a specific quantity (i.e., consumers do not observe the inventory level when making a purchasing decision).[10] Each player in the game (the retailer and each individual consumer) possesses beliefs about the actions of the other players. Throughout, we use the "hat" symbol (ˆ) to denote beliefs. For example, consumers believe that the stocking level of the retailer is $\hat{q}$. When we wish to make explicit the dependence of the retailer's profit on beliefs, we denote the profit function $\pi(q, \hat{v})$, where $\hat{v}$ represents the beliefs about consumer behavior. (The precise nature of $\hat{v}$ will be discussed later.) Similarly, the second-period surplus of a strategic consumer with valuation v can be written $\psi(v, \hat{v}, \hat{q})$, which highlights that each consumer possesses beliefs about both the actions of the retailer and the actions of other consumers.

We seek to identify a subgame perfect Nash equilibrium with rational expectations, which means that

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[9] Alternatively, strategic consumers might choose a purchase period before traveling to the store; the resulting model is identical, so long as these consumers are committed to shop in one of the two periods. An interesting extension incorporates an option to not shop at all and an explicit cost to shop, as in Dana and Petruzzi (2001). In that case, first-period demand can be increasing in the inventory level: by choosing a higher first-period availability, consumers are more likely to shop relative to the "not shop at all" option given that shopping is costly. This effect argues for a higher initial stocking quantity, which counteracts the effect we identify for a lower initial stocking quantity.

[10] We also considered an extension of the model in which consumers observe q before making their decisions (i.e., a sequential game with the retailer moving first). This clearly works to the advantage of the retailer: by directly influencing consumer expectations the retailer can be no worse off. Nevertheless, our qualitative conclusions continue to hold.

each player (consumers and the firm) chooses optimal actions given their belief about how the others will play and that those beliefs are correct.[11] Hence, all consumers have the same beliefs about the retailer's behavior and the behavior of other consumers, which leads to the following preliminary result.

LEMMA 1. *In equilibrium, there exists some $v^* \in [\underline{v}, \overline{v}]$ such that all strategic consumers with second-period value less than v^* purchase in the first period and all consumers with value greater than v^* wait for the sale period. A consumer with value v^* is indifferent between purchasing in the first or second period.*

PROOF. The proofs of all lemmas appear in the online technical appendix. □

As a result of Lemma 1, we may simplify the action space of the strategic consumers. Rather than concern ourselves with the purchasing decision of each individual consumer, we may consider instead the equilibrium value threshold $v^*(\hat{q})$ that is induced by $\hat{q}$. We refer to $v^*(\hat{q})$ as the consumer best response correspondence. (Note that we do not claim now, nor is it true in general, that there is a unique best reply to a given $\hat{q}$.) Given Lemma 1 and $v^*(\hat{q})$, we may now define the equilibrium to this game. The following three sections proceed to characterize the equilibrium.

DEFINITION 2. A subgame perfect Nash equilibrium with rational expectations, (q^*, v^*), to the game between the retailer and strategic consumers satisfies:

1. The retailer plays a best response given beliefs about consumer behavior: $q^* \in \arg\max_{q \geq 0} \pi(q, \hat{v})$;

2. The consumers play a best response given beliefs about retailer behavior: $v^* \in v^*(\hat{q})$;

3. Beliefs are consistent with the equilibrium outcome: $\hat{q} = q^*$, $\hat{v} = v^*$.

4. The Retailer's Profit Function

In this section, we derive the retailer's optimal sale price (chosen at the start of the second period), analyze the retailer's initial stocking decision, and demonstrate that the retailer's profit function is quasiconcave in q, a critical feature to prove existence of an equilibrium in §6.

4.1. Pricing in the Sale Period

As a consequence of Lemma 1, the retailer's only rational belief is that the proportion $\xi \equiv 1 - \overline{G}(\hat{v})\alpha$ of total first-period demand attempts to purchase in the

first period. (Although some consumers may be indifferent between the two periods, indifferent consumers have measure zero and their behavior is therefore inconsequential to the retailer.) The retailer's expected profit given belief $\hat{v}$ is thus

$$\pi(q, \hat{v}) = \mathbb{E}[p \min(q, \xi D) - cq + \max_s R(s, I)], \quad (1)$$

where the on-hand inventory at the start of the sale period is $I = (q - \xi D)^+$. Given a sale price s, consumers purchase the product if their valuation weakly exceeds s; thus, the retailer's second-period revenue function is

$$R(s, I) = \begin{cases} s\min(\overline{G}(s)\alpha D, I) & \text{if } \overline{v} \geq s \geq \hat{v}, \\ s\min(\overline{G}(\hat{v})\alpha D, I) & \text{if } \hat{v} > s > v_B, \\ sI & \text{if } s \leq v_B. \end{cases}$$

The following lemma demonstrates the form of the optimal sale-period pricing policy given this revenue function.

LEMMA 2. *Define the critical demand levels $D_l = q/(\xi + s_m \overline{G}(s_m)\alpha/s_l)$, $D_m = q/(\xi + \overline{G}(s_m)\alpha)$, and $D_h = q/\xi$, where l, m, and h stand for low, medium, and high, respectively. Then, given a demand level D, there is a unique optimal sale price determined by*

$$s^*(D) = \begin{cases} s_h(D) & \text{if } D_m < D \leq D_h, \\ s_m & \text{if } D_l < D \leq D_m, \\ s_l & \text{if } D \leq D_l, \end{cases}$$

where $s_l = v_B$ is the low sale price,

$$s_m = \arg\max_{s \geq \hat{v}} s(\overline{v} - s)$$
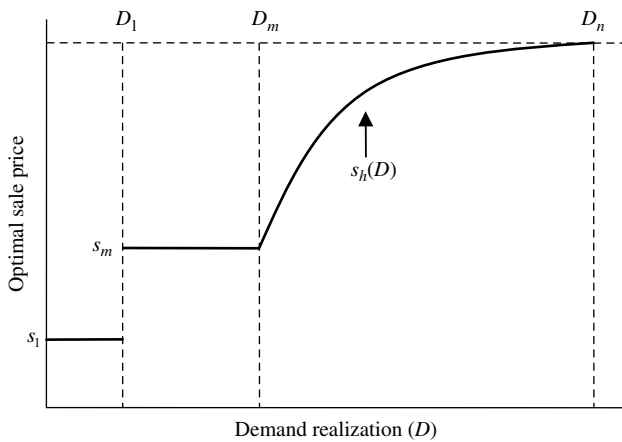
is the medium sale price, and

$$s_h(D) = (\overline{v} - \underline{v})(D - q)/\alpha D + \hat{v}$$

is the high sale price, which is contingent on the demand realization and remaining inventory.

