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# Markdown or Everyday-Low-Price? The Role of Behavioral Motives

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We study a seller's optimal pricing and inventory strategies when behavioral (non-pecuniary) motives affect consumers' purchase decisions. In particular, the seller chooses between two pricing strategies, markdown or everyday-low-price, and determines the optimal prices and inventory level at the beginning of a two-period selling season. Two salient behavioral motives that impact consumers' purchase decisions and the seller's optimal strategies are anticipated regret and misperception of product availability. Regret arises when a consumer initially chooses to wait but encounters stockout later, or when the consumer buys the product at the high price but realizes that the product is still available at the markdown price. In addition, consumers often perceive the product's future availability to be different than its actual availability. We determine and quantify that both regret and availability misperception have significant operational and profit implications for the seller. For example, ignoring these behavioral factors can result in up to 10% profit losses. We contrast the roles of consumers' strategic (pecuniary) motives with their behavioral (non-pecuniary) motives in affecting purchase, pricing, and inventory decisions. The presence of the behavioral motives reinstates the profitability of markdown over everyday-low-price, in sharp contrast to prior studies of only strategic motives which suggest the contrary. We characterize how and why strategic versus behavioral motives affect decisions in distinctive manners. In doing so, this paper also introduces and determines the *behavioral* benefits of pricing in leveraging consumers' behavioral regularities. We advocate that tactics which may intensify consumers' misperception of availability, such as intentionally disclosing low inventory levels, can have a far-reaching impact on improving the seller's profit.\*

*Key words:* Regret; availability misperception; markdown; everyday-low-price; inventory rationing; revenue management; consumer model; behavioral economics

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## 1. Introduction

It is the beginning of June. Emma, who has just been promoted to a senior management position in her company, is shopping for professional outfits to prepare for her exciting new position starting in September. She finds a newly-designed dress in Ann Taylor with a price tag of \$148. She thinks to herself, "This dress is gorgeous and worth the price. But I know Ann Taylor often marks down their new arrivals by 30% within 2 months. Should I wait until then to buy it, and perhaps get a nice scarf with the money I save? But what if they no longer have my size by then?"

The practice of price markdowns in various industries such as fashion and consumer electronics has

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taught consumers to be forward-looking. Consumers learn that they can potentially take advantage of a future price discount and save money. Nevertheless, this advantage comes with a price. Consumers may eventually find that the desired product is no longer available and regret that they did not buy it in the first place. What complicates matters further is that consumers often perceive a product's future availability to be different than its actual availability. Hence, the intricate debate between buy and wait is greatly impacted by possible regretful emotions and consumers' misperception of availability. Then how should a profit-maximizing firm respond to these latent behavioral issues underlying consumers' purchase decisions? Should the firm apply markdown or charge the same price all the time? What should be the optimal price(s) under either strategy? What is the optimal amount of inventory the firm should stock?

How to manage forward-looking consumers has gained increasing attention from both industry practitioners and academic researchers. Historic data on department store sales indicate that there is an increasing tendency that consumers only shop in promotion or clearance periods (Fickes 2001, Phillips 2005). Empirical studies also show that consumers are forward-looking in their purchase decisions in industries such as consumer packaged goods, college textbooks, and apparel (Erdem and Keane 1996, Chevalier and Goolsbee 2009, Soysal and Krishnamurthi 2012). Recently, researchers have started to investigate how consumers' strategic motives of considering future price drops affect the seller's retail strategies. These models offer new and important insights for retail operations. For example, they alert that when consumers strategically time their purchase, applying markdown may not be as profitable as previously thought, and charging a single price for the entire selling season can be optimal (e.g., Coase 1972, Stokey 1979, Aviv and Pazgal 2008). Some researchers also propose tactics to discourage consumers' strategic behavior for the seller's benefit. One such tactic, defined as "inventory rationing," is to intentionally understock and create a rationing risk among consumers to encourage them to buy early (Gallego et al. 2008, Liu and van Ryzin 2008).

This paper builds on the above studies to perfect the consumer model by incorporating important but latent behavioral regularities, that is, regret and misperception of future product availability. The more fine-tuned consumer model accounts for both strategic (pecuniary) and behavioral (non-pecuniary) motives. Throughout our discussion, we treat "strategic" synonymous to "forward-looking." That is, a consumer is strategic (forward-looking) if she considers future purchase opportunity when making purchase decisions. We do not impose that this consideration be rational as assumed in the current literature on strategic consumers. Our new consumer model allows us to answer whether the managerial prescriptions from previous studies remain accurate when behavioral motives affect consumers' purchase decisions. It also allows us to determine how the seller should optimally adjust relevant tactics in the face of such behavioral motives. To do so, we study a stylized model in which a seller sells a product over two periods. The seller chooses between two pricing strategies, markdown or everyday-low-price, and

determines how much inventory to procure at the beginning of Period 1. Consumers then decide whether and when to buy the product. By contrasting these two widely used pricing strategies, we characterize the conditions under which markdown is more profitable than everyday-low-price (and vice versa) when consumers are affected by both strategic and behavioral motives.

Under a markdown strategy, the product is sold at a high price initially in Period 1. Any leftover inventory is offered for sale at a lower price in Period 2. Markdown is the most commonly observed practice of “intertemporal price discrimination.” In particular, by offering different prices at different time points, the seller segments the market based on consumers’ heterogeneous valuations of the product. Consumers who value the product more purchase early at the high price to ensure that they obtain the product, whereas lower-value consumers wait to take advantage of potential markdowns. Thus, consumers are segmented over time, leading to intertemporal price discrimination. Both practitioners and researchers have devoted substantial effort to optimizing the pricing and inventory decisions under a markdown policy. Due to management and marketing reasons, many industries adopt markdowns by fixing the level of discount while optimizing the initial full price. For example, fashion retailers such as Gap and Zara mark down their products to the same limited set of discounts in every clearance season (Caro and Gallien 2012). Retailers such as Bath & Body Works, Godiva Chocolatier, and Victoria’s Secret launch semi-annual sale events twice every year with the same percentage discounts. Motivated by these practices, we optimize the first-period price while keeping the second-period price as a predetermined discount of the former under the markdown strategy.

Conversely, under everyday-low-price, the product is sold at a single price over the entire selling season (i.e., in both Periods 1 and 2). Warehouse wholesalers such as Costco and Sam’s Club are well-known for their everyday-low-price policy. To counteract consumers’ increasing tendency to wait for promotions, department stores such as Macy’s have introduced everyday-low-price items (e.g., Macy’s Everyday Values product lines) in their product portfolio. J.C. Penney, who traditionally adopted markdown pricing, have lately switched to everyday-low-price throughout their stores (Associated Press 2012). However, the strategy shift turned out to be a failure (Mourdoukoutas 2013). Puzzled by these contradicting outcomes, we contrast markdown with the everyday-low-price strategy in which the seller optimally determines the single price and the inventory level.

Given the seller’s pricing and inventory decisions, consumers determine whether and when to buy the product. There are two salient behavioral issues that impact consumers’ purchase decisions. The first one is the feeling of regret. Regret stems from consumers’ counterfactual thinking, in which consumers compare the outcome of the chosen action with that of the unchosen one (Roese 1994). In hindsight, the consumer may realize that she could have been better off had she chosen differently. If so, she is likely to regret her earlier choice. For example, Emma would very likely regret not buying the dress in June if

she found that by the time Ann Taylor put up a discount, her size had been sold out. Conversely, Emma may also regret for having paid the high price if she found that the dress was available at the markdown price. Anticipating these regretful emotions can change consumers' decisions *ex ante*, as documented in numerous studies (e.g., Simonson 1992, Zeelenberg et al. 2000, Inman and Zeelenberg 2002).

Another salient behavioral issue regards consumers' misperception of the likelihood that the product will be available in the markdown period. Henceforth, we refer to this behavioral issue as consumers' misperception of availability, or simply, availability misperception. This misperception may occur for two reasons. First, consumers often lack the ability to process all relevant information to form an assessment. For example, Emma needs to consider the potential popularity of the dress to assess how likely she can get the dress two months later. Second, misperception can also arise simply because consumers perceive an uncertain outcome to occur with a different likelihood than its actual probability (Camerer and Weber 1992, Tversky and Kahneman 1992). Thus, consumers often behave as if they have mentally misperceived the probabilities (even when the probabilities are explicitly known).

This paper formalizes and captures the above behavioral factors in the consumer model to answer the following questions: (i) How does the presence of regret and availability misperception affect the consumers' purchase decisions and the seller's pricing and inventory strategies? In particular, does the seller retain the benefit of using markdown as opposed to everyday-low-price? How do these factors impact the extent of inventory rationing the seller should use to motivate early purchase? (ii) Does the seller benefit or suffer from these behavioral factors? (iii) How much will the seller potentially lose if he ignores regret and availability misperception when forming his operational strategies, as opposed to correctly incorporating them?

Our contributions to the literature are threefold. First, we draw on well-established behavioral decision theories to formalize both regret and availability misperception in our consumer model. We are also the first study that investigates the impacts of these behavioral factors on the joint pricing and inventory decisions of the seller. This comprehensive account allows us to determine and quantify the operational and profit implications of the behavioral factors. We demonstrate that what have been thought to be the correct strategies turn out to be suboptimal and can lead to excessive profit losses when consumers' purchase decisions are influenced by behavioral motives. In contrast to prior studies that champion the use of everyday-low-price, the presence of regret and availability misperception reinstates the profitability of applying markdown and mitigates the extent of inventory rationing that the seller should use. We quantify that ignoring these behavioral factors leads the seller to under-stock too much and unnecessarily forgo up to 14% of potential demand.

Second, we define and determine the *behavioral* benefits of pricing. In the pricing and revenue management literature that does not consider consumers' behavioral motives, pricing is a mechanism for

segmenting different types of consumers to better match demand with supply. We show that in addition, having the capability to optimize prices offers the seller important levers to utilize consumers' behavioral regularities towards his own benefit. It also protects the seller from potential negative consequences of mis-calibrating the relevant behavioral parameters when devising the optimal strategies.

Third, we demonstrate that availability misperception has a greater impact on the consumers' purchase decisions and the seller's resulting profit than regret. Thus, we advocate that acting on availability misperception can have a more far-reaching influence than common marketing campaigns that only emphasize regret. A plausible venue is to intentionally disclose low inventory levels. For example, we increasingly observe that e-commerce sites such as Amazon.com highlight information such as "Only 2 left in stock" in product pages.<sup>1</sup> Similarly, a retail store can put limited quantities of each item on the shelf but keep a large inventory in the stockroom. Our insights suggest the potential profitability of deliberately disclosing such inventory information.

## 2. Literature Review

The broad field of pricing and revenue management has developed for over three decades. The evolution of this field goes through three distinct stages. The first stage establishes and quantifies the value of price discrimination and capacity allocation based on consumers' heterogeneous valuations of a good or service (see Talluri and van Ryzin 2005 for a comprehensive review). These studies promote the application of dynamic pricing and markdown management in various industries including airlines, hotels, and retail (Phillips 2005). More recently, a group of researchers advance the field to the second stage by considering consumers' strategic reactions to the above techniques. They examine how the strategic interactions between consumers and firms may impact the optimality and application of pricing and revenue management strategies (see Aviv and Vulcano 2012 for a recent review). The majority of these studies focus on pricing decisions with a fixed inventory (e.g., Su 2007, Elmaghraby et al. 2008). A consensus in this literature is that the presence of strategic consumers hurts the profitability of dynamic pricing practices (e.g., Besanko and Winston 1990, Nair 2007, Aviv and Pazgal 2008, Levin et al. 2009) and often leads to the optimality of a single-price policy (e.g., Coase 1972, Stokey 1979, Wilson 1988, Su 2007, Gallego et al. 2008). A few recent studies discuss several operational reasons (e.g., uncertain valuation, product variety, and cost of visiting a retailer) that may retain the benefit of dynamic pricing with strategic consumers (e.g., Swinney 2011, Parlakturk 2012, Cachon and Feldman 2013). Some studies introduce an inventory focus, with either fixed or endogenous prices (e.g., Gallego et al. 2008, Liu and van Ryzin 2008, 2011, Zhang and Cooper 2008, Cachon and Swinney 2009). Our paper is most relevant to Gallego et al. (2008) and Liu and van Ryzin (2008, 2011). They investigate settings of markdown

<sup>1</sup> See Appendix B for examples retrieved online (as of December 13, 2012).

management and show that when consumers are strategic, it is beneficial for the seller to withhold the amount of inventory put up for sale at the markdown period (i.e., adopting inventory rationing).

We join a handful of researchers to advance pricing and revenue management research to the third stage: capturing consumers' behavioral regularities. The second stage of the pricing and revenue management literature enhances and complements the first stage by endogenizing consumers' strategic decisions instead of viewing consumers as purely myopic. This enhancement generates new and important insights that challenge prior conclusions and prescribe optimal policies which can work better in practice. Incorporating behavioral regularities shares the same spirit. The current literature on strategic consumers imposes two common assumptions: (i) a consumer's utility is measured by her reservation price of the product less the selling price; i.e., consumers are solely motivated by pecuniary concerns; and (ii) consumers have rational expectations about future prices and/or product availability.<sup>2</sup> In contrast, a growing stream of literature relaxes these assumptions to investigate the impacts of consumers' behavioral issues on their purchase decisions and the seller's optimal pricing strategies. The behavioral issues that have been studied include loss aversion (Popescu and Wu 2007, Heidhues and Köszegi 2008, Nasiry and Popescu 2011, Baron et al. 2014), hyperbolic discounting (Su 2009, Baucells et al. 2014), and anticipated regret (Diecidue et al. 2012, Nasiry and Popescu 2012). We refer the reader to Özer and Zheng (2012) for a comprehensive review of the behavioral pricing literature.

This paper contributes to the pricing and revenue management literature in three aspects. First, we develop a consumer model that incorporates two behavioral factors well established in behavioral decision theories: anticipated regret and misperception of availability. The latter behavioral factor is pervasively observed (Tversky and Kahneman 1992) but has not been studied in a revenue management context. Our refined consumer model enables us to determine and quantify the operational and profit implications of these behavioral factors. Second, we study how these behavioral issues affect the joint pricing and inventory decisions of the seller. Third, the comprehensive account of both salient behavioral issues allows us to investigate the interplay between them. The results offer important insights on potential tactics that firms can utilize to leverage these behavioral issues to improve profitability. Several researchers such as Narasimhan et al. (2005) and Ho et al. (2006) advocate that more studies that examine the joint impacts of multiple behavioral factors should be encouraged to advance consumer behavior research. The present paper takes a step along this direction.

Researchers have documented ample empirical evidence to demonstrate the impacts of both regret and probability misperception on individual decisions. We refer the reader to Zeelenberg et al. (2000) and Stott (2006) for comprehensive reviews. A few recent studies have started to investigate the impact of

<sup>2</sup> The only exceptions are Gallego et al. (2008) and Liu and van Ryzin (2011) who consider a case in which consumers engage in adaptive learning to form expectations of future availability.

regret on operations and marketing policies with formal modeling (see Engelbrecht-Wiggans and Katok 2007, Diecidue et al. 2012, Nasiry and Popescu 2012 for studies in the contexts of auctions and advance selling). We add to this literature by studying regret in a new context; i.e., markdown management. Regarding probability misperception, current studies mainly focus on using simple lottery choice experiments to estimate the functional relationship between perceived and actual probabilities. To the best of our knowledge, the only exception is a recent paper by Davis et al. (2011). They test whether the suboptimal reservation prices set by auctioneers in procurement auctions can be explained by the auctioneers' misperception of probabilities. We note that these studies do not offer direct implications regarding how probability misperception may impact actual business tactics. Thus, our paper contributes to this literature by formally studying probability misperception in a concrete revenue management context, which enables one to prescribe managerial strategies.