The form of the optimal policy is natural (see Figure 2). If demand is greater than D_h, the retailer sells out in the first period. If demand is between D_h and D_m, the retailer sets the highest price that clears inventory (selling only to the strategic segment). If demand is between D_m and D_l, the retailer has ample inventory and chooses the revenue-maximizing price to serve the strategic segment (and some inventory is left unsold). Finally, if demand is less than D_l, there is a large amount of inventory at the start of the sale period, so the retailer prices to clear all remaining inventory with the lowest sale price. In fact, if all consumers are myopic (i.e., $\alpha = 0$) then $D_l = q$, which implies that the clearance price is deterministically equal to s_l in period 2.

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[11] The concept of "rational expectations" here is useful for expositional purposes but is not strictly necessary. In a Nash equilibrium each player believes that the other players will choose the equilibrium strategies, and in equilibrium all players have an incentive to do so. This is also the case in our model. Furthermore, there is no need to draw on a more elaborate equilibrium concept, such as Bayesian equilibrium.

Figure 2   Optimal Sale Price as a Function of D

Figure 3   (a) Example of Nonconcavity of the Retailer's Profit Function with Deterministic Demand, All Strategic Consumers Purchasing in Period Two, and All Strategic Consumers with Valuations Equal to s_h (m Denotes Slope or Margin); (b) Retailer's Profit Function in the Same Example with $\alpha = 0$

(a) αD strategic consumers and subgame perfect salvaging

(b) D myopic consumers

### 4.2.   Initial Inventory Decision

By substituting the optimal sale price function from Lemma 2 into the retailer's profit function in (1), we may analyze the retailer's initial inventory decision. The following lemma demonstrates that the retailer's profit function is unimodal.

LEMMA 3. *The retailer's profit $\pi(q, \hat{v})$ is quasiconcave in q, and the optimal order quantity is determined by the unique solution to the first-order condition,*

$$\frac{d\pi(q, \hat{v})}{dq} = p - c - pF(D_h) + s_l F(D_l)$$

$$+ \int_{D_m}^{D_h} (2s_h(x) - \bar{v}) \, dF(x) = 0. \qquad (2)$$

Unlike the profit function in a traditional newsvendor model (which corresponds to our model with no strategic consumers, $\alpha = 0$), the retailer's profit function is generally not concave. To illustrate why, Figure 3(a) plots the retailer's profit function in the simple case with deterministic demand, $\bar{v} = \underline{v} = s_h$ (i.e., homogeneous strategic consumers), $(1 - \alpha)D$ myopic consumers, and αD strategic consumers, when the retailer expects all strategic consumers to purchase in the sale period. The retailer sells the first $(1 - \alpha)D$ units to the myopic consumers and the next αD units to the strategic consumers at a lower marginal rate. Only when initial inventory is quite ample, above $D + (s_h - s_l)\alpha D/s_l$, does the retailer choose to clear at the low sales price, s_l. Thus, the retailer's profit function exhibits a concave-convex shape. Figure 3(b) plots the corresponding profit function for a newsvendor model ($\alpha = 0$). Note, relative to the maximum profit at the optimal order quantity, with strategic consumers the retailer is *less* sensitive to underordering (i.e., the profit function is flatter) and the retailer is *more* sensitive to overordering (i.e., the profit function is steeper).
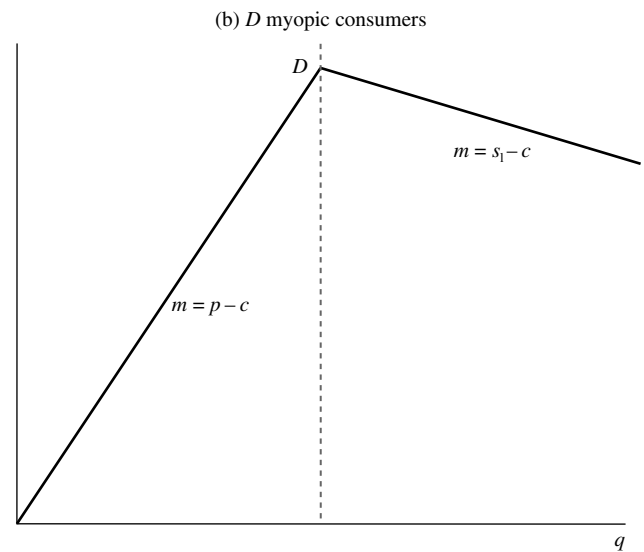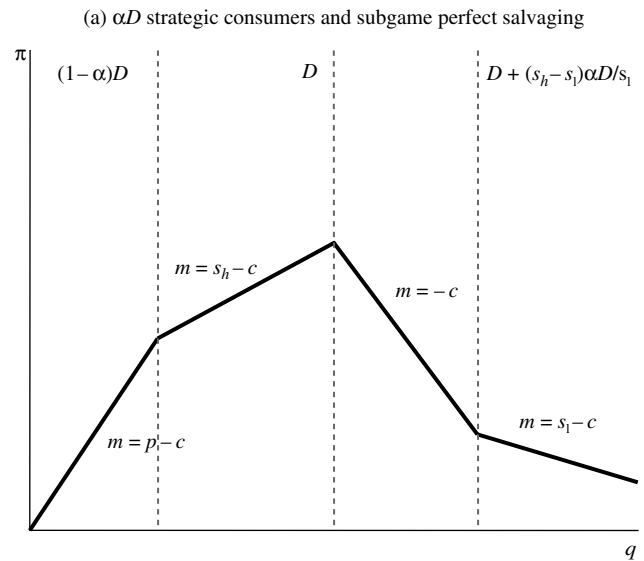
5.   Best Response of Strategic Consumers

According to Lemma 1, the strategic consumer with value $v^*(\hat{q})$ is indifferent between purchasing in either period. This consumer's second-period surplus is nonzero only if $s < v^*(\hat{q})$, and from Theorem 1, this occurs only if the retailer chooses the lowest sale price (i.e., $s = s_l = v_B$, which occurs when $D < D_l$). Hence, the expected surplus for the indifferent strategic consumer is

$$(v^*(\hat{q}) - v_B) \times \Pr(D < D_l \text{ and}$$

$$\text{the consumer receives a unit}). \qquad (3)$$

With the lowest sale price there are both strategic and bargain-hunting consumers vying to purchase limited inventory. As a result, the probability that the indifferent strategic consumer actually receives a unit in the sale period, which we call the fill rate, is not a priori guaranteed to be 100%. Hence, we must discuss how inventory is allocated when demand exceeds supply in the salvage period.

We introduce a new parameter $\theta \in [0, 1]$ which represents the level of optimism of the strategic segment. Suppose demand in the second period forms a queue composed of both strategic and bargain-hunting consumers. Customers are served in first-come-first-served order until inventory (I) is depleted. Strategic consumers represent every $1/\theta$th customer in the queue until there are no more strategic consumers and all remaining consumers are bargain hunters (i.e., strategic consumers are uniformly distributed among the first $(1 - \xi)D/\theta$ customers in the queue).[12] If $\theta = 1$, then all of the strategic consumers are at the front of the queue (this is the assumption made in Su and Zhang 2008b). If $\theta = 0$, then all strategic consumers are at the end of the queue; because there is an infinite number of bargain hunters, this implies that strategic consumers are never served.

As a result of this supply allocation mechanism, the effective inventory available to strategic consumers in the sale period is θI, and the probability term in (3) is the second-period fill rate conditional on $D < D_l$, which is provided in part (i) of the following lemma.

Lemma 4. (i) *Define* $\theta_c = s_l/s_m$ *and let* $D_\theta = \theta q/ (1 - \xi + \theta \xi)$. *Assume consumers' expectation of the firm's quantity is correct,* $\hat{q} = q$, *and the firm's expectation of the indifferent strategic consumer is correct,* $\hat{v} = v^*(\hat{q})$. *Then, the probability that the indifferent strategic consumer purchases and receives a unit in the sale period is*

$$F(D_l) \qquad\qquad\qquad if\ \theta \geq \theta_c,$$

$$F(D_\theta) + \int_{D_\theta}^{D_l} \frac{\theta I}{(1 - \xi)x}\, dF(x) \quad otherwise.$$

(ii) *The consumer best response* $v^*(\hat{q})$ *satisfies*

$$\lim_{\hat{q} \to 0} v^*(\hat{q}) = \bar{v} \quad and$$

$$\lim_{\hat{q} \to \infty} v^*(\hat{q}) = \max\{\underline{v}, v_M - p + v_B\}.$$

Lemma 4 demonstrates that if consumers are sufficiently optimistic (i.e., $\theta \geq \theta_c$), then there is no

rationing risk. In other words, for all $\theta \geq \theta_c$, a strategic consumer expects to receive (with probability 1) a unit in the sale period conditional that the lowest sale price is chosen. Consequently, for all $\theta \in [\theta_c, 1]$ there exists the same set of equilibria, and the retailer's profit and the consumers' expected surplus in these equilibria are independent of θ. For simplicity, we assume $\theta \geq \theta_c$ for the remainder of our analysis.[13]

The second part of Lemma 4 shows that, as might be expected, if the retailer chooses a very low initial inventory, all strategic consumers purchase in the first period. If the retailer chooses a very high initial inventory, then all strategic consumers prefer buying in the sale period for certain at the discounted price v_B to buying at the full price. These results are useful for demonstrating the existence of an equilibrium.

We now note the crucial role of the bargain-hunting segment. Suppose there were no bargain-hunting consumers but there continues to exist a strategic consumer with period-2 value $v^*(\hat{q})$ who is indifferent between purchasing in either period. Because there are no bargain hunters, all consumers in period 2 are strategic and have value $v^*(\hat{q})$ or higher (as per Lemma 1). The retailer's optimal period-2 price is then never less than $v^*(\hat{q})$. It follows that the indifferent strategic consumer's period 2 surplus is zero, which means that consumer strictly prefers to purchase in period 1. Thus, we have established a contradiction—there cannot be an indifferent strategic consumer. Hence, without the possibility of a deep discount created by bargain hunters, all strategic consumers rationally purchase in period 1; i.e., they always behave as if they are myopic.

6. Equilibrium

We are now prepared to demonstrate the existence of an equilibrium. In addition, we derive a result comparing the equilibrium order quantity with strategic consumers ($\alpha > 0$) to the optimal order quantity without strategic consumers ($\alpha = 0$). In what follows, the superscript m signifies optimal values when all consumers are myopic ($\alpha = 0$).

Theorem 1. *There exists a subgame perfect Nash equilibrium with rational expectations* (q^*, v^*) *to the game*

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[12] Suppose customers arrive with a Poisson process and $1/\theta$ is the probability that a customer is a strategic customer until all strategic customers are accounted for. As customers are atomistic, this process will resemble ours. See Lariviere and Van Mieghem (2004) for an analysis of how strategic customer behavior might lead to an arrival process that resembles a Poisson process.