### 3. The Consumer's Purchase Decision

We consider a monopolistic seller (he) who sells a single product to a group of consumers over two periods. The seller first chooses between two pricing strategies: everyday-low-price or markdown. Under everyday-low-price, the seller optimizes the single price at which he sells the product throughout both periods. Under markdown, the seller optimally determines the first-period price  $p_1$  and charges  $p_2 = \delta p_1$  at Period 2. Here  $\delta \in (0, 1)$  is the discount factor known to consumers. Under either pricing strategy, the seller also optimally determines how much inventory  $K$  to procure at a unit cost of  $c$  at the beginning of Period 1. Due to a long replenishment lead time, the seller cannot replenish inventory during the selling season. Therefore, a stockout is possible.

Given the seller's decisions, consumers then decide whether and when to buy the product. Each consumer (she) buys at most one unit. In addition, every consumer has a privately known and heterogeneous reservation price  $v$  for the product. The seller only knows that  $v$  is uniformly distributed on  $[0, \bar{v}]$ . Let  $F(\cdot)$  and  $f(\cdot)$  denote the cumulative distribution function (c.d.f.) and probability density function (p.d.f.) of  $v$ , respectively. Also define  $\bar{F}(\cdot) \equiv 1 - F(\cdot)$ . The total market size is known and fixed at  $N$ . Hence, consumers' uniformly distributed reservation prices result in a linear inverse demand curve, which is a well-accepted demand model in the literature (e.g., Phillips 2005, Cui et al. 2007, Ho and Zhang 2008). Note that under everyday-low-price, a consumer buys the product as long as her reservation price is higher than the selling price. Thus, whether or not consumers are forward-looking is not relevant under the everyday-low-price strategy. In contrast, under a markdown strategy, the key trade-off for a consumer is to buy the product at a high price with sure availability versus to buy at a low price but with the risk of stockout. In what follows, we first focus on building the consumer model and analyzing consumers' purchase decisions under the markdown strategy. We then analyze the seller's optimal price and inventory



decisions when he follows either the everyday-low-price or the markdown strategy. Finally, we compare these two strategies to derive the seller’s optimal policy. Appendix A summarizes our notation.

We capture two key behavioral issues that affect consumers’ purchase decisions: regret and availability misperception. Regret arises when a consumer engages in counterfactual thinking (Kahneman and Miller 1986, Medvec et al. 1995, Roesse 1997). That is, the consumer compares the outcome of her choice with the outcomes of other forgone alternatives. If an unchosen alternative turns out (ex post) to generate a better outcome than the chosen one, the consumer will experience a mental cost for losing the forgone surplus. Two conditions are essential for regret to impact decision making (Loomes and Sugden 1982). First, the consumer must be able to observe the outcomes of both her choice and the forgone alternatives. “If you cannot compare what is with what might have been, there should be no reason for regret” (Zeelenberg et al. 1996). Second, the consumer must anticipate and take into account possible regret when making her decision ex ante. In our context, two types of regret may arise depending on a consumer’s purchase timing. If the consumer buys the product in Period 1, since she knows that price will drop in Period 2, she will likely experience a mental cost for not taking advantage of the possible discount. We define this mental cost as the “high-price regret.” Conversely, if she waits until Period 2 only to find that the product is no longer available, she will incur a mental cost for losing the surplus that she could have gained had she bought the product in Period 1. We define this mental cost as the “stockout regret.”

Following a formal development of regret theory (Bell 1982, Loomes and Sugden 1982), we model both types of regret as the forgone surplus multiplied by the probability that this forgone surplus is incurred (also see Zeelenberg et al. 2000 for a review). Let  $q$  denote the consumer’s *perceived* probability that the product will be available in Period 2. We characterize the expected values<sup>3</sup> of buying the product in Periods 1 and 2 for a consumer as follows:

$$U_1(v, p_1) = (v - p_1) - q\alpha(p_1 - \delta p_1), \quad (1)$$

$$U_2(v, p_1) = q(v - \delta p_1) - (1 - q)\beta \max\{(v - p_1), 0\}. \quad (2)$$

The first term in both equations is the (expected) value of consuming the product. We use a linear value function following prior studies that model regret (e.g., Nasiry and Popescu 2012). All of our analyses and insights remain valid with a concave value function (see §6.4). The second terms in (1) and (2) capture the loss in expected value due to high-price regret and stockout regret, respectively. The parameter  $\alpha$  measures the marginal value of the high-price regret in comparison to the consumption value. We posit that  $\alpha \in [0, 1]$  because one unit of actual consumption value is likely to be valued more by consumers than

<sup>3</sup> Following rank-dependent utility theory (Yaari 1987) and (cumulative) prospect theory (Tversky and Kahneman 1992), we call the consumer’s evaluation of a risky outcome the “expected value” (as opposed to expected utility) of that outcome. We do so to ensure consistency in terminology as we model perceived probabilities based on these theories.

one unit of counterfactual value (e.g., Camerer and Ho 1999, Lim and Ho 2007). Similarly, the parameter  $\beta \in [0, 1]$  measures the marginal value of the stockout regret.

The stockout regret is believed to be more salient than the high-price regret in our context for three reasons. First, the stockout regret is associated with taking a bet and induces a stronger feeling of responsibility if the decision turns out to be bad (i.e., if the consumer decides to wait for the markdown but the product is no longer available; see Simonson 1992, Tsiros and Mittal 2000, Abendroth and Diehl 2006). Second, the high-price regret occurs only when the consumer continues to shop for the same product in the markdown period even after she has bought it. Thus, this regret requires the consumer to proactively seek the outcome of a forgone alternative – an action that a regret-prone consumer is unlikely to take (Zeelenberg 1999). Third, the recent practice by many retailers to offer price matching guarantees may further dampen the high-price regret. Hence, we focus on the case of  $\alpha \leq \beta$  in our theoretical analysis while incorporating the case of  $\alpha > \beta$  in our numerical studies.

The notation  $q$  in (1) and (2) represents the consumer’s *perceived* probability that the product will be available in Period 2. This perceived probability is not necessarily equal to the *actual* probability of availability. Hereafter, we refer to the actual (resp., perceived) probability that the product will be available in Period 2 as the actual (resp., perceived) Period 2 fill rate. The deviation between the actual probability of an outcome and an individual’s perceived probability is another robust behavioral phenomenon (Kahneman and Tversky 1979, Camerer and Ho 1994, Hey and Orme 1994).<sup>4</sup> Individuals often perceive a high-probability event to be less likely to occur than it actually does. In contrast, a small-probability event may be “either greatly overweighted or neglected altogether” (Tversky and Kahneman 1992, p. 303). Both over-reaction to rare events (e.g., Abdellaoui 2000, Stott 2006) and consistent underweighting of all probabilities (e.g., Qiu and Steiger 2011, van de Kuilen and Wakker 2011) are observed in the experimental literature. Hence, we first focus on the case of consistent underweighting in our theoretical analysis. Later in §6.4, we examine the robustness of our conclusions when small probabilities may be overweighted.

Studying a model of underweighting offers a unified framework to analyze how probability misperception may impact consumers’ decisions for both cases of known and unknown product fill rates. Studies have consistently demonstrated underweighting of small probabilities when probabilities need to be inferred from experience (Hertwig et al. 2004, Barron and Yechiam 2009). In many retail environments, consumers’ decisions are closer to the experience-based decision regime because product fill rates are often not

<sup>4</sup> Note that the perceived probability is not an individual’s subjective probability assessment. Rather, it is the decision weight that the individual assigns to a probabilistic event when making decisions. Hence, the contextual interpretation of a decision weight is the perceived probability inferred from the individual’s choice. When actual probabilities are objectively known, the deviation between actual and perceived probabilities reflects that an event has a greater impact when it turns possibility into certainty (e.g., 90% to 100%) than when it makes a possibility more likely (e.g., 50% to 60%; Tversky and Kahneman 1992). The way we incorporate a consumer’s perceived Period 2 fill rate into the expected values as in (1) and (2) follows from rank-dependent utility theory (Yaari 1987, Tversky and Wakker 1995).

explicitly shown to consumers. Further, the literature on ambiguity aversion also shows that individuals underweight the (expected) winning probability of a gamble when the winning probability is not explicitly known (Camerer and Weber 1992, Klibanoff et al. 2005). Thus, analyzing consistent underweighting helps to strengthen the applicability of our parsimonious model to more general settings.

Let  $r$  denote the actual Period 2 fill rate. Then the perceived Period 2 fill rate can be modeled as

$$q(r) = r^\theta, \text{ where } \theta \geq 1. \quad (3)$$

This functional form is well established and closely approximates convex probability weighting functions estimated from empirical studies (e.g., Qiu and Steiger 2011, van de Kuilen and Wakker 2011).<sup>5</sup> The parameter  $\theta$  captures the strength of deviation between the actual and perceived Period 2 fill rates. A larger value of  $\theta$  implies that consumers' perceived Period 2 fill rate deviates more from the actual one. When  $\theta = 1$ , there is no distortion in consumers' perceived Period 2 fill rate. Note from (1), (2), and (3) that if  $\alpha = \beta = 0$  and  $\theta = 1$ , we revert to a model in which neither regret nor availability misperception is in effect.

We next analyze consumers' purchase decisions given the above formulation. When the seller follows a markdown strategy, a consumer makes her purchase decision by comparing the expected values from buying in either period. Specifically, she buys in Period 1 if and only if  $U_1(v, p_1) \geq \max\{U_2(v, p_1), 0\}$ . The following proposition characterizes the consumers' purchase decision given the first-period price, the perceived Period 2 fill rate, and the behavioral factors. All proofs are deferred to the online appendix.

**PROPOSITION 1.** *Define threshold  $Q$  and cutoff value  $v_1$  as follows:*

$$Q \equiv \frac{(1 + \beta)(\bar{v} - p_1)}{(1 + \beta)\bar{v} + (\alpha - \beta - (1 + \alpha)\delta)p_1} < 1, \quad v_1 \equiv \left( \frac{(1 + \alpha)(1 - \delta)q}{(1 + \beta)(1 - q)} + 1 \right) p_1 \geq p_1. \quad (4)$$

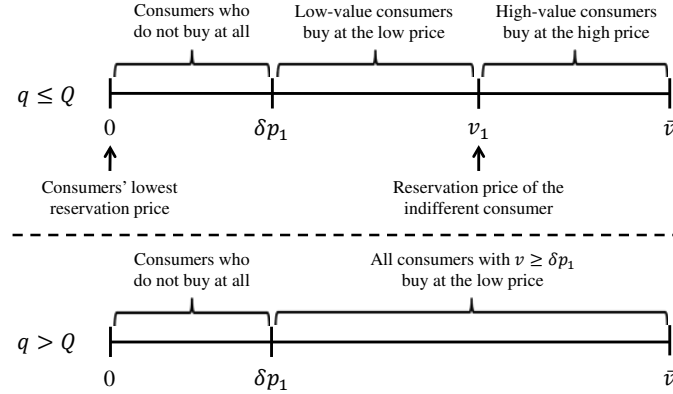
*If the seller follows a markdown strategy, then:*

- (i) *For any  $q \in [0, Q]$ , a consumer buys in Period 1 if her reservation price  $v \in [v_1, \bar{v}]$ , buys in Period 2 if  $v \in [\delta p_1, v_1)$ , and does not buy at all if  $v \in [0, \delta p_1)$ .*
- (ii) *For any  $q \in (Q, 1]$ , a consumer buys in Period 2 if  $v \in [\delta p_1, \bar{v}]$ , and does not buy at all if  $v \in [0, \delta p_1)$ .*

Proposition 1 characterizes how the market may be segmented intertemporally under the markdown strategy. Figure 1 visualizes the market segmentation. When consumers perceive the Period 2 fill rate to be low (i.e.,  $q \leq Q$ ), those consumers whose reservation prices exceed the markdown price (i.e.,  $v \in [\delta p_1, \bar{v}]$ ) are segmented into two groups. The high-value consumers (with  $v \in [v_1, \bar{v}]$ ) buy at the high price in Period

<sup>5</sup> This form is a special case of the switch-power weighting function proposed by Diecidue et al. (2009). Diecidue et al. (2009) also propose a class of dual-power weighting functions (i.e.,  $q(r) = 1 - (1 - r)^\theta$  with  $\theta \in (0, 1]$ ) that can exhibit convexity. We verified that all of our results hold with this alternative formulation. We present the power weighting function here to simplify mathematical presentation.

1. The low-value consumers (with  $v \in [\delta p_1, v_1]$ ) wait and buy at the low price in Period 2 if the product is still available. The cutoff value  $v_1$  is the reservation price of the consumer who is indifferent between buying at either price. In contrast, if the perceived Period 2 fill rate is sufficiently high (i.e.,  $q > Q$ ), no consumer buys at the high price. Only those consumers whose reservation prices exceed the markdown price ( $v \in [\delta p_1, \bar{v}]$ ) wait and buy the product at the low price.



**Figure 1** Market Segmentation under the Markdown Strategy

Given the market segmentation, we can characterize the resulting demand in each period ( $D_1, D_2$ ) and the total demand ( $D_T$ ) in the following lemma.

LEMMA 1.

$$(i) \quad \begin{array}{ccc} D_1 & D_2 & D_T \\ \hline q \leq Q & N(\bar{v} - v_1)/\bar{v} & N(v_1 - \delta p_1)/\bar{v} & N(\bar{v} - \delta p_1)/\bar{v} \\ q > Q & 0 & N(\bar{v} - \delta p_1)/\bar{v} & N(\bar{v} - \delta p_1)/\bar{v} \end{array}$$

(ii)  $D_1, D_T$ , and  $Q$  are decreasing in  $p_1$ ;  $D_2$  is increasing in  $p_1$ .<sup>6</sup>

The above demand characterization follows from the market segmentation and the distribution of consumers' reservation prices. Lemma 1(ii) shows how the demands and the threshold  $Q$  change with the first-period price  $p_1$ . These monotonicity results imply that increasing the first-period price reduces both the total demand size ( $D_T$ ) and the portion of demand that the seller charges a high price ( $D_1/D_T$ ). In addition, having a high  $p_1$  may also trigger consumers to wait for the markdown (e.g., when  $Q$  becomes low). Hence, consumers' strategic motive affects the extent that the seller can use pricing to intertemporally segment the market, i.e., the use of intertemporal price discrimination.

We next consider the impact of consumers' behavioral motives on intertemporal market segmentation. Define  $S_1 \equiv \partial D_1 / \partial p_1$  as the price sensitivity of  $D_1$  with respect to  $p_1$ . Note that the total demand size  $D_T$  given  $p_1$  is independent of the behavioral parameters. Hence, the impacts of consumers' behavioral

<sup>6</sup> We use the terms "increasing" and "decreasing" in the strict sense; i.e., increasing (decreasing) means strictly increasing (decreasing).

motives on market segmentation are manifested in two aspects. First, they affect the price sensitivity of the high-value consumers (i.e.,  $S_1$ ) and hence the portion of demand that the seller can effectively charge a high price (i.e.,  $D_1$  when  $q \leq Q$ ). Second, they affect the critical threshold  $Q$  beyond which the market can no longer be intertemporally segmented. The next proposition describes how  $Q$  and  $S_1$  are affected by the regret parameters.

PROPOSITION 2. (i)  $Q$  is increasing in  $\beta$  and decreasing in  $\alpha$ .

(ii) The magnitude of  $S_1$  is decreasing in  $\beta$  and increasing in  $\alpha$ .

Proposition 2 implies that compared to the case of no regret, the presence of stockout regret ( $\beta > 0$ ) encourages the use of intertemporal price discrimination in two ways. First, it increases the chance that the market can be intertemporally segmented (i.e., when  $q \leq Q$ ). Second, it mitigates the high-value consumers' price sensitivity, thereby increasing the portion of high-value consumers who continue to buy at the high price when  $p_1$  increases. Conversely, the high-price regret ( $\alpha > 0$ ) has the opposite effect. It increases the chance that all consumers wait for the markdown, and it makes the high-value consumers more sensitive to an increase in  $p_1$ . In summary, consumers' *behavioral* motives may counteract or reinforce their *strategic* motive to define their purchase decisions. Hence, these two motives play distinct roles in consumers' purchase decisions.

As the first mover, the seller anticipates and accounts for consumers' strategic and behavioral motives when determining whether and how to intertemporally segment the market with pricing. In addition, by adjusting the inventory level, he also manipulates the consumers' perceived Period 2 fill rate ( $q$ ). This in turn affects whether the market can be effectively segmented under the markdown strategy. In the next section, we follow a backward induction approach to characterize the seller's optimal policy. Given the consumers' purchase decision discussed above, we first analyze the optimal pricing and inventory decisions under either the everyday-low-price or the markdown strategy. We then compare the seller's profit under these two strategies and determine the conditions under which applying markdown (or everyday-low-price) is optimal.

## 4. The Seller's Optimal Pricing and Inventory Policy

### 4.1. The Optimal Everyday-Low-Price Strategy

First consider the everyday-low-price strategy in which the seller sells the product at a single price  $p$ . Given the price, a consumer buys the product if and only if her reservation price  $v \geq p$ . Hence, the total expected demand given price  $p$  is  $N \cdot \text{Prob}(v \geq p) = N\bar{F}(p) = N(\bar{v} - p)/\bar{v}$ . The seller optimally sets his inventory level to be exactly equal to this expected demand. The seller's profit is then equal to  $\Pi(p) = (p - c)N(\bar{v} - p)/\bar{v}$ . The following result characterizes the optimal price, inventory level, and seller profit under everyday-low-price.

PROPOSITION 3. *Under everyday-low-price, the optimal price is  $p^e = (\bar{v} + c)/2$ , the optimal inventory level is  $K^e = N(\bar{v} - c)/(2\bar{v})$ , and the seller's optimal profit is  $\Pi^e = N(\bar{v} - c)^2/(4\bar{v})$ . The seller's optimal decisions and profit are independent of the consumers' behavioral factors  $\alpha, \beta$ , and  $\theta$ .*

#### 4.2. The Optimal Markdown Strategy

Next consider the markdown strategy in which the seller sells the product at  $p_1$  in Period 1 and  $p_2 = \delta p_1$  in Period 2. From Proposition 1, we know that for a markdown strategy to be optimal, the seller's optimal inventory level must satisfy  $K \in [D_1, D_1 + D_2]$ , where  $D_1$  and  $D_2$  are defined in Lemma 1(i). Otherwise, the seller is effectively selling at a single price,<sup>7</sup> and his resulting profit cannot exceed that under the optimal everyday-low-price strategy (i.e.,  $\Pi^e$  in Proposition 3). Therefore, the seller's total profit under a markdown strategy is given by

$$\begin{aligned} \Pi(p_1, K) &= (p_1 - c) \min\{K, D_1\} + (\delta p_1 - c) \min\{K - \min\{K, D_1\}, D_2\} \\ &= (p_1 - c)N\bar{F}(v_1) + (\delta p_1 - c)(K - N\bar{F}(v_1)). \end{aligned}$$

In addition, the actual Period 2 fill rate is the ratio of the inventory available in Period 2 to the demand in Period 2; i.e.,

$$r = \frac{K - D_1}{D_2} = \frac{v_1 - (1 - K/N)\bar{v}}{v_1 - \delta p_1}.$$

The seller determines the optimal price and inventory level by maximizing his total profit from both periods while taking into account the consumers' purchase behavior. We characterize the seller's decision problem as follows.

$$\begin{aligned} \max_{p_1, K} \quad & \Pi(p_1, K) \equiv \frac{N}{\bar{v}} [(p_1 - c)(\bar{v} - v_1) + (\delta p_1 - c)(v_1 - (1 - K/N)\bar{v})] \\ \text{s.t.} \quad & v_1 = \left( \frac{(1 + \alpha)(1 - \delta)q}{(1 + \beta)(1 - q)} + 1 \right) p_1 \in [p_1, \bar{v}], \\ & q = r^\theta, \\ & r = \frac{v_1 - (1 - K/N)\bar{v}}{v_1 - \delta p_1}, \\ & K \in \left[ \frac{N}{\bar{v}}(\bar{v} - v_1), \frac{N}{\bar{v}}(\bar{v} - \delta p_1) \right]. \end{aligned} \tag{5}$$

The first constraint specifies the reservation price of the indifferent consumer, i.e., the cutoff value  $v_1$ . The second constraint specifies the relationship between consumers' perceived Period 2 fill rate and the actual one. The third constraint specifies the actual Period 2 fill rate given the cutoff value  $v_1$ , the second-period

<sup>7</sup> In particular,  $K < D_1$  implies selling only at the high price and  $K > D_1 + D_2$  implies selling only at the low price. The former follows from Proposition 1(i). To see the latter, note that  $D_1 + D_2$  is the maximum number of consumers who can afford the product at the low price. If  $K > D_1 + D_2$ , then both the actual and perceived Period 2 fill rates are equal to 1. By Proposition 1(ii), we know that all consumers whose reservation prices exceed the low price will wait and buy the product in Period 2. Hence, the seller effectively sells the product only at the low price.

price  $\delta p_1$ , and the inventory  $K$ . These constraints together demonstrate the interplay between the seller's decisions and the consumers' purchase behavior through regret and availability misperception. Note that the realized sales in Period 2 ( $K - D_1 = rD_2$ ) is determined by the actual Period 2 fill rate  $r$ . The perceived Period 2 fill rate ( $q$ ) impacts sales only indirectly by affecting the market segmentation (i.e., affecting  $v_1$ ).

We next analyze the seller's optimal markdown strategy. The first three constraints in (5) determine the following relationships among the inventory level  $K$ , the actual Period 2 fill rate  $r$ , the first-period price  $p_1$ , and the cutoff value  $v_1$ , which must be satisfied in the optimal markdown solution:

$$K(p_1, v_1) = \frac{N}{\bar{v}} \left[ \bar{v} - v_1 + (v_1 - \delta p_1) \left( \frac{(1 + \beta)(v_1 - p_1)}{(1 + \beta)v_1 + (\alpha - \beta - (1 + \alpha)\delta)p_1} \right)^{1/\theta} \right], \quad (6)$$

$$r(p_1, v_1) = \left( \frac{(1 + \beta)(v_1 - p_1)}{(1 + \beta)v_1 + (\alpha - \beta - (1 + \alpha)\delta)p_1} \right)^{1/\theta}. \quad (7)$$

We know from (6) that given any price  $p_1$ , there is a one-to-one correspondence between  $K$  and  $v_1$  (see Lemma O.1 in Appendix O.7). Intuitively, given  $p_1$ , increasing  $K$  increases the actual and perceived Period 2 fill rates ( $r$  and  $q$ ). The increase in  $q$  in turn raises the cutoff value  $v_1$  as seen in (4). Thus, we can substitute (6) into (5) and transform the seller's decision problem to the following:

$$\max_{p_1 \in [c, \bar{v}], v \in [p_1, \bar{v}]} J(p_1, v) \equiv (p_1 - c)(\bar{v} - v) + (\delta p_1 - c)(v - \delta p_1) \left( \frac{(1 + \beta)(v - p_1)}{(1 + \beta)v + (\alpha - \beta - (1 + \alpha)\delta)p_1} \right)^{1/\theta}. \quad (8)$$

Here, we drop the subscript in  $v_1$  and the constant  $N/\bar{v}$  for simplicity. The following proposition characterizes the unique optimal solution under the markdown strategy.

**PROPOSITION 4.**  *$J(p_1, v)$  in (8) is quasiconcave in  $(p_1, v)$ . Let  $(p_o, v_o)$  be the joint solution to the first-order conditions:*

$$\frac{\bar{v} - v_o + \delta(v_o + c - 2\delta p_o)r_o}{\delta p_o - c} - \frac{(1 + \alpha)(v_o - \delta p_o)(1 - \delta)v_o r_o^{1+\theta}}{\theta(1 + \beta)(v_o - p_o)^2} = 0, \quad (9)$$

$$\frac{(1 + \alpha)(v_o - \delta p_o)(1 - \delta)p_o r_o^{1+\theta}}{\theta(1 + \beta)(v_o - p_o)^2} + r_o - \frac{p_o - c}{\delta p_o - c} = 0, \quad (10)$$

where  $r_o = r(p_o, v_o)$  by (7). Then

(i) *If  $v_o < \bar{v}$ , the unique optimal markdown solution is achieved at the interior of the feasible region: the optimal cutoff value  $v^m = v_o \in (p_o, \bar{v})$ , the optimal first-period price  $p_1^m = p_o \in (c, \bar{v})$ , the optimal inventory  $K^m = K(p_o, v_o)$  by (6), and the optimal actual Period 2 fill rate  $r^m = r_o \in (0, 1)$ .*

(ii) *If  $v_o \geq \bar{v}$ , the unique optimal markdown solution is achieved at the boundary: the optimal cutoff value  $v^m = \bar{v}$ , the optimal first-period price  $p_1^m = \arg \max_{p_1 \in (c, \bar{v})} J(p_1, \bar{v})$ , the optimal inventory  $K^m = K(p_1^s, \bar{v})$  by (6), and the optimal actual Period 2 fill rate  $r^m = r(p_1^s, \bar{v}) \in (0, 1]$  by (7).*

Proposition 4 characterizes the optimal markdown solution in two distinct cases. Part (i) shows the case when the optimal solution is an interior solution: the optimal actual Period 2 fill rate  $r^m$  is strictly between

0 and 1. Hence, the seller earns positive profits in both periods with different prices. Conversely, Part (ii) describes the case when the optimal markdown solution is achieved at the boundary. In particular, the optimal cutoff value is equal to the highest reservation price, implying that all consumers wait for the markdown. In this case, the seller is effectively selling only at the low price. Thus, the seller's resulting profit cannot exceed that under the optimal everyday-low-price strategy, leading to the following corollary.

**COROLLARY 1.** *When the optimal markdown solution is achieved at the boundary, the everyday-low-price strategy weakly dominates the markdown strategy.*

Given the optimal markdown solution specified in Proposition 4, the seller's resulting optimal profit is equal to

$$\Pi^m = \frac{N}{\bar{v}} [(p_1^m - c)(\bar{v} - v^m) + (\delta p_1^m - c)(v^m - \delta p_1^m)r^m]. \quad (11)$$

### 4.3. The Seller's Optimal Policy

The discussion in §4.1 and §4.2 formulates how the optimal price and inventory level can be determined under either everyday-low-price or markdown. Which strategy is the eventual optimal one for the seller depends on whether  $\Pi^e$  in Proposition 3 or  $\Pi^m$  in (11) is higher. The following proposition characterizes the seller's optimal policy.

**PROPOSITION 5.** (i) *If  $\alpha < \beta$  and  $\theta \geq 1$ , there exists a  $\bar{v}^*$  such that*

(a) *for all  $\bar{v} > \bar{v}^*$ , the markdown strategy is optimal, and the optimal solution must be an interior solution with the optimal actual Period 2 fill rate  $r^* \in (0, 1)$ ;*

(b) *for all  $\bar{v} \leq \bar{v}^*$ , everyday-low-price is optimal.*

(ii) *If  $\alpha \geq \beta$  and  $\theta = 1$ , everyday-low-price is always optimal.*

Proposition 5(i)-(a) describes the sufficient conditions under which the markdown strategy is optimal: First, the stockout regret has a greater impact than the high-price regret; and second, consumers value the product sufficiently high. Under these conditions, high-value consumers are motivated to buy at the high price because the negative sentiment associated with possibly not obtaining the product outweighs the negative sentiment corresponding to paying a premium. Conversely, if the high-price regret has the same or greater impact than the stockout regret *and* consumers are not subject to availability misperception (i.e.,  $\alpha \geq \beta$  and  $\theta = 1$  as in part (ii) of the proposition), it is optimal for the seller to follow everyday-low-price.

## 5. Consumers' Behavioral Motives versus Strategic Motives

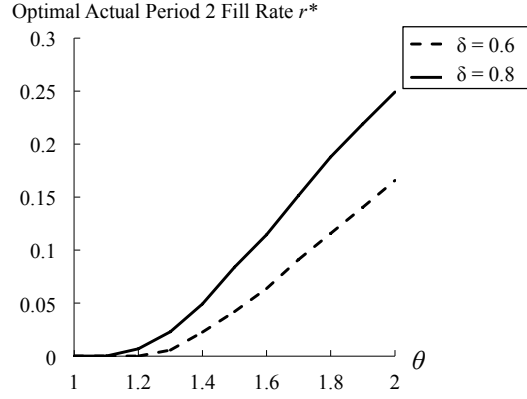
Here, we demonstrate the distinctive roles of consumers' strategic (pecuniary) versus behavioral (non-pecuniary) motives in affecting the purchase, pricing, and inventory decisions. Our discussion also highlights why the implications from our model cannot be obtained by simply considering our setting to be in the middle ground between the fully-myopic-consumer regime and the fully-rational-consumer regime.



First, our results highlight that *strategies prescribed by models that only consider consumers' strategic motives but ignore their behavioral motives can be suboptimal*. We remark that a special case of Proposition 5(ii) is when  $\alpha = \beta = 0$  and  $\theta = 1$ ; i.e., when consumers are not affected by regret or availability misperception. Thus, Proposition 5 generalizes prior results that only consider consumers' strategic motives based on rational expectations and determines how consumers' behavioral motives impact the seller's optimal policy. In particular, Proposition 5(ii) encompasses earlier conclusions that everyday-low-price is optimal when behavioral factors of risk-neutral consumers are not captured (e.g., Gallego et al. 2008, Liu and van Ryzin 2008). In stark contrast, Proposition 5(i)-(a) shows that in a market composed of high-value consumers who are influenced by regret and/or availability misperception, it can be more profitable to apply a markdown strategy. The optimal markdown strategy utilizes both intertemporal price discrimination and inventory rationing. The optimal actual Period 2 fill rate  $r^*$  being strictly greater than 0 implies that consumers buy at different prices in different periods based on their reservation prices; i.e., intertemporal price discrimination is applied. In addition,  $r^*$  being strictly less than 1 indicates that the seller intentionally limits product supply at the low price; i.e., he adopts inventory rationing.

Second, our model demonstrates an important interplay among the behavioral factors: *Availability misperception reinforces stockout regret and alleviates high-price regret*. When consumers underweight the product availability at the low price (i.e.,  $\theta > 1$  and hence  $q < r$ ), we observe from (1) and (2) that the stockout regret is aggravated, whereas the high-price regret is alleviated. As a result, consumers become more willing to buy at the high price. Indeed, when consumers' misperception of availability is sufficiently strong (i.e., when  $\theta$  is large), applying a markdown strategy can be optimal for the seller even when high-price regret dominates stockout regret (i.e.,  $\alpha > \beta$ ). Figure 2 illustrates an extreme example where only the high-price regret is in effect and has the highest possible marginal value (i.e.,  $\alpha = 1$  and  $\beta = 0$ ). We observe from Figure 2 that as  $\theta$  increases, the optimal actual Period 2 fill rate increases and lies strictly between 0 and 1. That is, the markdown strategy becomes optimal. Intuitively, when consumers are highly pessimistic about the possibility of obtaining the product at the low price, the high-price regret almost becomes irrelevant. Thus, consumers' decision to buy at the high price is primarily driven by the mentally amplified stockout risk that they perceive.