[13] Our results qualitatively hold (e.g., quick response can be more valuable with strategic consumers, and dynamic pricing may be preferred to static pricing) even with $\theta_c > \theta$, but the analysis is more complex, and the impact of strategic behavior is lessened—if strategic consumers expect to have a low fill rate in the sale period, then they are more likely to purchase in the first period, thereby acting more like myopic consumers. When $\theta = 0$, all strategics always act myopically because they expect that they will never be able to purchase in the sales period if the sale price is low (equal to s_l)—hence, there can be no "indifferent" consumer because any such consumer receives zero surplus from waiting for the sale.

between the retailer and strategic consumers, and any equilibrium satisfies $q^* \leq q^m$ and $\pi^* \leq \pi^m$.

PROOF. (i) *Existence.* An equilibrium, (q^*, v^*), exists if (1) $\pi(q, \hat{v})$ is quasiconcave in q, and (2) a solution to

$$\left. \frac{\partial \pi(q, \hat{v})}{\partial q} \right|_{\hat{v}=v^*(q)} = 0 \tag{4}$$

exists. Note that, from Lemma 4, $\lim_{q \to 0} v^*(q) = \bar{v}$, and given $v^*(q)$,

$$\lim_{q \to 0} D_l = \lim_{q \to 0} D_m = \lim_{q \to 0} D_h = 0.$$

Similarly, $\lim_{q \to \infty} v^*(q) = \max\{\underline{v}, v_M - p + v_B\}$, and

$$\lim_{q \to \infty} D_l = \lim_{q \to \infty} D_m = \lim_{q \to \infty} D_h = \infty.$$

The expression for the high sale price, $s_h(D)$, satisfies $\lim_{q \to \infty} |s_h(D)| < \infty$ and $\lim_{q \to 0} |s_h(D)| < \infty$ for $D \in [D_m, D_h]$. By taking the limits of the first-order condition evaluated at $\hat{v} = v^*(q)$, we then see that

$$\lim_{q \to 0} \left. \frac{\partial \pi(q, \hat{v})}{\partial q} \right|_{\hat{v}=v^*(q)} = p - c > 0 \quad \text{and}$$

$$\lim_{q \to \infty} \left. \frac{\partial \pi(q, \hat{v})}{\partial q} \right|_{\hat{v}=v^*(q)} = s_l - c < 0.$$

By the continuity of $(\partial \pi(q, \hat{v})/\partial q)|_{\hat{v}=v^*(q)}$, a solution to (4) must exist; hence, combined with the results of Lemmas 2 and 3, an equilibrium must exist.

(ii) *Equilibrium Comparison.* Let $\pi^m(q)$ be the retailer's profit function with purely myopic consumers (i.e., with $\alpha = 0$). This is equivalent to the typical newsvendor model with salvage at price s_l, which yields

$$\frac{\partial \pi^m(q)}{\partial q} = p - c - pF(q) + s_l F(q) = 0.$$

It follows that

$$\frac{\partial \pi^m(q)}{\partial q} - \frac{\partial \pi(q, \hat{v})}{\partial q}$$

$$= p(F(D_h) - F(q)) + s_l(F(q) - F(D_l))$$

$$+ \int_{D_m}^{D_h} (2s_h(x) - \bar{v}) \, dF(x). \tag{5}$$

Because $s_h(x) \geq \bar{v}/2$, each term in (5) is positive. Therefore, for any $\hat{v}$ the optimal myopic order quantity is (weakly) greater than the optimal order quantity with strategic consumers, and the optimal profits exhibit the same relationship. The result also holds for any equilibrium belief. □

Theorem 1 demonstrates that the retailer orders less with strategic consumers than with myopic consumers; by lowering its initial inventory, the retailer

raises the expected period-2 price (markdowns become less generous), which induces some strategic consumers to purchase at the full price. Others have also found that the presence of strategic consumers causes a firm to lower its order quantity (e.g., Liu and van Ryzin 2008, Su and Zhang 2008b). However, the mechanism by which this result is obtained is different: they depend on rationing risk, whereas in our model the result is due to price risk—strategic consumers expect that they will receive a unit in the markdown period, but they do not know what the price will be.

We also note that, although Theorem 1 proves the existence of an equilibrium, multiple equilibria to the game can exist. However, in our numerical analysis (discussed in §8) we found multiple equilibria in only 2.5% of our sample (21 instances of 840 cases). Thus, although multiple equilibria may occur, it appears that such cases are rare.

7. The Value of Quick Response

In this section, we analyze a retailer with quick response capabilities and explore precisely how strategic consumer behavior affects the value of quick response. To model quick response, we modify the base model described in §3 by allowing the retailer to submit and receive an additional order at the start of the first period after observing demand, D. The original order before the selling season remains (i.e., before observing demand D), and those units cost the retailer c_1 per unit. Units procured in the second order cost c_2 per unit, where $p \geq c_2 \geq c_1$, and they are received prior to any potential stockout (i.e., all demand in the first period is served).[14] With purely myopic consumers, this model is equivalent to the quick response with the reactive capacity model in Cachon and Terwiesch (2009). As such, we use the subscript r to denote "reactive capacity" where relevant. Figure 4 depicts the new sequence of events.

Our first result mirrors Lemma 2 by providing the form of the optimal second-period pricing policy with quick response.

LEMMA 5. *Assume the retailer has quick response capabilities. (i) Let* $s_r = \arg\max_{s \geq \hat{v}} (s - c_2)\bar{G}(s)$ *and let*

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[14] The results remain qualitatively unchanged if excess first-period demand is lost prior to receiving a replenishment via quick response. In that case quick response does not help to match supply with demand in period 1, but it does reduce the expected price in period 2. Consequently, with quick response the firm orders less and more strategic consumers decide to purchase in period 1. Furthermore, our results extend to the case of an imperfect demand signal. When the demand signal is pure noise, quick response provides no value, and that model is identical to our original model without quick response.

Figure 4   Sequence of Events with Quick Response
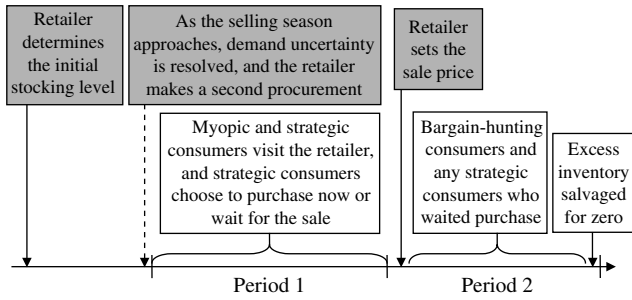
$D_r = q/(\xi + \bar{G}(s_r)\alpha)$. Then, if $c_2 \le \bar{v}$, given a demand level D, there is a unique optimal sale price determined by

$$s^* = \begin{cases} s_r & \text{if } D_r < D, \\ s_h(D) & \text{if } D_m < D \le D_r, \\ s_m & \text{if } D_l < D \le D_m, \\ s_l & \text{if } D \le D_l, \end{cases}$$

where D_l, D_m, s_l, s_m, and $s_h(D)$ are as in Lemma 2, and $D_r \le D_h$ from Lemma 2. If $c_2 > \bar{v}$, then reactive capacity is never used to satisfy sale-period demand, and the optimal sale price is identical to that derived in Lemma 2.

(ii) *The retailer's profit with quick response, $\pi_r(q, \hat{v})$, is quasiconcave in q.*

Like in the model without quick response, the retailer offers a deep discount, s_l, only when demand is sufficiently low, $D \le D_l$. With slightly higher demand, inventory is sufficiently restrictive that the retailer chooses the revenue-maximizing price, s_m, leaving some units unsold. If demand is yet higher, the retailer chooses a price to clear inventory. However, the retailer never prices higher than s_r, which is the optimal price when the marginal unit is procured at c_2.

As a consequence of Lemma 5, the consumer best response function is identical with and without quick response. The consumer best response depends only on the probability of a low sale price (s_l), and this probability is the same for a given q with and without quick response: if the retailer's optimal action is to offer a deep discount to clear excess inventory, then quick response is clearly of no use to the retailer. (Whereas the addition of quick response does not change $v^*(\hat{q})$, the equilibrium in general does change.) In other words, the ability of the retailer to obtain an inventory replenishment after learning demand information does not alter consumer behavior because that capability is put to use only when demand is high and the discount in the sale period is relatively small. This is a robust result because it is never profitable to

both procure additional inventory and serve the lowest value segment.

Analogous to Theorem 1, an equilibrium exists in the quick-response game.[15] Furthermore, quick response induces the retailer to lower its initial stocking level, and the retailer earns a higher profit with quick response than without.

THEOREM 2. *There exists a subgame perfect Nash equilibrium with rational expectations, (q_r^*, v_r^*), to the game between the retailer with quick response and strategic consumers. It yields equilibrium expected profit π_r^* and satisfies $q_r^* \le q^*$ and $\pi_r^* \ge \pi^*$. Furthermore, if*

$$\frac{v_M - p}{\bar{v} - v_B} \ge \frac{c_2 - c_1}{c_2 - v_B}, \tag{6}$$

then in equilibrium all strategic consumers purchase in the first period.

PROOF. (i) *Existence.* The proof is identical to Theorem 1.

(ii) *Equilibrium Comparison.* We note that the model without quick response is equivalent to the model with quick response, with $c_2 = p$. By analyzing how equilibrium quantities and profits change as a function of c_2, we may derive the results. There are subsequently three cases: $c_2 \le \bar{v}$ and $s_r = (\bar{v} + c_2)/2$ or $s_r \ne (\bar{v} + c_2)/2$ or $c_2 > \bar{v}$. By substituting the optimal sale period pricing policy from Lemma 5 into the retailer's profit function and taking partial derivatives, we have, for the $s_r \ne (\bar{v} + c_2)/2$ case or the $c_2 > \bar{v}$ case,

$$\frac{\partial \pi_r}{\partial c_2} = \int_{D_h}^{\infty} (q - \xi x)\, dF(x) \le 0 \quad \text{and} \quad \frac{\partial^2 \pi_r}{\partial q \partial c_2} = \bar{F}(D_h) \ge 0.$$

If $s_r = (\bar{v} + c_2)/2$, then

$$\frac{\partial \pi_r}{\partial c_2} = \int_{D_r}^{\infty} (q - (\xi + \bar{G}(s_r)\alpha)x)\, dF(x) \le 0 \quad \text{and}$$

$$\frac{\partial^2 \pi_r}{\partial q \partial c_2} = \bar{F}(D_r) \ge 0.$$

From the implicit function theorem and the fact that the indifferent consumer's surplus (and hence the consumer best response) contains no explicit dependence on c_2,

$$\frac{\partial q_r^*}{\partial c_2} = -\frac{\partial^2 \pi_r}{\partial q \partial c_2} \Big/ \frac{\partial^2 \pi_r}{\partial q^2} \ge 0.$$

Thus, it follows that q_r^* is greatest when c_2 is largest, i.e., when $c_2 = p$ and there is effectively no quick-response option. From the envelope theorem,

$$\frac{d\pi_r^*}{dc_2} = \frac{\partial \pi_r}{\partial c_2} + \frac{\partial \pi_r}{\partial q}\frac{\partial q_r^*}{\partial c_2} = \frac{\partial \pi_r}{\partial c_2} \le 0.$$

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[15] It is important to note here that multiple equilibria may also exist in this game, just as in the game without quick response; however, in 840 numerical examples with quick response, we found no instance of multiple equilibria.