Another striking observation from our model is that *the superiority of markdown is primarily attributed to introducing the discount rather than charging a higher first-period price compared to the optimal everyday low price*. This observation implies that when consumers are driven by both strategic and behavioral motives, the seller should bravely leverage discounts while cautiously limiting the extent of markup from the optimal everyday low price in his markdown strategy. In our extensive numerical analysis (§6), we observe that the optimal first-period price  $p_1^*$  is on average 1.6% (and no more than 8%) higher than the optimal everyday low price ( $p^e$  defined in Proposition 3), whereas the optimal second-period price  $p_2^*$  is



**Figure 2 Optimal Actual Period 2 Fill Rate  $r^*$  as a Function of  $\theta$  When Only High-Price Regret Is in Effect**

Note: The figure is created with parameters  $\bar{v} = 100$ ,  $\delta \in \{0.6, 0.8\}$ ,  $\alpha = 1$ , and  $\beta = 0$ ;  $r^* = 0$  indicates that everyday-low-price is optimal.

on average 45.8% (and up to 80%) lower than  $p^e$ . Further, the gap between  $p_1^*$  and  $p^e$  is always smaller than that between  $p_2^*$  and  $p^e$ .<sup>8</sup> The intuition is as follows. If the first-period price in a markdown strategy is low, the price advantage of waiting for the markdown relative to her valuation is small for a high-value consumer (i.e.,  $(1 - \delta)p_1/v$  is small). Hence, introducing the discount offers weak strategic motive for a high-value consumer to delay her purchase (see Lemma 1). Since the stockout regret promotes the optimality of markdown (see Proposition 2) and availability misperception reinforces the stockout regret, the presence of these two factors can provide sufficient behavioral motives to ensure that the majority of the high-value consumers continue to buy at the high price. However, if the first-period price is higher, much stronger stockout regret and availability misperception are needed to counteract the high-value consumers' strategic motive of waiting for the discount. Thus, the joint influence of consumers' strategic and behavioral motives constrains how much the seller can raise the first-period price in the optimal markdown strategy.

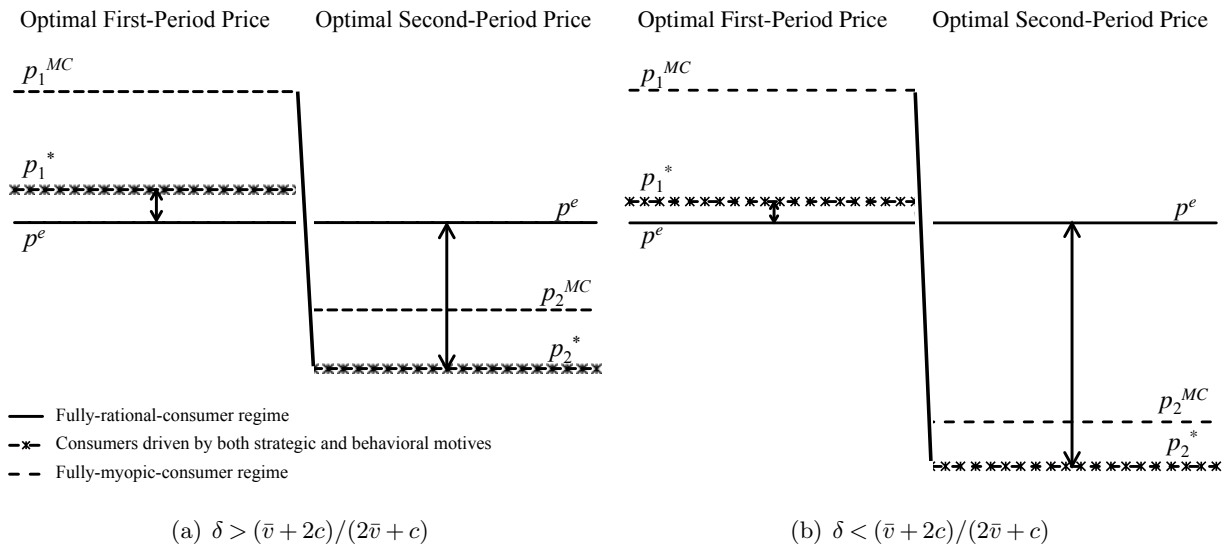
By only considering a setting in the middle ground between the fully-myopic-consumer and fully-rational-consumer regimes without explicitly accounting for behavioral motives, one cannot prescribe how the seller should optimally utilize the pricing levers in a markdown strategy. To see why, first note that there are two levers in intertemporal price discrimination: raising the first-period price above the optimal everyday low price and introducing a discount. If all consumers are myopic in our setting, then  $p_1^{MC} - p^e > p^e - p_2^{MC}$  if  $\delta > (\bar{v} + 2c)/(2\bar{v} + c)$ , and  $p_1^{MC} - p^e < p^e - p_2^{MC}$  otherwise, where  $p_1^{MC}$  and  $p_2^{MC}$  denote the optimal first-period price and second-period price with myopic consumers (see Appendix C).<sup>9</sup>

<sup>8</sup> These results continue to hold even if the seller can optimize both prices in the markdown strategy (as opposed to using a fixed percentage discount  $\delta$ ). In this case,  $p_1^*$  is on average 2.5% and no more than 8.7% higher than  $p^e$ , whereas  $p_2^*$  is on average 20% and up to 30% lower than  $p^e$ . We remark that optimizing both prices is equivalent to optimizing both the first-period price and the discount factor.

<sup>9</sup> If the seller can optimize both prices, then  $p_1^{MC} - p^e = p^e - p_2^{MC}$  always holds.

Hence, if  $\delta > (\bar{v} + 2c)/(2\bar{v} + c)$ , the optimal markdown strategy implements a substantially high first-period price with a moderate discount. Otherwise, if  $\delta < (\bar{v} + 2c)/(2\bar{v} + c)$ , the optimal markdown strategy applies a deep discount and a moderate markup from the optimal everyday low price. Conversely, if all consumers are fully rational, everyday-low-price is always optimal (by Proposition 5(ii)).

Figure 3 compares the optimal prices in the fully-myopic-consumer regime (the dash lines) and the fully-rational-consumer regime (the solid lines) with those prescribed by our model when markdown is optimal (the star-dash lines). We observe that regardless of the value of  $\delta$ , the behavioral factors have the same *asymmetric* effect on markup versus discount: In the optimal markdown strategy, the extent of markup from the optimal everyday low price is always smaller than the extent of discount.<sup>10</sup> However, in the fully-myopic-consumer regime (the dash lines), the extent of markup can be larger (in Figure 3(a)) or smaller (in Figure 3(b)) than the extent of discount. Hence, one would not be able to predict the above asymmetric effect if one were to consider our setting as a middle ground between the fully-myopic-consumer and fully-rational-consumer regimes. These comparisons demonstrate that analyzing the joint impacts of consumers' strategic and behavioral motives is necessary to offer precise prescription of how prices should be optimized for a markdown strategy.



**Figure 3** Comparing Optimal Prices under Fully-Myopic-Consumer Regime, Fully-Rational-Consumer Regime, and Our Model

Finally, our next result implies that *strong stockout regret and availability misperception encourage the seller to increasingly price discriminate high- and low-value consumers intertemporally, and reduce the extent of inventory rationing.*

<sup>10</sup> A similar pattern is observed for the scenario where the seller optimizes both prices.

PROPOSITION 6. *Under markdown, the optimal first-period price  $p_1^m$ , the optimal inventory  $K^m$ , and the seller's optimal profit  $\Pi^m$  are increasing in  $\beta$  and  $\theta$  but decreasing in  $\alpha$ .*

As stockout regret and/or availability misperception becomes stronger, the seller charges a higher first-period price and stocks a higher level of inventory under the optimal markdown strategy. As a result, the absolute price difference between the two periods  $((1 - \delta)p_1)$  becomes larger; i.e., stronger intertemporal price discrimination is in place. In addition, increasing total inventory means that the seller uses inventory rationing to a lesser extent. Intuitively, stronger stockout regret and/or availability misperception makes consumers more eager to buy at the high price, whereas stronger high-price regret leads to the contrary. Thus, the seller benefits from the former two behavioral factors and suffers from the high-price regret. Note that the seller's profit under everyday-low-price is constant and independent of the behavioral factors (Proposition 3). Therefore, as the strength of stockout regret and/or availability misperception increases, it is more profitable for the seller to use the markdown strategy.

**Managerial Implications:** Our results provide insights and actionable strategies regarding how companies may leverage consumers' behavioral motives to improve profitability. For example, industries in which the negative sentiment related to stockout is likely to play an important role include hot toys for holiday seasons, high-fashion apparel, and luxury accessories. The results suggest that companies in these industries do not need to worry too much about the potential negative impact of price markdowns. Instead, it is profitable for them to leverage consumers' misperception of product availability. One possible tactic is to explicitly provide inventory information to their favor. For example, if companies frequently announce stockout and thus influence consumers to underweight product availability, consumers are likely to be more eager to buy at a high price.<sup>11</sup> We indeed observe an analogous strategy being increasingly used by e-commerce Web sites, where sellers deliberately make statements such as "only 5 left in stock" or "only 2 seats left" on their product pages to create a sense of urgency among the consumers (see Figure 8 in Appendix B). We postulate that this sense of urgency may be due to the fact that consumers often perceive future availability to be lower than the actual availability, and showing low inventory information makes this misperception more salient. Similarly, in traditional brick-and-mortar stores, retailers can heighten the sense of possible stockout risk by placing limited quantities of each item on the shelf while keeping a large inventory in the stockroom. Since availability misperception reinforces stockout regret and subsumes high-price regret, such information strategy is likely to create more lucrative outcomes than common marketing campaigns that only act on consumer regret (e.g., by provoking the discomfort about missing the vogue of the season).

<sup>11</sup> Note that we do not propose that companies present falsified information. Rather, we suggest that companies can benefit from showing information when such information intensifies consumer's availability misperception.

## 6. Quantifying the Impacts of Regret and Availability Misperception

In this section, we answer and quantify the following questions: (i) How much profit will the seller potentially lose if he ignores consumers' behavioral factors in his decisions, as opposed to correctly incorporating them? (ii) How do the behavioral factors interact with each other and jointly affect the seller's optimal profit? (iii) What is the profit implication if the seller has inaccurate estimates about the behavioral parameters in his analysis? Addressing these questions enables us to further determine the conditions under which the behavioral factors of interest have the most significant operational and profit implications.

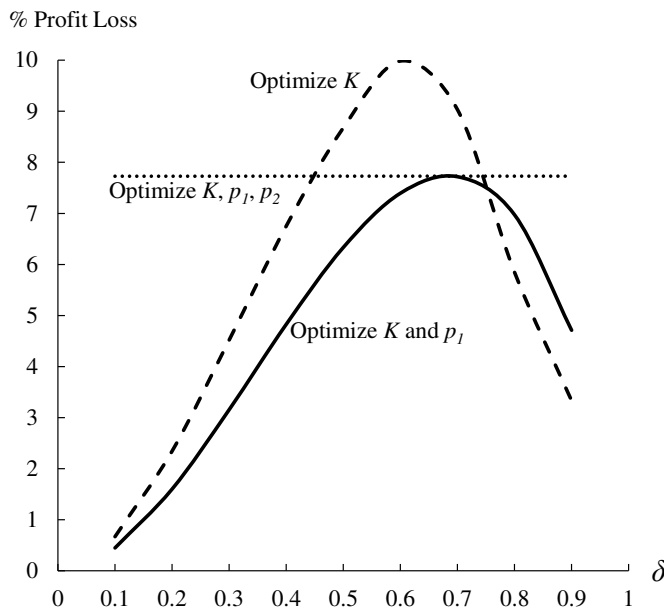
### 6.1. Profit Losses When Ignoring Regret and Availability Misperception

We examine three different scenarios regarding the operational levers that are available to the seller under the markdown strategy. In particular, we consider (i) the seller can only optimize the inventory level given exogenous prices, (ii) the seller optimizes both inventory and the first-period price, and (iii) the seller optimizes inventory and prices in both periods. Thus, the seller has increasing operational control from Scenario (i) to (iii). All three scenarios are relevant to practice. Scenario (i) corresponds to industries in which competition is intensive and consumers have formed strong reference prices from past purchases or easily accessible price information. An example is the consumer electronics industry in which prices are largely shaped by competitive forces in the market. Scenario (ii) represents industries where products are relatively differentiated. Hence, companies in such industries have some flexibility in optimizing the full price. Nevertheless, companies may follow conventional markdown schedules due to their managerial simplicity and marketing appeal. One example is the apparel industry. Finally, Scenario (iii) corresponds to industries that provide highly differentiated products such as designer or luxury fashion industries.

Our analysis of each scenario consists of the following steps. We first find the seller's "optimal" decisions when he ignores the behavioral factors, i.e., by assuming that  $\alpha = \beta = 0$  and  $\theta = 1$ . Given these suboptimal decisions, we compute the seller's resulting profit when consumers' purchase decisions are in fact affected by the ignored behavioral factors (e.g., when  $\beta = 1$  and  $\theta = 2$ ). We then compare the seller's suboptimal profit and decisions with the optimal ones when the seller is aware and fully incorporates the behavioral factors in his decisions.

We choose a large parameter set to ensure the robustness of our conclusions. In particular, we examine the following numerical values:  $\bar{v} \in [10, 100]$  with an increment of 10,  $\delta \in [0.1, 0.9]$  with an increment of 0.1 (for Scenarios (i) and (ii)),  $p_1 \in [\bar{v}/10, \bar{v}]$  with an increment of  $\bar{v}/10$  (for Scenario (i)),  $N = 5000$ ,  $c = 0$ ,  $\alpha \in [0, 1]$ ,  $\beta \in [0, 1]$ , and  $\theta \in [1, 2]$  with increments of 0.1 for all three behavioral parameters. Thus, for Scenario (ii) which corresponds to our model in the previous sections, we study a total of 119,790 parameter combinations. Figure 4 demonstrates the representative pattern commonly observed in our analysis. The dashed, solid, and dotted lines show the results for Scenarios (i), (ii), and (iii), respectively. We define the percentage profit loss as the difference between the optimal profit and the profit under suboptimal

decisions divided by the optimal profit. We plot the percentage profit loss against the discount factor  $\delta$  for Scenarios (i) and (ii). The percentage profit loss for Scenario (iii) does not depend on the value of  $\delta$  and thus is shown as a flat line. Table 1 summarizes the statistics for our complete numerical sample.



**Figure 4 Profit Impact of Ignoring Behavioral Factors**

Note: The figure is generated with  $\bar{v} = 100$ ,  $p_1 = 60$  for Scenario (i), and the true parameters:  $(\alpha, \beta, \theta) = (0, 1, 2)$ .

**Table 1 Statistics for Profit Losses and Suboptimal Decisions When Ignoring Behavioral Factors**

	% Differences between Suboptimal and Optimal Values*								
	(i) Optimize $K$		(ii) Optimize $(K, p_1)$			(iii) Optimize $(K, p_1, p_2)$			
	$\Pi$	$K$	$\Pi$	$K$	$p_1$	$\Pi$	$K$	$p_1$	$p_2$
<b>Average</b>	2.36	8.41	3.14	6.86	3.68	4.86	5.69	5.63	-10.17
<b>Std. Dev.</b>	2.46	8.30	2.15	3.97	2.17	2.12	1.71	1.73	10.45
<b>Max</b>	10.12	45.95	7.72	13.52	7.75	7.73	8.07	7.98	-35.14

\*: % difference  $\equiv$  (optimal value – suboptimal value)/(optimal value)  $\times$  100%.

Notes: (a)  $\Pi, K, p_1$ , and  $p_2$  denote the seller’s profit, inventory, first-period price, and second-period price.

(b) In Scenario (i), the suboptimal  $K$  is predominantly lower than the optimal one; in Scenarios (ii) and (iii), the suboptimal  $K$  and  $p_1$  are always lower than the optimal ones; in Scenario (iii), the suboptimal  $p_2$  is always higher than the optimal one.

We highlight three observations. First, ignoring the behavioral factors can generate substantial profit losses. Table 1 shows that the potential profit loss can be as high as 10.1% when the seller does not have pricing power. Remarkably, even when the seller has pricing power, he may still leave up to 7.7% of potential profit on the table if he ignores the behavioral factors. We note that industries frequently practicing markdowns often have slim profit margins. For example, the average profit margins for the grocery and non-branded apparel industries are 1% and 8% respectively.<sup>12</sup> Even for the higher-margin

<sup>12</sup> See <http://smallbusiness.chron.com/industry-standard-gross-margin-groceries-38121.html> and <http://smallbusiness.chron.com/profit-margin-retail-clothes-25123.html>.

branded fashion and department store industries, a 7.7% profit loss has a serious financial consequence.<sup>13</sup> In addition, our data show that the magnitude of profit losses is mainly affected by the discount factor  $\delta$  and rarely varies in the highest reservation price  $\bar{v}$ . As shown in Figure 4, the large profit losses occur when  $\delta$  is in the range of  $[0.4, 0.8]$  (for Scenarios (i) and (ii)). This range corresponds to the most commonly observed markdown levels in the market; i.e., 20% – 60% markdowns. Therefore, the magnitude of profit losses that we quantify is highly relevant.

Second, when examining the suboptimal decisions, we observe that the profit losses are associated with setting both the inventory and the first-period price too low, and setting the second-period price too high.<sup>14</sup> As shown in Table 1, when the seller optimizes both inventory and first-period price, his suboptimal inventory and first-period price can be respectively 13.5% and 7.8% lower than the optimal levels. In addition, when the seller has full control in determining inventory and both prices, his suboptimal inventory and first-period price are 8% lower than the optimal levels, and the suboptimal second-period price can be 35% higher than the optimal one. These observations conform to the implication from Proposition 6 that the presence of stockout regret and availability misperception encourages the seller to increasingly use intertemporal price discrimination and reduce the extent of inventory rationing.

Third, we examine the effect of increasing the seller’s pricing power on the magnitude of profit losses. We observe from Figure 4 that adding the flexibility of optimizing the first-period price (with an exogenous discount factor) can mitigate the potential profit loss due to negligence of consumers’ behavioral motives. This can be seen from the fact that the solid line is mostly below the dashed line. However, if in addition, the seller can also optimize the second-period price, he suffers from a higher potential profit loss (the dotted line is above the solid line). This seemingly counterintuitive observation is jointly driven by two results: (i) The seller earns a higher *optimal* profit when he has full pricing power and correctly incorporates consumers’ behavioral factors; (ii) when the seller ignores the behavioral factors, he adopts everyday-low-price (Proposition 5(i)) and the optimization of the second-period price becomes irrelevant. Consequently, the seller effectively forgoes a larger portion of the optimal profit when he has full pricing power than when he optimizes only the first-period price. Therefore, this observation does not imply that adding more operational control hurts the seller. Rather, it demonstrates a *behavioral* benefit of pricing: *Increasing the seller’s pricing power offers him more instrument to leverage consumers’ behavioral motives towards his benefit, thereby improving profitability.*

<sup>13</sup> For instance, a mere 1.1% drop in J.C. Penney’s gross margin meant a \$31.5 million loss in the company’s quarterly revenue and sent its stock price down by 1% (see <http://www.reuters.com/article/2011/08/12/us-jcpenney-idUKTRE77B26S20110812>).

<sup>14</sup> When the seller only optimizes inventory given fixed prices, he sets inventory lower than the optimal level in 91.6% of 1,197,900 total samples if ignoring the behavioral factors.

## 6.2. The Joint Effect of Regret and Availability Misperception on the Seller's Optimal Profit

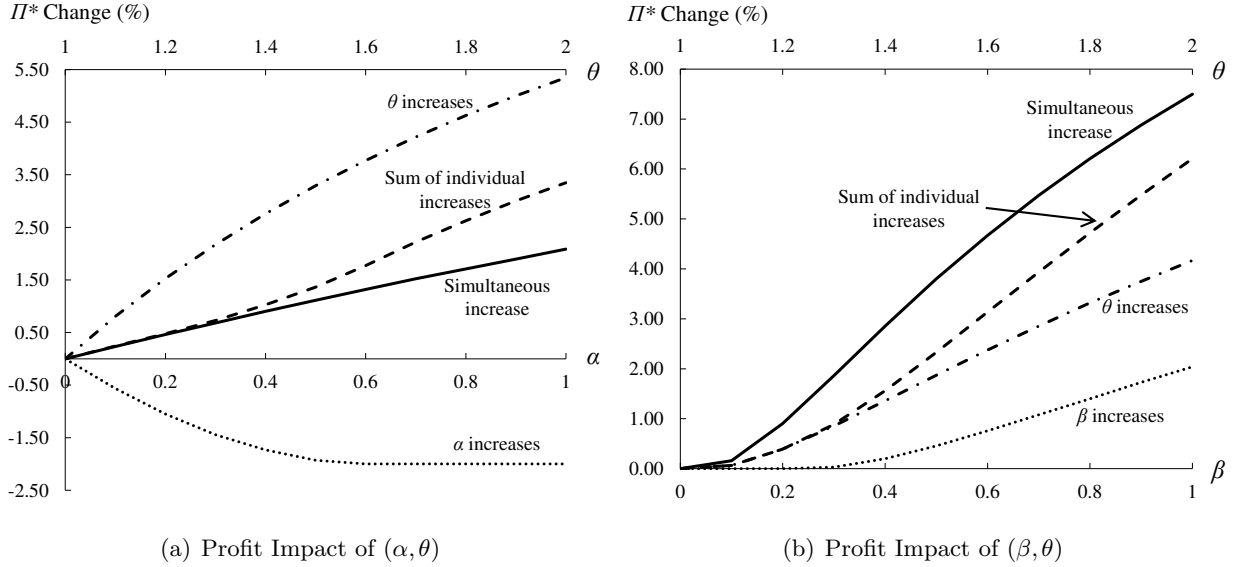
We follow three steps in this analysis. First, we compute the change in the seller's optimal profit when two of the behavioral factors jointly increase in equal increments. Second, we compute the change in the seller's optimal profit when either of the two factors individually increases and sum up the two changes. Third, we compare the profit change in Step 1 to the sum of profit changes in Step 2. The difference in these two values indicate whether the behavioral factors reinforce or mitigate each other to influence the seller's optimal profit. We focus our discussion on the joint effect of  $\alpha$  and  $\theta$  and that of  $\beta$  and  $\theta$ .<sup>15</sup> We use the same parameter set as in §6.1 for this analysis. Figure 5 presents a representative example of these two interactions. In both figures, the solid line shows the percentage change in the seller's optimal profit when both behavioral parameters simultaneously increase. The dashed line shows the sum of the percentage profit changes due to individual increases of each behavioral parameter. We highlight three observations. First, Figure 5(a) shows that the joint effect of high-price regret and availability misperception is positive for the seller; i.e., the seller earns a positive profit gain (indicated by the solid line) even though the two behavioral factors individually drive the seller's profit in opposite directions. Second, Figure 5(b) demonstrates that stockout regret and availability misperception reinforce each other in improving the seller's profit. That is, the profit increase when both  $\beta$  and  $\theta$  jointly increase (the solid line) is substantially higher than the sum of profit increases when either factor increases (the dashed line). Third, under the same magnitude of parameter change, availability misperception has a greater impact on the seller's profit than either regret (the magnitude of the dash-dot line is larger than that of the dotted line in both figures). These observations corroborate our earlier discussion that availability misperception strengthens stockout regret and mitigates high-price regret, rendering the joint impact of these behavioral factors to be in the seller's favor. We note that the above results always hold in our entire sample.

## 6.3. Sensitivity to Inaccurate Estimates of Behavioral Parameters

We show in the previous sections that correctly incorporating regret and availability misperception in the seller's operational decisions can substantially improve the seller's profit. A question arises whether such benefit is robust to potential inaccuracy in the seller's estimates of the relevant behavioral parameters (i.e.,  $\alpha$ ,  $\beta$ , and  $\theta$ ). We answer this question by examining the profit consequence when the seller miscalibrates  $\theta$  in his analysis. The reasons to focus on  $\theta$  are twofold. First, ample empirical results have shown that the most observed values of  $\theta$  fall in the range of  $[1.5, 2]$  given our specification (e.g., Qiu and Steiger 2011, van de Kuilen and Wakker 2011). This empirically validated range offers a reliable basis for our sensitivity analysis. Second, as discussed earlier, availability misperception has a greater impact

<sup>15</sup> We can derive from Proposition 1 that if  $\alpha = \beta$ , the threshold  $Q$  and cutoff value  $v_1$  are independent of these two factors; i.e., consumers' purchase behavior is not affected by either regret. Hence, increasing  $\alpha$  and  $\beta$  jointly in equal increments will have no effect on the seller's optimal profit.



(a) Profit Impact of  $(\alpha, \theta)$ (b) Profit Impact of  $(\beta, \theta)$ **Figure 5 The Joint Impact of Multiple Behavioral Factors on the Seller's Profit**

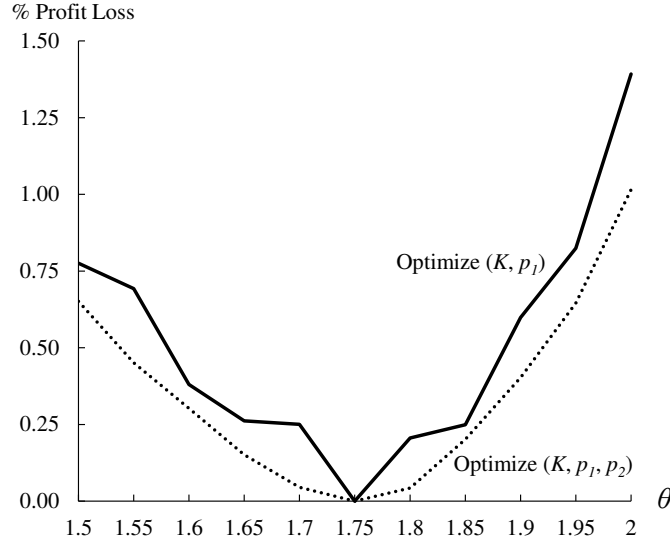
Note: The figure is created with parameters  $\bar{v} = 100$ ,  $\delta = 0.8$ ,  $\beta = 1$  in (a), and  $\alpha = 0$  in (b).

than regret on the seller's profit (e.g., see Figure 5). Hence, testing the robustness of our results with respect to possible inaccuracy in estimating  $\theta$  has first-order importance. Figure 6 demonstrates how the seller's profit compares to the optimal profit if he under- or over-estimates  $\theta$  in two scenarios: (i) when the seller optimizes inventory and first-period price, and (ii) when he optimizes inventory and both prices. Here we assume the true value of  $\theta$  to be the midpoint of the empirical range, i.e.,  $\theta = 1.75$ . The seller may underestimate  $\theta$  down to 1.5 or overestimate it up to 2. We observe that the maximum profit loss is capped at 1.5%, and it is within 1% for the majority of the range ( $[1.5, 1.95]$ ). When the seller has full operational control, the maximum profit loss is always lower than 1%. Thus, compared to the 7.7% profit loss due to complete ignorance of the behavioral factors, the profit consequence of mis-calibrating the behavioral parameters is much smaller. These results suggest another behavioral benefit of pricing: *Having pricing power protects the seller from possible negative impact of inaccurate estimates about the relevant behavioral factors*. In addition, if the seller intentionally increases the salience of availability misperception by taking managerial actions as discussed in §4, we expect that  $\theta$  tends to take a high value among the consumers, further alleviating the concerns of inaccurate estimates.<sup>16</sup>

#### 6.4. Robustness

Here we discuss the robustness of our insights with respect to two variations to our model setup. The first variation considers risk-averse instead of risk-neutral consumers.

<sup>16</sup> We also perform a similar analysis with respect to  $\alpha$  and  $\beta$ . In particular, we assume that the true values of  $\alpha$  and  $\beta$  are 0.5. The seller may underestimate these parameters down to 0 or overestimate them up to 1. We observe that the average profit loss due to inaccurate estimates of  $\alpha$  or  $\beta$  is 0.76% and 0.45% respectively, with standard deviations of 2.1% and 1.1%. The profit loss is within 1% in 90% of the total 990 numerical instances for each parameter.



**Figure 6 Profit Impact of Inaccurate Estimate about  $\theta$**

Note: The figure shows the maximum profit loss for  $\bar{v} \in [10, 100]$  and  $\delta \in [0.1, 0.9]$  (for Scenario (i)) with increments of 10 and 0.1. The true  $\theta$  value is 1.75.

**Risk-averse consumers:** In our consumer model, we use a linear value function by following the common approach of prior studies (e.g., Nasiry and Popescu 2012). Here, we verify the robustness of our conclusions when the value function is concave; i.e., when consumers are intrinsically risk-averse. We analyze the seller’s optimal policy with the value function taking the form of  $u(x) = x^{1-\gamma}$ .<sup>17</sup> The parameter  $\gamma$  measures the degree of risk aversion, with a larger value indicating that the consumer is more risk-averse. We use the same parameter set as in §6.1 and in addition  $\gamma \in \{0, 0.25, 0.5, 0.75\}$ . We highlight that our insights remain valid under this variation. First, when  $\gamma$  is small (i.e., when consumers are close to risk-neutral),  $\alpha \geq \beta$ , and  $\theta = 1$ , everyday-low-price is optimal, similar to Proposition 5(ii). When  $\gamma$  is large (i.e., when consumers are highly risk-averse), markdown becomes optimal because intrinsic risk aversion contributes to negative sentiment of stockout. Second, the comparative statics results discussed in Proposition 6 continue to hold. Further, the seller benefits from consumers’ risk aversion. The more risk-averse consumers are, the more eager they are to buy the product at the high price, thereby producing higher profit. Finally, we observe identical pattern as in Figure 4 regarding the potential profit losses if the seller ignores the behavioral factors when optimizing his decisions. The potential profit loss remains as high as 9% even when the seller has pricing power.

**Inverse-S shaped misperception of availability:** In the behavioral literature, another commonly recognized pattern regarding individuals’ probability misperception is that they underweight large probabilities but overweight small ones. This pattern can be characterized by an inverse-S shaped probability weighting function (e.g., Tversky and Fox 1995, Gonzalez and Wu 1999). Researchers have developed

<sup>17</sup> Given this value function, Equations (1) and (2) are revised to  $U_1(v, p_1) = (v - p_1)^{1-\gamma} - q\alpha[(v - p_1)^{1-\gamma} - (v - \delta p_1)^{1-\gamma}]$  and  $U_2(v, p_1) = q(v - \delta p_1)^{1-\gamma} - (1 - q)\beta \max\{(v - p_1)^{1-\gamma}, 0\}$ , respectively.

various forms of weighting functions and estimated the associated parameter values based on experimental data. Table 2 summarizes the most-studied weighting functions and the estimated parameter values. To study how our earlier results may change when consumers exhibit the inverse-S shaped misperception pattern, we numerically solve for the seller’s optimal policy under the models and parameter values in Table 2.<sup>18</sup> We highlight three findings. First, the inverse-S shaped probability misperception makes everyday-low-price optimal for a larger parameter range, primarily when markdown is optimal with a very low actual Period 2 fill rate in the original model. Nevertheless, markdown remains optimal for a large fraction of all numerical instances (23,363 out of 77,440 instances, i.e., 30%). Second, when markdown is optimal, consumers always underweight the actual Period 2 fill rate. Third, the potential profit losses due to negligence of consumers’ behavioral factors remain significant and can amount to 7% in our sample.