Hence, equilibrium profits are smallest when $c_2 = p$, i.e., when there is no quick response. (iii) *All Consumers Purchasing Early*. If all strategic consumers purchase in the first period in equilibrium, then the equilibrium stocking level must be the myopic optimal with quick response, q_r^m, and the consumer best response must be equal to $\bar{v}$, i.e., $v^*(q_r^m) = \bar{v}$. This occurs when all consumers have an incentive to purchase in the first period, i.e., when

$$v_M - p \geq F(q_r^m)(\bar{v} - v_B).$$

Because $q_r^m = F^{-1}((c_2 - c_1)/(c_2 - v_B))$, this condition reduces to (6). $\square$

The final result in Theorem 2 provides a condition for when quick response induces all strategic consumers to purchase at the full price. In these cases quick response enables the retailer to restrict its initial stocking quantity to a point that effectively eliminates strategic behavior: given the retailer's low initial inventory, a strategic consumer expects only a very small chance that there will be a deep discount in the second period, and thus the consumer is better off buying at the full price in period 1. This result emphasizes that strategic consumers may exist in a market even if their behavior in equilibrium mirrors the behavior of myopic consumers. If the retailer were to increase its quantity (possibly based on the incorrect conjecture that the lack of strategic behavior implies a lack of strategic consumers) then the retailer may start to observe explicit strategic behavior.

The next theorem provides a sufficient condition for when quick response is more valuable to a retailer that has strategic customers than to a retailer that has only myopic consumers. As we demonstrate in §8, this condition is by no means necessary.

Theorem 3. *If (6) holds, the value of quick response, given by $\Delta = \pi_r^* - \pi^*$, is greater if some consumers are strategic than if all consumers are myopic.*

Proof. Let $\Delta_m = \pi_r^m - \pi^m$ be the value of quick response with purely myopic consumers ($\alpha = 0$). If (6) holds, because all consumers purchase in the first period with quick response, $\pi_r^* = \pi_r^m$, and hence

$$\Delta - \Delta_m = (\pi_r^* - \pi^*) - (\pi_r^m - \pi^m) = \pi^m - \pi^* \geq 0,$$

where the inequality follows from Theorem 1. $\square$

The combination of Theorems 1 and 3 leads to the following result on the relative value of quick response.

Corollary 1. *If (6) holds, the percentage increase in profit due to quick response, given by $\Delta/\pi^* = (\pi_r^* - \pi^*)/\pi^*$, is greater if some consumers are strategic than if all consumers are myopic.*

With myopic consumers it is well known that quick response allows the retailer to better match its supply to its exogenous demand. Demand is endogenous with strategic consumers, so quick response provides the additional benefit of influencing demand. In particular, quick response allows the retailer to force strategic consumers to buy at the full price rather than wait for a possible discount: the retailer's optimal quick-response quantity can be sufficiently low that all strategic consumers purchase in the first period because they expect that a deep discount is unlikely in the second period. However, it should be noted that quick response is not always more valuable in the presence of strategic consumers. Suppose strategic consumers purchase in the second period either with or without quick response. Then there are $(1 - \alpha)D$ full-price consumers with $\alpha > 0$ but D full price consumers when $\alpha = 0$. In that case, quick response can be more valuable with myopic consumers because the myopic consumer case has more full-price demand. Nevertheless, as we previously mentioned, in §8 we find that quick response is more valuable with strategic consumers in the vast majority of situations (i.e., condition (6) is merely sufficient for the results of Theorem 3 and Corollary 1).

It is interesting to compare quick response as a mechanism for influencing consumer behavior to strategies studied previously in the literature. For instance, Liu and van Ryzin (2008) and Su and Zhang (2008a, b) discuss various ways of signaling low inventory—that is, of credibly demonstrating limited availability. In our model, quick response does not reduce availability; on the contrary, quick response manages to mitigate strategic purchasing while simultaneously increasing availability—when condition (6) holds, the entire strategic segment is always served when the firm operates with quick response but may be rationed without it. As previously mentioned, the effectiveness of quick response derives from the reduced likelihood of deep markdowns. A consequence of these facts is that quick response has an ambiguous effect on total consumer welfare: more strategic (and myopic) consumers are served with quick response (when condition (6) holds, 100% of these consumers are served) but at a higher price than if the retailer operated without quick response and was likely to discount heavily.

8. Discussion
In this section, we report on a numerical study that investigates the magnitude of the analytical results presented in the previous sections. Furthermore, we present results regarding the value of dynamic pricing versus committing to a price path, and we investigate the consequence of assuming that all consumers are myopic when in fact a portion of them are strategic.

Table 2   Parameter Values Used in Numerical Experiments

| Parameter	Values
Demand distribution	Gamma
μ	100
σ	$\{25, 50, 100, 150\}$
p	10
c_1	$\{2.5, 5, 7.5\}$
c_2	$\{c_1 + 1, c_1 + 2\}$
v_M	$\{12, 15\}$
v_B	$\{1, 2\}$
$[\underline{v}, \overline{v}]$	$\{[2, 10], [3, 4], [6, 7], [9, 10]\}$
α	$\{0, 0.25, 0.5, 0.75, 1\}$

We first constructed 1,920 examples using all combinations of the parameters in Table 2. In 1,080 of them (56.25%) the myopic and strategic models yield identical equilibria (with or without quick response) because all strategic consumers prefer to purchase at the full price even at the myopic optimal quantity, q^m. (Those examples satisfy the condition $v_M - p \geq (\overline{v} - v_B) F(q^m)$.) Consequently, we discarded those uninteresting examples and now report results for the remaining 840 scenarios in which strategic behavior occurs in equilibrium. For each of those scenarios we found all equilibria both with and without quick response.

Table 3 presents data on the value of quick response with strategic consumers relative to the case without strategic consumers. We find that quick response is more valuable with strategic consumers than with myopic consumers in 98.7% of the 840 scenarios, even though (6) holds in only 38.1% of sample, which demonstrates that (6) is a sufficient but not necessary condition. Furthermore, the table reveals that the magnitude of the difference in value between the myopic and strategic cases can be significant. As previous work on quick response with myopic consumers has shown, the profit increase due to quick response can be enormous, quadrupling profits in

Table 3   Value of Quick Response (QR) with Strategic Consumers, Δ, Relative to the Value of Quick Response with Myopic Consumers, Δ_m

Parameters		Mean value of QR relative to myopic case (Δ/Δ_m)				Maximum value of Δ/Δ_m
σ/μ	$c_2 - c_1$	$\alpha = 0.25$	$\alpha = 0.50$	$\alpha = 0.75$	$\alpha = 1.00$	
0.25	2	2.08	2.07	2.05	2.02	5.58
	1	1.96	1.94	1.92	1.91	5.27
0.50	2	1.74	1.87	1.88	1.89	4.71
	1	1.72	1.80	1.79	1.79	4.50
1.00	2	1.24	1.42	1.52	1.59	3.74
	1	1.29	1.46	1.54	1.59	3.51
1.50	2	1.08	1.13	1.19	1.26	2.04
	1	1.12	1.21	1.29	1.36	2.88
All		1.53	1.61	1.65	1.67	5.58

Figure 5   Value of Quick Response (Expressed in Both Absolute Profit Increase and Percentage Profit Increase) as a Function of α, with $p = 10$, $c_1 = 2.5$, $c_2 = 3.5$, $v_M = 12$, $v_B = 2$, $[\underline{v}, \overline{v}] \in [6, 7]$, and Demand Gamma Distributed with Mean 100 and Standard Deviation 50
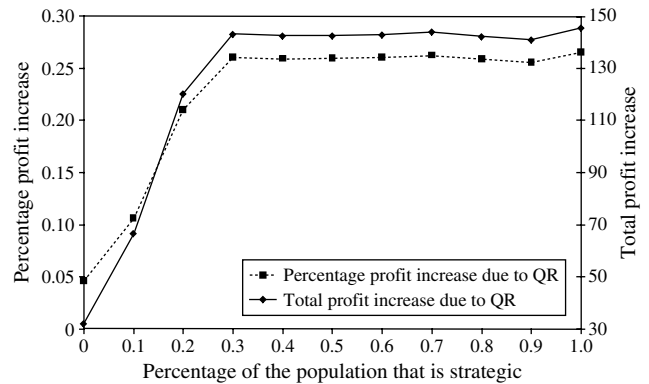
some cases. We find that with strategic consumers the potential profit increase can be far greater. In fact, if all consumers are strategic, then quick response is on average 67% more valuable than with purely myopic consumers and can be more than *five times* more valuable. Consequently, a significant portion of the value of quick response may lie in the ability of quick response to mitigate the negative consequences of strategic consumers.

The largest entry in Table 3 occurs when the cost of quick response is high (i.e., when $c_2 - c_1$ is large) and demand variability is low (on average 2.08 times more valuable). In those scenarios quick response does not add much value as a means of reacting to updated forecast information, but it does add significant value by inducing strategic consumers to purchase at the full price.

We have generally observed that the value of quick response is roughly concave in the fraction of strategic consumers, α (though it need not be monotonic). Figure 5 provides an example; for small α, the value of quick response is rapidly increasing in α, whereas for any α greater than 0.3, the value is relatively flat. The consequence is that a small number of strategic consumers in the population is enough to produce a rather large impact on the retailer's decisions and the value of quick response. In our sample, an average of 88% of the maximum potential profit increase due to quick response is captured when $\alpha = 0.25$.

We evaluated θ_c for each scenario and found that the average θ_c is 0.22 and the maximum is 0.57. This suggests that there is no rationing risk ($\theta \geq \theta_c$) even if strategic consumers are not overly optimistic about their chances to purchase discounted units: $\theta \geq 0.22$ implies that bargain hunters arrive during the sale period at a rate that is up to 4.5 (1/0.22) times faster than the arrival rate of strategic consumers.

Table 4   Average and Maximum Profit Loss Incurred When Ignoring Strategic Behavior (Cases with Multiple Equilibria Excluded)

	Without quick response		With quick response	
α	Mean % cost	Max % cost	Mean % cost	Max % cost
0.25	2.46	10.84	1.08	11.71
0.50	6.41	32.07	2.80	28.47
0.75	10.87	64.37	3.73	42.56
1.00	15.87	90.51	6.66	60.23

Furthermore, recall that these numerical results apply for all $\theta \geq \theta_c$.

Now we measure the reduction in the retailer's profit if it were to make decisions assuming that all consumers are myopic (i.e., choose q^m, the optimal quantity if $\alpha = 0$) when in fact they are strategic ($\alpha > 0$). Table 4 provides data on the cost of failing to recognize strategic behavior both with and without quick-response. If the firm does not have quick response capabilities and there is indeed a large number of strategic consumers, ignoring their strategic behavior can lead to a profit loss of more than 90%. However, the consequence of failing to recognize strategic behavior is smaller for a quick-response firm. A quick-response firm is likely to be conservative with its initial order quantity even if it assumes that all consumers are myopic. As a result, the quick-response firm suffers less from this type of error. For example, if condition (6) holds, then the quick-response retailer does not suffer at all from assuming that all consumers are myopic because all of the strategic consumers act as if they are myopic at the retailer's chosen order quantity.

We next consider when a static pricing policy is favored over a subgame perfect, dynamic pricing policy, again, both with and without quick response. Recall that Aviv and Pazgal (2008) find that static pricing may be preferred over dynamic pricing and that Liu and van Ryzin (2008) assume that the retailer commits to a static pricing policy. In our model, if the retailer chooses to commit to any particular sale price (and is able to credibly signal such commitment), then the optimal action is to choose to not mark down at all.[16] As a result, all strategic consumers purchase in the first period, and no bargain hunters purchase in period two. Hence, price commitment is beneficial in that it shifts strategic demand to the full-price period, but it is costly in that the retailer forgoes the opportunity to salvage inventory. Whether static pricing is a

prudent strategy depends on the relative importance of those two effects.