**Table 2 Empirically Validated Probability Weighting Functions**

Weighting Function	Estimated Parameter Values*	Source
$q = \frac{r^\theta}{[r^\theta + (1-r)^\theta]^{1/\theta}}$ by Tversky and Kahneman (1992)	$\theta = 0.61$ or $0.69$	Tversky and Kahneman (1992)
	$\theta = 0.56$	Camerer and Ho (1994)
	$\theta = 0.71$	Wu and Gonzalez (1996)
	$\theta = 0.6$ or $0.7$	Abdellaoui (2000)
$q = \exp\{-\eta(-\ln r)^\theta\}$ by Prelec (1998)	$\eta = 1, \theta = 0.74$	Wu and Gonzalez (1996)
	$\eta = 0.588, \theta = 0.26$ or $\eta = 1.11, \theta = 0.2$ or $\eta = 0.476, \theta = 0.26$	Baucells et al. (2011)
	$\eta = 1.578, \theta = 1.145$ or $\eta = 1.763, \theta = 1.054$	van de Kuilen and Wakker (2011)
$q = \frac{\eta r^\theta}{\eta r^\theta + (1-r)^\theta}$ by Gonzalez and Wu (1999)	$\eta = 0.77, \theta = 0.44$	Gonzalez and Wu (1999)
	$\eta = 0.65, \theta = 0.6$ or $\eta = 0.84, \theta = 0.65$	Abdellaoui (2000)
	$\eta = 0.46, \theta = 1.08$	Qiu and Steiger (2011)

\*: Multiple values for the same parameter were estimated from different data sets.

Note:  $r$  and  $q$  are the actual and perceived Period 2 fill rates, respectively.

To summarize, we conclude that our major insights are robust to intrinsic risk aversion of the consumers and an inverse-S shaped misperception of availability. Therefore, our model reliably quantifies the operational and profit impacts of the behavioral factors. Hence, it is useful for prescribing practical tactics to help companies leverage these factors to enhance profitability.

## 7. Discussion and Conclusion

Returning to our opening anecdote, how many units of the newly-designed dress that Emma adores should Ann Taylor stock at the beginning of the season? Is charging \$148 initially and applying a 30% markdown towards the end of the season the right strategy for the company? Earlier research suggests that consumers’ strategic motives force the company to adopt everyday-low-price and stock enough to serve all consumers who can afford the dress at that price. In sharp contrast, our analysis shows that

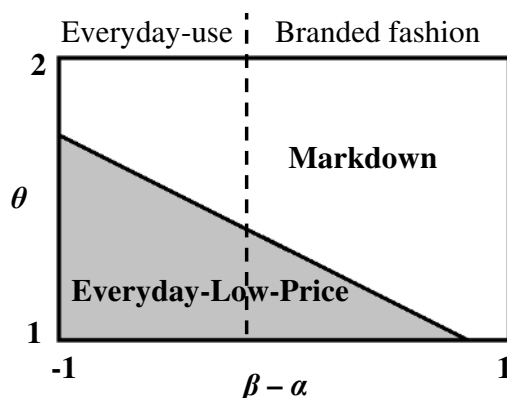
<sup>18</sup>The numerical values for the other model parameters are as follows:  $\bar{v} \in [10, 100]$  with an increment of 10,  $\delta \in \{0.2, 0.4, 0.6, 0.8\}$ ,  $N = 5000$ ,  $c = 0$ ,  $\alpha \in [0, 1]$ , and  $\beta \in [0, 1]$  with an increment of 0.1 for both behavioral parameters. Thus, we tested 77,440 numerical instances in total.

consumers' latent behavioral motives, regret and availability misperception, can reinstate the superiority of markdown over everyday-low-price. In addition, intentionally leveraging these behavioral factors, particularly strengthening the salience of availability misperception, can further enhance profit. For example, one possible tactic that Ann Taylor may use is to present a small quantity of the dress on the shop floor while keeping a large inventory in the stockroom.

Motivated by retail scenarios like what Emma and Ann Taylor often face, we study in this paper how consumers' behavioral motives impact a seller's pricing and inventory strategies. We consider a stylized setting where the seller sells a product over two periods. The seller chooses between two pricing strategies, markdown or everyday-low-price, and optimally determines the first-period price and the inventory level. We investigate two salient behavioral motives of the consumers: anticipated regret and misperception of availability. When faced with a markdown strategy, consumers may experience the high-price regret or the stockout regret depending on when they purchase the product. In addition, consumers tend to underweight the likelihood that the product will be available in Period 2.

We determine that both regret and availability misperception have a significant impact on the seller's optimal policy and the resulting profit. Figure 7 qualitatively summarizes the optimality of markdown versus everyday-low-price with respect to the strength of the behavioral factors. The horizontal axis shows the strength of stockout regret as compared to high-price regret. The vertical axis shows the strength of availability misperception. The white (resp., gray) region indicates the optimality of markdown (resp., everyday-low-price). When consumers are more influenced by negative sentiment due to stockout than that due to paying a premium (moving right horizontally), markdown outperforms everyday-low-price more often to be the seller's optimal policy. In addition, availability misperception reinforces stockout regret and subsumes high-price regret, further driving the optimality of the markdown strategy (moving up vertically). The optimal markdown strategy entails price discriminating high-value consumers from low-value ones intertemporally and applying some level of inventory rationing. Thus, compared to models that do not capture regret or availability misperception, the presence of these behavioral factors encourages the use of intertemporal price discrimination and discourages inventory rationing. In addition, the behavioral factors have an asymmetric effect on the two pricing levers under markdown. This asymmetry governs that the superiority of markdown over everyday-low-price is primarily attributed to introducing a discount rather than charging a higher first-period price than the optimal everyday low price. These results lead to important profit implications for the seller. If the seller ignores the behavioral factors when optimizing his operational decisions, he can leave as much as 7.7% of potential profit on the table. This loss can be up to 10% if the seller does not have pricing power. We also postulate that this negative effect will only escalate when companies further consider competition from substitute products and loss of goodwill due to not satisfying their customers. Finally, we define and demonstrate the *behavioral* benefits of pricing. The

seller's pricing power offers him additional means to leverage consumers' behavioral motives to increase profit. In addition, it mitigates the potential negative profit consequences due to mis-calibrating the relevant behavioral parameters.



**Figure 7** Optimality of Markdown versus Everyday-Low-Price with Respect to Behavioral Factors

Our results provide insights for the interesting contrast between Macy's and J.C. Penney's recent changes of their pricing practices. We conjecture that different products induce different strengths of the behavioral factors and thus fall in different regions of Figure 7. Consider apparel as an example. Everyday-use items such as T-shirts are likely to be associated with strong high-price regret but weak stockout regret (i.e., falling in the left region of Figure 7). In contrast, branded fashion items tend to induce strong stockout regret but weak high-price regret (i.e., falling in the right region of Figure 7). Our results suggest that Macy's strategy of applying everyday-low-price to everyday-use items while practicing markdown for branded fashion items may be a smarter policy compared to J.C. Penney's failing strategy of completely switching to everyday-low-price. A product-dependent policy such as that by Macy's leverages the benefits of both pricing strategies under the right conditions, thereby enhancing overall profitability. We remark that this discussion is meant to illustrate potential managerial implications of our results and requires further analyses to be conclusive. Nevertheless, it highlights that it is imperative for the seller to be aware and take full account of consumers' behavioral motives when devising optimal retail strategies.

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## Appendix A: Notation

### Market parameters

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$N$ :	total number of consumers in the market
$c$ :	unit cost for procuring inventory
$p_i$ :	unit price in Period $i$ , with $i \in \{1, 2\}$
$\delta$ :	discount factor of the second-period price, $p_2 = \delta p_1$
$K$ :	total inventory of the product
$r$ :	actual probability that the product is available in Period 2 (also called the actual Period 2 fill rate)
$q$ :	consumers' perceived probability that the product is available in Period 2 (also called the perceived Period 2 fill rate)
$v$ :	a consumer's reservation price for the product
$\bar{v}$ :	the highest reservation price for the product among all consumers
$v_1$ :	the reservation price of the indifferent consumer (also called the cutoff value)
$F(\cdot), f(\cdot)$ :	the cumulative distribution function and probability density function of consumers' reservation prices; $\bar{F}(\cdot) \equiv 1 - F(\cdot)$
$D_i$ :	demand in Period $i$ under markdown, with $i \in \{1, 2\}$
$D_T$ :	total demand in both periods under markdown

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### Behavioral parameters

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$\alpha$ :	marginal value of high-price regret, $\alpha \in [0, 1]$
$\beta$ :	marginal value of stockout regret, $\beta \in [0, 1]$
$\theta$ :	availability misperception parameter, $\theta \geq 1$
$\gamma$ :	risk-aversion parameter, $\gamma \in [0, 1]$

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### Decision and profit

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$p_1$ with $\cdot \in \{m, *\}$ :	the optimal first-period price under markdown ( $\cdot = m$ ) and the optimal policy ( $\cdot = *$ )
$p^e$ :	the optimal price under everyday-low-price
$p^{MC}$ with $\cdot \in \{1, 2\}$ :	the optimal first-period price ( $\cdot = 1$ ) and second-period price ( $\cdot = 2$ ) when all consumers are myopic
$K$ with $\cdot \in \{e, m, *\}$ :	the optimal inventory level under everyday-low-price ( $\cdot = e$ ), markdown ( $\cdot = m$ ), and the optimal policy ( $\cdot = *$ )
$v$ with $\cdot \in \{m, *\}$ :	the optimal cutoff value under markdown ( $\cdot = m$ ) and the optimal policy ( $\cdot = *$ )
$r$ with $\cdot \in \{m, *\}$ :	the optimal actual Period 2 fill rate under markdown ( $\cdot = m$ ) and the optimal policy ( $\cdot = *$ )
$\Pi$ with $\cdot \in \{e, m, *\}$ :	the seller's optimal profit under everyday-low-price ( $\cdot = e$ ), markdown ( $\cdot = m$ ), and the optimal policy ( $\cdot = *$ )
$\bar{v}^*$ :	a threshold on consumers' highest reservation price such that if $\bar{v} > \bar{v}^*$ , the markdown strategy is optimal

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## Appendix B: E-Commerce Examples with Inventory Information

### Appendix C: Optimal Price and Inventory Decisions with Myopic Consumers

Here, we analyze the seller's optimal prices and inventory level when all consumers in our setting are myopic; i.e., a consumer purchases the product as long as his/her reservation price is greater than or equal to the purchase price. Hence, the demands for Periods 1 and 2 are  $D_1^{MC} = N\bar{F}(p_1)$  and  $D_2^{MC} = N(F(p_1) - F(p_2))$ , where the superscript  $MC$  denotes the fully-myopic-consumer regime. In this regime, it is optimal for the seller to set  $K^{MC} = D_1^{MC} + D_2^{MC}$ . We consider the following two scenarios to determine the optimal prices.

Scenario (a): The seller optimizes the first-period price  $p_1$  and the inventory level  $K$  given a fixed discount percentage  $\delta$ . In this scenario, the seller's objective function can be written as  $\max_{p_1 \in [c, \bar{v}]} (p_1 - c)N\bar{F}(p_1) + (\delta p_1 - c)N(F(p_1) - F(\delta p_1))$ . The optimal price is  $p_1^{MC} = (\bar{v} + \delta c)/(2(1 - \delta + \delta^2))$ . Hence,  $p_1^{MC} - p^e = (1 - \delta)(\delta \bar{v} - (1 - \delta)c)/(2(1 - \delta + \delta^2))$ , and  $p^e - p_2^{MC} = p^e - \delta p_1^{MC} = (1 - \delta)((1 - \delta)\bar{v} + c)/(2(1 - \delta + \delta^2))$ . One can derive that  $p_1^{MC} - p^e > p^e - p_2^{MC}$  if and only if  $\delta > (\bar{v} + 2c)/(2\bar{v} + c)$ .

Sources (retrieved on December 13, 2012): Top left: [www.amazon.com](http://www.amazon.com); top right: [www.zappos.com](http://www.zappos.com); bottom: [www.kayak.com](http://www.kayak.com).

**Figure 8** Product Pages Showing Low Inventory Levels

Scenario (b): The seller optimizes both prices  $p_1, p_2$  and the inventory level  $K$ . In this scenario, the seller's objective function can be written as  $\max_{p_1 \in [p_2, \bar{v}], p_2 \in [c, p_1]} (p_1 - c)N\bar{F}(p_1) + (p_2 - c)N(F(p_1) - F(p_2))$ . One can show that the objective function is jointly concave in  $(p_1, p_2)$ . Therefore, the first-order condition gives the optimal prices:  $p_1^{MC} = (2\bar{v} + c)/3$  and  $p_2^{MC} = (\bar{v} + 2c)/3$ . Hence,  $p_1^{MC} - p^e = p^e - p_2^{MC} = (\bar{v} - c)/6$ .

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# Online Appendix for “Markdown or Everyday-Low-Price? The Role of Behavioral Motives”

## Proofs of Theoretical Results

### Appendix O.1: Proof of Proposition 1

First note that if  $v < \delta p_1$ , the consumer will not buy the product in either period. Hence, we can restrict our attention to  $v \geq \delta p_1$ . We consider 3 cases.

Case (a):  $U_1(v, p_1) \geq 0$ ; i.e.,  $v \geq (1 + \alpha q(1 - \delta))p_1 \geq p_1$ . Here we can write  $U_2(v, p_1) = q(v - \delta p_1) - \beta(1 - q)(v - p_1)$ . The consumer buys in Period 1 if and only if  $U_1(v, p_1) \geq U_2(v, p_1)$ ; i.e.,

$$v \geq \frac{[1 + \beta + (\alpha - \beta - (1 + \alpha)\delta)q]p_1}{(1 - q)(1 + \beta)}. \quad (\text{O.1})$$

Define the right hand side of (O.1) as  $v_1(q)$ . By  $\alpha \in [0, 1]$  and  $\beta \in [0, 1]$ , it can be verified that  $v_1(q) \geq (1 + \alpha q(1 - \delta))p_1 \geq p_1$  for all  $q \in [0, 1]$ . Thus, in case (a), the consumer buys in Period 1 if  $v \geq v_1(q)$  and buys in Period 2 otherwise.

Case (b):  $v \in [p_1, (1 + \alpha q(1 - \delta))p_1)$ . In this case,  $U_1(v, p_1) < 0$  and the consumer will not buy in Period 1. Then she buys in Period 2 if and only if  $U_2(v, p_1) \geq 0$ ; i.e.,  $(q - (1 - q)\beta)v \geq (\delta q - (1 - q)\beta)p_1$ . If  $q - (1 - q)\beta > 0$ , this condition holds for  $v \geq p_1$ . If  $q - (1 - q)\beta = 0$ , it holds for all  $v$  because  $\delta \in (0, 1)$ . If  $q - (1 - q)\beta < 0$ , the above condition can be rewritten as  $v \leq ((1 - q)\beta - \delta q)p_1 / ((1 - q)\beta - q)$ , which is true for all  $v < (1 + \alpha q(1 - \delta))p_1$  because  $\alpha \in [0, 1], \beta \in [0, 1]$ , and  $q \in [0, 1]$ . Hence, the consumer buys in Period 2 in case (b).

Case (c):  $v \in [\delta p_1, p_1)$ . Here  $U_2(v, p_1) = q(v - \delta p_1)$ . Thus, the consumer buys in Period 2 if  $v \geq \delta p_1$  and does not buy otherwise.

Combining all 3 cases, we know that the consumer buys in Period 1 if  $v \in [v_1(q), \bar{v}]$ , buys in Period 2 if  $v \in [\delta p_1, v_1(q))$ , and does not buy if  $v \in [0, \delta p_1)$ . For part (i) of the proposition to occur, we need the first interval to be nonempty; i.e., we need  $v_1(q) \leq \bar{v}$ . We can rewrite  $v_1(q)$  as

$$v_1(q) = \frac{\beta - \alpha + (1 + \alpha)\delta}{\beta + 1} \left( 1 + \frac{(1 + \alpha)(1 - \delta)}{(\beta - \alpha + (1 + \alpha)\delta)(1 - q)} \right).$$

By  $\alpha \leq \beta$ ,  $v_1(q)$  is increasing in  $q$ . Define  $Q$  such that  $v_1(Q) = \bar{v}$ . Then for all  $q \leq Q$ , we must have  $v_1(q) \leq \bar{v}$  with equality only when  $q = Q$ . Solving for  $Q$  in  $v_1(Q) = \bar{v}$  yields (4). Thus, for all  $q \in [0, Q]$ , part (i) of the proposition holds. Finally, for all  $q \in (Q, 1]$ ,  $v_1(q) > \bar{v}$  and hence the consumer only buys in Period 2 as specified in part (ii) of the proposition. This completes the proof. ■

## Appendix O.2: Proof of Lemma 1

Part (i) follows from the market segmentation in Figure 1 and the assumption that consumers' reservation prices are uniformly distributed on  $[0, \bar{v}]$ . Here, we prove part (ii). Since  $D_1$  is decreasing in  $v_1$  and  $v_1$  is increasing in  $p_1$  as seen in (4), we know that  $D_1$  is decreasing in  $p_1$ . By definition,  $D_L$  is decreasing in  $p_1$ .

We can rewrite  $Q$  as

$$Q = 1 - \frac{(1 + \alpha)(1 - \delta)}{(1 + \beta)\frac{\bar{v}}{p_1} + (\alpha - \beta - (1 + \alpha)\delta)}.$$

Since the denominator of the second term in the above equation is positive for all  $p_1 \in [c, \bar{v}]$ , it follows that  $Q$  is decreasing in  $p_1$ . Finally, we can rewrite  $D_2$  as

$$D_2 = \frac{N}{\bar{v}} \left( \frac{(1 + \alpha)(1 - \delta)q}{(1 + \beta)(1 - q)} + 1 - \delta \right) p_1.$$

It immediately follows that  $D_2$  is increasing in  $p_1$ . This completes the proof. ■

## Appendix O.3: Proof of Proposition 2

We first show part (i). We can rewrite  $Q$  as

$$Q = 1 - \frac{(1 + \alpha)(1 - \delta)p_1}{\beta(\bar{v} - p_1) + \bar{v} - \delta p_1 + \alpha(1 - \delta)p_1}.$$

Since the denominator of the second term is positive for all  $p_1 \in [c, \bar{v}]$ ,  $\alpha \in [0, 1]$ ,  $\beta \in [0, 1]$ , and  $\delta \in [0, 1]$ , we have  $Q$  is increasing in  $\beta$ . Similarly, we can rewrite  $Q$  as

$$Q = \frac{(1 + \beta)(\bar{v} - p_1)}{(1 + \beta)\bar{v} - (\beta + \delta)p_1 + \alpha(1 - \delta)p_1}.$$

Hence,  $Q$  is decreasing in  $\alpha$ .

We next show part (ii). By the definition of  $D_1$ ,  $S_1$ , and (4), we know that

$$S_1 \propto - \left( \frac{(1 + \alpha)(1 - \delta)q}{(1 + \beta)(1 - q)} + 1 \right) < 0,$$

where  $\propto$  means the left hand side is equal to the right hand side times a positive constant. It follows that the magnitude of  $S_1$  is decreasing in  $\beta$  and increasing in  $\alpha$ . This completes the proof. ■

## Appendix O.4: Proof of Proposition 3

Given price  $p$ , the seller's profit is given by  $\Pi = (p - c)N(\bar{v} - p)/\bar{v}$ , which is a strictly concave function of  $p$ . Hence, the first-order condition is both sufficient and necessary to determine the unique optimal price:  $\bar{v} - p^e - p^e + c = 0$ , i.e.,  $p^e = (\bar{v} + c)/2$ . The optimal inventory level and seller profit can be obtained by plugging  $p^e$  into the expected demand and profit functions. Finally, note that under everyday-low-price, consumers do not make purchase timing decisions. Hence, the behavioral factors of regret or availability misperception are not relevant in this case; i.e., the seller's optimal decisions and profit are independent of these behavioral factors. ■

## Appendix O.5: Proof of Proposition 4

We drop the subscript of  $p_1$  for simplicity. Differentiating  $J(p, v)$  in (8) with respect to  $p$  and  $v$  yields  $\partial J/\partial p \propto$  left hand side of (9) and  $\partial J/\partial v \propto$  left hand side of (10). We also obtain the following second-order derivatives of  $J(p, v)$ :

$$\frac{\partial^2 J}{\partial p^2} = -r \left[ 2\delta^2 + \frac{2(1+\alpha)(1-\delta)(v-\delta p)(\delta p-c)(\beta-\alpha+(1+\alpha)\delta)vr^{2\theta}}{\theta(1+\beta)^2(v-p)^3} + \frac{(1+\alpha)^2(1-\delta)^2(\theta-1)(\delta p-c)(v-\delta p)v^2r^{2\theta}}{\theta^2(1+\beta)^2(v-p)^4} + \frac{2(1+\alpha)(1-\delta)(v+c-2\delta p)\delta vr^\theta}{\theta(1+\beta)(v-p)^2} \right], \quad (\text{O.2})$$

$$\frac{\partial^2 J}{\partial v^2} = \frac{-(1+\alpha)(1-\delta)^2(\delta p-c)p^2r^{1+2\theta}}{\theta^2(1+\beta)^2(v-p)^4} [(1+\alpha)(\theta-1)(v-\delta p) + 2(\beta-\alpha)\theta(v-p)], \quad (\text{O.3})$$

$$\frac{\partial^2 J}{\partial p \partial v} = -1 + \delta r + \frac{(1+\alpha)(1-\delta)(v+c-2\delta p)\delta pr^{1+\theta}}{\theta(1+\beta)(v-p)^2} - \frac{(1+\alpha)^2(1-\delta)^2(\delta p-c)(v-\delta p)vpr^{1+2\theta}}{\theta^2(1+\beta)^2(v-p)^4} + \frac{(1+\alpha)(1-\delta)(v-\delta p)(\delta p-c)(\beta-\alpha+(1+\alpha)\delta)pr^{1+2\theta}}{\theta(1+\beta)^2(v-p)^3}. \quad (\text{O.4})$$

To prove the quasiconcavity of  $J(p, v)$ , we will show: (a)  $\partial^2 J/\partial p^2|_{p=p_o, v=v_o} < 0$ ; (b)  $\partial^2 J/\partial v^2|_{p=p_o, v=v_o} < 0$ ; and (c)  $[(\partial^2 J/\partial p^2)(\partial^2 J/\partial v^2) - (\partial^2 J/\partial p \partial v)^2]|_{p=p_o, v=v_o} > 0$ . If conditions (a) – (c) hold for all  $(p_o, v_o)$  that satisfy the first-order conditions, then  $J(p, v)$  must be quasiconcave because these conditions imply that there is no local minimum. Hence, there must be a unique pair  $(p_o, v_o)$  that satisfies the first-order conditions and constitutes the global maximizer of  $J(p, v)$ .

To show (a), note from (O.2) that the sum of the second and the fourth terms in the square bracket is equal to  $M[\delta(c+v-2\delta p) + (v-\delta p)(\delta p-c)(\beta-\alpha+(1+\alpha)\delta)/((1+\beta)v - (\beta-\alpha+(1+\alpha)\delta)p)]$ , where  $M$  is a positive constant. Since  $\alpha \leq \beta$ , we have  $\beta-\alpha+(1+\alpha)\delta \geq (1+\beta)\delta$  for all  $\delta \in (0, 1)$ . Hence, the above expression is greater than or equal to  $M[\delta(c+v-2\delta p) + (v-\delta p)(\delta p-c)(1+\beta)\delta/((1+\beta)(v-\delta p))] = M\delta(c+v-\delta p-c)$ . We can derive from (10) that  $\partial J/\partial v|_{v \rightarrow p^+} \rightarrow +\infty$ , where “ $\rightarrow$ ” means the variable on the left converges to the value on the right, and  $v \rightarrow p^+$  means  $v$  converges to  $p$  from above. Then for any  $(p_o, v_o)$  that satisfies the first-order conditions, we must have  $v_o > p_o > \delta p_o$ . Hence,  $M\delta(c+v-\delta p-c) > 0$ , and the square bracket term in (O.2) is positive for any  $(p_o, v_o)$ . Thus,  $\partial^2 J/\partial p^2|_{p=p_o, v=v_o} < 0$ .

To show (b), since  $v_o > \delta p_o$  and  $\alpha \leq \beta$ , we know that the square bracket term in (O.3) is positive. Hence,  $\partial^2 J/\partial v^2|_{p=p_o, v=v_o} < 0$ .

To show (c), we first simplify the exposition of (O.2)–(O.4) to the following:  $\partial^2 J/\partial p^2 = -(M_1 + M_2 + M_3 + M_4)$ ,  $\partial^2 J/\partial v^2 = -(M_5 + M_6)$ ,  $\partial^2 J/\partial p \partial v = -M_7 + M_8 - M_9 + M_{10}$ , where  $M_7 \equiv 1 - \delta r$  and the other  $M_i$ 's correspond to the fractional terms. Since  $M_7 + M_9 > 0$  and  $M_8 + M_{10} = (M_2 + M_4)p/(2v) > 0$ , we know  $(\partial^2 J/\partial p \partial v)^2 < (M_7 + M_9)^2 + (M_8 + M_{10})^2$ . Thus, to show (c), it suffices to show  $(\partial^2 J/\partial p^2)(\partial^2 J/\partial v^2) \geq (M_7 + M_9)^2 + (M_8 + M_{10})^2$  at  $(p_o, v_o)$ , or equivalently,  $(M_1 + M_2 + M_3 + M_4)(M_5 + M_6) \geq (M_7 + M_9)^2 + (M_8 + M_{10})^2$ . By using  $(1+\alpha)(1-\delta)(v_o - \delta p_o)(\delta p_o - c)p_o r_o^{1+\theta}/[\theta(1+\beta)(v_o - p_o)^2] = p_o - c - r_o(\delta p_o - c)$

from (10),  $v_o/p_o = [\bar{v} - v_o + \delta(v_o + c - 2\delta p_o)r_o]/[p_o - c - r_o(\delta p_o - c)]$  from (9) and (10), and  $v_o > p_o > \delta p_o$ , we can show that  $2v(M_5 + M_6)/p \geq M_8 + M_{10}$ . Since  $M_2 + M_4 = 2v(M_8 + M_{10})/p$ , we have  $(M_2 + M_4)(M_5 + M_6) = (M_8 + M_{10})2v(M_5 + M_6)/p \geq (M_8 + M_{10})^2$ . With similar manipulation, we can show that  $(M_1 + M_3)(M_5 + M_6) \geq (M_7 + M_9)^2$ . Therefore, we have  $(\partial^2 J/\partial p^2)(\partial^2 J/\partial v^2) \geq (M_7 + M_9)^2 + (M_8 + M_{10})^2$  at  $(p_o, v_o)$ ; i.e.,  $[(\partial^2 J/\partial p^2)(\partial^2 J/\partial v^2) - (\partial^2 J/\partial p\partial v)^2]|_{p=p_o, v=v_o} > 0$ . This completes the proof that  $J(p, v)$  is quasiconcave.

Since  $J(p, v)$  is quasiconcave in  $(p, v)$ , the joint solution to the first-order conditions, i.e.,  $(p_o, v_o)$  defined by (9) and (10), is the unique global maximizer of  $J(p, v)$  when the constraint  $c \leq p \leq v \leq \bar{v}$  is not considered. We next discuss how we incorporate this constraint. We first show that in any optimal solution  $(p_1^m, v^m)$  to  $J(p, v)$ ,  $(p_1^m, v^m)$  must satisfy  $c < p_1^m < v^m$ . We have shown above that we must have  $v^m > p_1^m$ . Also note that  $\partial J/\partial p|_{p=c} > 0$  for all  $v$ . Then by the quasiconcavity of  $J$ , we must have  $c < p_1^m < v^m$ . This result implies that the only constraint that may be binding is  $v \leq \bar{v}$ . We discuss two cases.

Case (i): If  $v_o < \bar{v}$ , then  $(p_o, v_o)$  is indeed the unique optimal solution to (8). The optimal inventory and actual Period 2 fill rate are then determined by plugging  $(p_o, v_o)$  into (6) and (7). Since  $p_o < v_o$ , we have  $r(p_o, v_o) \in (0, 1)$  from (7). This completes the proof of part (i).

Case (ii): If  $v_o \geq \bar{v}$ , the optimal solution must be achieved at the boundary  $v^m = \bar{v}$ . We show above that  $\partial^2 J/\partial p^2 < 0$  for all  $p \in (c, v^m)$ . Hence, there must exist a unique  $p_1^m \in (c, \bar{v})$  that maximizes  $J(p_1, \bar{v})$ . Finally, the optimal inventory level and actual Period 2 fill rate in this case are determined similarly as in case (i). This completes the proof of the proposition. ■

## Appendix O.6: Proof of Proposition 5

We first prove part (i). In this case, the markdown strategy is optimal if and only if  $\Pi^m > \Pi^e$ . Let  $V(\bar{v})$  denote the expression inside the square bracket in (11). Then  $\Pi^m - \Pi^e = (N/\bar{v})(V(\bar{v}) - (\bar{v} - c)^2/4)$ . Let  $g(\bar{v}) \equiv V(\bar{v}) - (\bar{v} - c)^2/4$ . We will show that  $g(\bar{v}) > 0$  (i.e.,  $\Pi^m > \Pi^e$ ) for all  $\bar{v} > c$  if and only if the optimal markdown solution is an interior solution. The “only if” part follows directly from Corollary 1. It remains to show the “if” part. By the envelope theorem, we have  $g'(\bar{v}) = p_1^m - c - (\bar{v} - c)/2$ . Since  $p_1^m$  is the interior optimal first-period price under markdown, we must have  $p_1^m > p^e = (\bar{v} + c)/2$ . Hence,  $g'(\bar{v}) > 0$  if optimal markdown is achieved in the interior. Note that when  $\bar{v} = c$ ,  $\Pi^m = \Pi^e = 0$  and  $g(\bar{v}) = 0$ . Thus,  $g(\bar{v}) > 0$  for  $\bar{v} > c$ . Summarizing the above, we have  $\Pi^m > \Pi^e$  if and only if the optimal markdown solution is an interior solution. To complete the proof, we next derive the condition on  $\bar{v}$  such that optimal markdown is achieved at an interior solution. This is equivalent to  $v_o < \bar{v}$  by Proposition 4(i). Due to the quasiconcavity of  $J(p, v)$ , a sufficient condition for  $v_o < \bar{v}$  is  $\partial J/\partial v|_{v=\bar{v}} < 0$ . From the proof of Proposition 4, we know that  $\partial^2 J/\partial v^2 < 0$ ; i.e.,  $\partial J/\partial v$  is decreasing in  $v$ . Also note that given any  $p$ ,  $\partial J/\partial v|_{v \rightarrow p^+} \rightarrow +\infty$  and  $\partial J/\partial v|_{v \rightarrow +\infty} \rightarrow (\delta - 1)p < 0$ . Hence, there must exist a  $\bar{v}^*$  such that  $\partial J/\partial v|_{v=\bar{v}^*} = 0$ ,  $\partial J/\partial v|_{v=\bar{v}} > 0$  for all

$\bar{v} < \bar{v}^*$ , and  $\partial J/\partial v|_{v=\bar{v}} < 0$  for all  $\bar{v} > \bar{v}^*$ . Therefore, the markdown strategy is optimal for all  $\bar{v} > \bar{v}^*$ , and everyday-low-price is optimal otherwise.