Let us first consider the case in which the retailer operates without quick response. According to Table 5, static pricing can be substantially more profitable than dynamic pricing, but it is better than dynamic pricing in less than 8% of scenarios. Table 6 presents another view of the data: sorted by the six different newsvendor critical ratios (i.e., $(p-c)/(p-s_l)$) used in our sample. As this table shows, committing to a high sale price is profitable only when the critical ratio is very high (greater than 0.8333). In these cases, margins in the first period are large and the cost of leftover inventory is low. Hence, there can be considerable value in inducing all strategic consumers to purchase at the full price.

If the retailer has quick-response capabilities, then Table 5 reports a more favorable situation for static pricing: static pricing is more profitable than dynamic pricing in approximately 20% of the scenarios and can be as much as 65% more profitable. Committing to a price path is costly when there is likely to be a substantial amount of inventory left over at the end of the full-price period. Quick response lowers the amount of leftover inventory, so commitment is less costly. However, the benefit of commitment remains: it induces strategic consumers to buy at the full price.

Overall, despite the appeal of using static pricing to induce strategic consumers to purchase at the full price, our model suggests that a firm is generally better off using dynamic pricing even if the firm could commit to a static pricing policy. However, there are situations in which static pricing is beneficial, especially if the firm has quick-response capabilities.

9. Conclusion

Some consumers act strategically: they choose not only *whether* to buy a product but *when* to buy the product. They time their purchase based on their expectations of the retailer's markdown behavior as well as their own disutility from purchasing late in the season. In our model, the retailer chooses an optimal inventory and pricing policy given her expectation of consumer behavior, and each consumer chooses an optimal purchasing strategy given his expectation of the retailer's behavior and the behavior of other consumers. We demonstrate that an equilibrium exists, and we study its properties.

In our base model, in which the retailer does not have quick-response capabilities, we find that a retailer can incur a substantial loss in profit by ignoring strategic behavior—failing to recognize strategic behavior leads the firm to order too much inventory, which makes deep discounts to clear inventory at the end of the season more likely. When consumers expect deep discounts, they are more likely to be patient and

[16] Committing to a sale price of s_l results in the largest number of consumers waiting for the sale, in addition to the lowest average price in the sale period, so a dynamic pricing policy is clearly preferred. Conditional on committing to any price greater than s_l, the optimal action is to price as high as possible, which induces all strategic consumers to purchase in the first period.

Table 5   Frequency and Profitability of Sale Price Commitment When the Firm Does Not Have Quick Response (No QR) or Does Have Quick Response (QR)

QR?	α	% of examples with valuable commitment	Mean % profit increase	Max % profit increase	Mean % profit decrease	Min % profit decrease
No QR	0.25	4.17	2.39	5.24	−11.38	−48.10
No QR	0.50	6.77	4.30	11.06	−9.49	−45.21
No QR	0.75	7.81	7.74	38.55	−8.31	−43.02
No QR	1.00	7.29	16.35	93.62	−7.50	−41.43
QR	0.25	21.43	3.73	15.70	−1.72	−8.12
QR	0.50	20.83	6.36	42.00	−1.70	−7.87
QR	0.75	19.64	7.99	62.03	−1.68	−7.87
QR	1.00	18.45	8.89	64.96	−1.68	−8.05

Notes. Profit increase is calculated conditional on price commitment being profitable, and the profit decrease is calculated conditional on price commitment being unprofitable.

wait for a sale. This error is generally less costly when the retailer has quick response, but the profit loss can still be substantial.

Although retailers may dislike having to take markdowns, we find that a commitment to never mark down merchandise is generally not the best approach to deal with strategic consumers (even if such a commitment could be made credibly), especially when the firm does not have quick-response capabilities. The better approach is to be prudent with the initial inventory and then to dynamically and optimally discount.

Our main result is that quick-response capabilities can be significantly more valuable to a retailer in the presence of strategic consumers relative to the case when consumers are not strategic. It has already been established in the literature that quick response can be quite valuable when consumers are myopic (i.e., nonstrategic); our result indicates that even the known value of quick response may underestimate its true value. With myopic consumers, quick response gives the retailer the ability to use updated forecasts to better match supply with demand. With strategic consumers, quick response also gives the retailer the ability to mitigate the negative consequences of strategic behavior. In particular, quick response allows

the retailer to manipulate its demand. Furthermore, this latter benefit can be substantial.

Our result with respect to quick response is important because a firm must make an investment to develop quick-response capabilities. For example, the fashion apparel retailer Zara invests in localized production, fast delivery, and information technology to exchange information across the firm quickly. The results of these policies at Zara have been dramatic: Ghemawat and Nueno (2003) report that Zara performs significantly better than the competition in both the number and severity of markdowns, with markdown percentages that are half the European average of 30%. We show that investments in quick response, like those made by Zara, are easier to justify when strategic consumer behavior is fully accounted for.

10.   Electronic Companion

An electronic companion to this paper is available as part of the online version that can be found at http://mansci.journal.informs.org/.

Table 6   Frequency of Profitable Sale Price Commitment as a Function of the Newsvendor Critical Ratio: $(p - c)/(p - s_l)$ in the Cases Without Quick Response, and $(c_2 - c_1)/(c_2 - s_l)$ in the Cases With Quick Response

No quick response		Quick response	
Critical ratio	% of examples with profitable commitment	Critical ratio	% of examples with profitable commitment
0.2778	0.00	<0.3333	0.00
0.3125	0.00	0.3333	15.00
0.5556	0.00	0.4000	16.11
0.6250	0.00	0.5714	25.00
0.8333	17.50	0.6666	32.00
0.9375	13.75	0.8000	35.00

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