We next show part (ii). When  $\alpha \geq \beta$  and  $\theta = 1$ , we have  $\partial J/\partial v \leq (\delta - 1)p_1/(\delta p_1 - c) < 0$ . Hence, the optimal solution to (8) must be at the boundary  $v = p_1$ . By (7), we know that in this case  $r = 0$ , and the seller is effectively selling at a single price  $p_1$ . Thus, the seller's resulting profit cannot exceed that under the optimal everyday-low-price strategy; i.e., everyday-low-price is optimal. This completes the proof. ■

## Appendix O.7: Proof of Proposition 6

We first show how the seller's optimal first-period price and inventory level under the markdown strategy are affected by the behavioral parameters. First we note that  $\partial^2 J/\partial v \partial p_1 \rightarrow \delta - 1 < 0$  as  $v \rightarrow +\infty$  and  $\partial^2 J/\partial v \partial p_1 \rightarrow +\infty$  as  $v \rightarrow p_1$ . Hence, the seller's objective function in (8) is neither supermodular nor submodular in its decision variables. Thus, we cannot apply multivariate Topkis' theorem to study comparative statics of the optimal solutions. Instead, we first show analytically that if we fix one decision variable (either  $v$  or  $p_1$ ) and optimize the other one, that optimal solution is monotonic in the behavioral parameters. We then complement the theoretical analysis with an extensive numerical study to show that the same monotonicity results persist in the true optimal decisions when both variables are optimized jointly.

We first analyze comparative statics with respect to the inventory decision. Let  $K^p$  denote the inventory level that maximizes (5) given a fixed price  $p_1$ . Let  $r^p$  be the resulting actual Period 2 fill rate under  $K^p$ . We first show that there exists a one-to-one correspondence among  $K$ ,  $v_1$ , and  $r$  when  $p_1$  is fixed.

LEMMA O.1. *Given  $p_1$ ,  $K$  is increasing in  $v_1$ , and  $v_1$  is increasing in  $r$ .*

**Proof:** For simplicity, we drop the subscripts in  $v_1$  and  $p_1$ . We first show that  $K$  is increasing in  $v$ . Compare (6) and (8), we know from (10) and (O.3) that

$$\begin{aligned} \frac{dK}{dv} &\propto \frac{(1+\alpha)(v-\delta p)(1-\delta)pr^{1+\theta}}{\theta(1+\beta)(v-p)^2} + r - 1, \\ \frac{d^2K}{dv^2} &\propto \frac{-(1+\alpha)(1-\delta)^2p^2r}{\theta^2(v-p)^2((1+\beta)v - (\beta-\alpha + (1+\alpha)\delta)p)^2} [(1+\alpha)(\theta-1)(v-\delta p) + 2(\beta-\alpha)\theta(v-p)]. \end{aligned}$$

Since  $\theta \geq 1$ ,  $\beta \geq \alpha$ , and  $v \geq p > \delta p$ , we have  $d^2K/dv^2 \leq 0$  with equality only when  $\theta = 1$  and  $\alpha = \beta$ . Hence,  $dK/dv$  is decreasing in  $v$ . Note that when  $v \rightarrow +\infty$ ,  $r \rightarrow 1$  and  $dK/dv \rightarrow 0$ . Thus, we must have  $dK/dv > 0$  for all feasible  $v$ ; i.e.,  $K$  is increasing in  $v$ .

We next show  $v$  is increasing in  $r$ . Note that (7) can be rewritten as

$$r(v) = \left( 1 - \frac{(1+\alpha)(1-\delta)p}{(1+\beta)v + (\alpha - \beta - (1+\alpha)\delta)p} \right)^{1/\theta},$$

which is increasing in  $v$ . This completes the proof of Lemma O.1. □

With Lemma O.1, we obtain the following result.

PROPOSITION O.1. *Given  $p_1$ ,  $K^p$  is increasing in  $\beta$  and  $\theta$  but decreasing in  $\alpha$ .*

**Proof:** For simplicity, we drop the subscript in  $p_1$ . By Lemma O.1, we know that  $K^p$  is increasing in  $r^p$ . Thus, it suffices to show that  $r^p$  is increasing in  $\beta$  and  $\theta$  but decreasing in  $\alpha$ . By substituting  $v$  with  $r$  in (10) based on (7), we obtain the first-order condition in terms of  $r$  as follows:

$$0 = J'(r) = -(p-c) + (\delta p - c)r + \frac{(\delta p - c)r(1-r^\theta)[(1+\beta)r^{-\theta} + \alpha - \beta]}{\theta(1+\alpha)}.$$

Taking the derivative of the right hand side with respect to  $r$ , we have

$$J''(r) \propto \frac{(r^\theta - 1)[(1+\beta)(\theta - 1)r^{-\theta} + (\beta - \alpha)(1 + \theta)]}{\theta(1+\alpha)}.$$

Since  $\theta \geq 1$ ,  $\beta \geq \alpha$ , and  $r \in (0, 1)$ , we have  $J''(r) \leq 0$  with equality only when  $\theta = 1$  and  $\alpha = \beta$ . Also note that  $J'(r) \rightarrow +\infty$  as  $r \rightarrow 0^+$  and  $J'(1) = (\delta - 1)p < 0$ . Hence, there must exist a unique solution  $r^p \in (0, 1)$  to  $J'(r) = 0$  such that it is the optimal actual Period 2 fill rate given  $p$ . Then for a parameter  $x \in \{\alpha, \beta, \theta\}$ , we must have  $J'(r^p, x) = 0$ . By the implicit function theorem, we know that

$$\frac{dr^p}{dx} = - \left. \frac{\partial J'(r, x)/\partial x}{J''(r)} \right|_{r=r^p}.$$

Here we explicitly include the parameter  $x$  in the function  $J'(r)$  to emphasize the parameter of interest. Since  $J''(r) \leq 0$ ,  $dr^p/dx$  must have the same sign as  $\partial J'(r, x)/\partial x$ . Therefore, it is sufficient to analyze the sign of  $\partial J'(r, x)/\partial x$ .

We first analyze  $\partial J'(r, \alpha)/\partial \alpha$ . Note that the only part in  $J'(r, \alpha)$  that is affected by  $\alpha$  is

$$g(\alpha) = \frac{(1+\beta)r^{-\theta} + \alpha - \beta}{\alpha + 1} = 1 + \frac{(1+\beta)(r^{-\theta} - 1)}{\alpha + 1}.$$

Since  $r \in (0, 1)$ ,  $g'(\alpha) < 0$ . Hence,  $\partial J'(r, \alpha)/\partial \alpha < 0$ . Thus,  $r^p$  is decreasing in  $\alpha$  and so is  $K^p$ .

We next analyze  $\partial J'(r, \beta)/\partial \beta$ . Note that the only part in  $J'(r, \beta)$  that is affected by  $\beta$  is

$$g(\beta) = (1+\beta)r^{-\theta} + \alpha - \beta = \beta(r^{-\theta} - 1) + r^{-\theta} + \alpha.$$

Since  $r \in (0, 1)$ ,  $g'(\beta) > 0$ . Hence,  $\partial J'(r, \beta)/\partial \beta > 0$ . Thus,  $r^p$  is increasing in  $\beta$  and so is  $K^p$ .

We finally analyze  $\partial J'(r, \theta)/\partial \theta$ . The only part in  $J'(r, \theta)$  that is affected by  $\theta$  is

$$g(\theta) = \frac{(1-r^\theta)[(1+\beta)r^{-\theta} + \alpha - \beta]}{\theta}.$$

Differentiate with respect to  $\theta$ , we have

$$g'(\theta) \propto 1 + 2\beta - \alpha + (\beta - \alpha)r^\theta(\ln r^\theta - 1) - (1 + \beta)\frac{\ln r^\theta + 1}{r^\theta}.$$

Let  $y = r^\theta$  and  $h(y) = 1 + 2\beta - \alpha + (\beta - \alpha)y(\ln y - 1) - (1 + \beta)(\ln y + 1)/y$ . Note that when  $y = 1$ ,  $h(1) = 0$ . Also,  $h'(y) = (\beta - \alpha + (1 + \beta)/y^2)\ln y < 0$  for all  $y \in (0, 1)$ . Hence,  $h(y) > 0$  for all  $y \in (0, 1)$ . Since  $g'(\theta) \propto$



$h(r^\theta)$ ,  $r \in (0, 1)$ , and  $\theta \geq 1$ , we have  $g'(\theta) > 0$ . Hence,  $\partial J'(r, \theta)/\partial \theta > 0$ . Thus,  $r^p$  is increasing in  $\theta$  and so is  $K^p$ . This completes the proof of Proposition O.1.  $\square$

We next analyze comparative statics with respect to the first-period pricing decision. Let  $p^K$  be the first-period price that maximizes (5) given a fixed inventory level  $K$ . Let  $v^K$  and  $r^K$  denote respectively the resulting cutoff value and actual Period 2 fill rate under  $p^K$ . We first show that there exists a one-to-one correspondence among  $p_1$ ,  $v_1$ , and  $r$  when  $K$  is fixed.

LEMMA O.2. *Given  $K$ ,  $p^K$  is increasing in  $v^K$ , and  $v^K$  is increasing in  $r^K$ .*

**Proof:** For simplicity, we drop the superscripts in  $p^K$ ,  $v^K$ , and  $r^K$ . We first show  $p$  is increasing in  $v$ . From (6) and (8), we can write

$$\begin{aligned} K &= f(v) + g(v, p), \\ J &= (p - c)f(v) + (\delta p - c)g(v, p), \end{aligned}$$

where

$$\begin{aligned} f(v) &\equiv \bar{v} - v, \\ g(v, p) &\equiv (v - \delta p) \left( \frac{(1 + \beta)(v - p)}{(1 + \beta)v + (\alpha - \beta - (1 + \alpha)\delta)p} \right)^{1/\theta}. \end{aligned}$$

Note that  $\partial f/\partial v = -1$ , and  $v^K$  must satisfy  $(p^K - c)\partial f/\partial v + (\delta p^K - c)\partial g/\partial v = 0$ . Thus, we have  $\partial g/\partial v = (p^K - c)/(\delta p^K - c) > 1$ . Hence,  $\partial f/\partial v + \partial g/\partial v > 0$ . When  $K$  is fixed, we have by the chain rule

$$\frac{\partial f}{\partial v} \cdot \frac{dv}{dp} + \frac{\partial g}{\partial v} \cdot \frac{dv}{dp} + \frac{\partial g}{\partial p} = 0.$$

We will show that  $\partial g/\partial p < 0$ , then by  $\partial f/\partial v + \partial g/\partial v > 0$ , we must have  $dv/dp > 0$ ; i.e.,  $p$  is increasing in  $v$ . Since  $v - \delta p$  is decreasing in  $p$ , to show  $\partial g/\partial p < 0$ , it suffices to show  $h(p) \equiv (1 + \beta)(v - p)/[(1 + \beta)v + (\alpha - \beta - (1 + \alpha)\delta)p]$  also decreases with  $p$ . Note that we can rewrite  $h(p)$  as

$$h(p) = 1 - \frac{(1 + \alpha)(1 - \delta)}{(1 + \beta)v - (\beta - \alpha + (1 + \alpha)\delta)p}.$$

Since  $\beta \geq \alpha$ , we have  $h(p)$  is decreasing in  $p$ . Thus, we prove that  $dv/dp > 0$ ; i.e.,  $p$  is increasing in  $v$ .

We next show  $v$  is increasing in  $r$ . By (6) and (7), we have

$$v(r) = \frac{1 + \beta + (\alpha - \beta - (1 + \alpha)\delta)r^\theta}{(1 - r + \delta r)(1 + \beta + (\alpha - \beta)r^\theta) - (1 + \alpha)\delta r^\theta}.$$

Differentiating with respect to  $r$ , we have

$$v'(r) \propto (\beta - \alpha)(\beta - \alpha + (1 + \alpha)\delta)r^{2\theta} + (1 + \beta)^2 + (1 + \beta)[2(\beta - \alpha) - (\theta - 1)(1 + \alpha)\delta]r^\theta.$$

Note that if the last term is positive, then  $v'(r) > 0$ . Otherwise, since  $r \in [0, 1]$ , we have

$$v'(r) \geq 1 + \beta + 2(\beta - \alpha) - (\theta - 1)(1 + \alpha)\delta.$$

Since  $\beta \geq \alpha$  and  $\theta \in [1, 2]$ , the right hand side of this inequality is positive. Hence, we have  $v'(r) > 0$ ; i.e.,  $v$  is increasing in  $r$ . This completes the proof of Lemma O.2.  $\square$

With Lemma O.2, we obtain the following result.

**PROPOSITION O.2.** *Given  $K$ ,  $p^K$  is increasing in  $\beta$  and  $\theta$  but decreasing in  $\alpha$ .*

**Proof:** By Lemma O.2, we know that  $p^K$  is increasing in  $r^K$ . Hence, it suffices to show that  $r^K$  is increasing in  $\beta$  and  $\theta$  but decreasing in  $\alpha$ . The rest of the proof is identical to the proof of Proposition O.1.  $\square$

The above analytical results show that given  $p_1$  (or  $K$ ), the corresponding  $K$  (or  $p_1$ ) that maximizes the seller's profit under markdown is increasing in  $\beta$  and  $\theta$  but decreasing in  $\alpha$ . We next turn to numerical analysis to show that the same monotonicity results hold when both  $p_1$  and  $K$  are jointly optimized. To ensure robustness, we examine a large parameter set as in §6.1 (we test 10,890 instances for each behavioral parameter). In all numerical results, the optimal inventory and first-period price under the markdown strategy always exhibit the same monotonicity property as characterized in Propositions O.1 and O.2.

Finally, we show how the seller's optimal profit  $\Pi^m$  under markdown changes with each behavioral parameter  $x \in \{\alpha, \beta, \theta\}$ . By the envelope theorem, we know that

$$\frac{d\Pi^m}{dx} = \left. \frac{\partial J(v, p_1, x)}{\partial x} \right|_{v=v^m, p_1=p_1^m},$$

where  $J(\cdot)$  is defined in (8). Let

$$g(\alpha, \beta, \theta) \equiv \left( \frac{(1 + \beta)(v^m - p_1^m)}{(1 + \beta)v^m + (\alpha - \beta - (1 + \alpha)\delta)p_1^m} \right)^{1/\theta}.$$

Note that  $g(\cdot)$  is the only part in  $J(\cdot)$  that is affected by the behavioral parameters. Hence,  $d\Pi^m/dx \propto dg/dx$ , and it suffices to show how  $g(\cdot)$  changes with the behavioral parameters.

First rewrite  $g(\cdot)$  to

$$g(\alpha) = \left( \frac{(1 + \beta)(v^m - p_1^m)}{\alpha(1 - \delta)p_1^m + (1 + \beta)v^m - (\beta + \delta)p_1^m} \right)^{1/\theta}.$$

We know from the above that  $dg/d\alpha < 0$ . Hence,  $\Pi^m$  is decreasing in  $\alpha$ .

Next note that

$$g(\beta) = \left( 1 - \frac{(1 + \alpha)(1 - \delta)p_1^m}{\beta(v^m - p_1^m) + v^m + \alpha p_1^m - (1 + \alpha)\delta p_1^m} \right)^{1/\theta}.$$

We see that  $dg/d\beta > 0$ . Hence,  $\Pi^m$  is increasing in  $\beta$ .

Finally, since  $[(1 + \beta)(v^m - p_1^m)]/[(1 + \beta)v^m + (\alpha - \beta - (1 + \alpha)\delta)p_1^m] < 1$ , we have  $dg/d\theta > 0$ . Hence,  $\Pi^m$  is increasing in  $\theta$ . This completes the proof of Proposition 6.  $\blacksquare$