Les Cahiers du GERAD ISSN: 0711–2440

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G–2022–21

May 2022

La publication de ces rapports de recherche est rendue possible grâce au soutien de HEC Montréal, Polytechnique Montréal, Université McGill, Université du Québec à Montréal, ainsi que du Fonds de recherche du Québec – Nature et technologies.

Dépôt légal – Bibliothèque et Archives nationales du Québec, 2022
– Bibliothèque et Archives Canada, 2022

The publication of these research reports is made possible thanks to the support of HEC Montréal, Polytechnique Montréal, McGill University, Université du Québec à Montréal, as well as the Fonds de recherche du Québec – Nature et technologies.

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Dynamic pricing in the presence of social externalities and reference-price effect

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May 2022
Les Cahiers du GERAD
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Abstract : This paper considers the pricing of a new product in the face of sophisticated consumer behaviors. At the individual level, consumers are forward-looking, whereby they may wait strategically for intertemporal arbitrage. Additionally, and in line with prospect theory, consumers might also look back to form a reference-price point with which they can compare the current price. Consumers are assumed to be loss averse where losses resonate more than gains. At the aggregate level, we account for the role of social influences in the form of externalities in consumers' adoption decision. We develop progressively different nested models to account for impact of each behavior. We find that skimming pricing strategy is advocated by reference-dependent loss-averse behaviors, whereas the penetration pricing strategy functions better in the presence of strong forward-looking behavior and social influences.

Keywords: Dynamic pricing, reference-price effect, social externalities, forward-looking behavior, loss aversion

1 Introduction

Farsighted or strategic consumers purchase a product during the period that yields the highest utility, that is, they consider current and future prices when making a decision. Such forward-looking behavior has been documented in many product categories, e.g., durable and electronic products (McWilliams, 2004), video games (Nair, 2007), and fashion goods (Dasu and Tong, 2010), and this impacts, notably, a new product launch (Lobel et al., 2016) and pricing strategies (Papanastasiou and Savva, 2017). Consumers may also look backward to judge the fairness of the current price by comparing it to an anchor value, a reference price, which could be the last-period price or the price history. These two (forward- and backward-looking) behaviors are practiced by technology-savvy consumers, for example, in purchasing Apple iPhones (Zhang and Chiang, 2020; Lobel et al., 2016). Research on behavioral decision-making suggests that consumers derive various transaction values from the difference between the current and the reference price (Thaler, 1985). This comparison plays a salient role in purchasing intentions and the timing of adoption, again, in different product categories (Kalyanaram and Winer, 1995; Lowe and Alpert, 2010; Mazumdar et al., 2005). Interestingly, the impact of this difference, however, is asymmetric, in the sense that the consumer reacts more strongly to a loss than to a gain (which is known as loss aversion), and this effect is manifested more in durable than in non-druable products (Neumann and Böckenholt, 2014). In a similar way, a negative word-of-mouth (WoM) has a stronger impact than a positive one (Arndt, 1967; Sweeney et al., 2005; Chevalier and Mayzlin, 2006; Yoon et al., 2017).

Beside these individual-based behaviors, social influences play a major role in the diffusion of a new product. Specifically, a positive externality, meaning that the utility of a product increases with the number of adopters, is widely considered as a growth driver, independently of the type of product (Peres et al., 2010; Huang et al., 2018). While some studies state that network externalities can accelerate adoption rate (e.g., Rohlfs, 2003), others suggest that it can decelerate the initial growth since consumers take a wait-and-see approach until more people adopt the product (Srinivasan et al., 2004). Consequently, the diffusion process is slow at the beginning and fast later on (Rogers, 2003). Further, it has been shown that externality can create a chilling effect on the diffusion of new product (Goldenberg et al., 2010; Mukherjee, 2014) or mitigate negative psychological aspects such as consumers' anxiety (Huang et al., 2018).

In this research, we consider a two-period choice model that captures both the individual and aggregate adoption behaviors of consumers. We assume that the consumers have heterogeneous valuations of the new product and use the concept of the rational expectation equilibrium (Stokey, 1979) to forecast future prices. Accordingly, their derived utility depends on the price and its psychological effects (considered an external influence) along with the network (social) externality (internal influence). In this setup, consumers solve an intertemporal optimization problem, in which the forward-looking monopolist uses a backward induction approach. Huang et al. (2018) provides a classification of different externality effects depending on the type of utility and their impact (see Table 1). Here, we consider a new product[1] where a consumer's (psychological) utility increases with the total number of adopters (upper right quadrant in Table 1).

Table 1: Four types of externality

	Functional utility	Psychological utility
Positive externality	Networked goods or complementary products	New technology products, innovations, restaurants, movies, fashion (conformity-seeking behavior)
Negative externality	Services (utilities, roads) due to congestion	Luxury products (exclusivity seeking behavior)

The firm should view the pricing design through a holistic lens in the face of behaviorally sophisticated consumers. Two common approaches can be used, namely, preannounced pricing and responsive

[1]We do not specify the type of product, which can be a durable or an experience good.

pricing. In the former, the firm commits to a predetermined pricing path, while in the latter it updates the prices in response to market conditions. Preannounced pricing has been implemented by, e.g., Wanamaker's discount department store in Philadelphia, Pricetack.com, Tuesday Morning discount stores, Filene Overstocks, Sam's Club, Dress for Less, and TKTS ticket booths in London and New York City (Yin et al., 2009; Liu et al., 2019). We examine the merit of each pricing regime under various consumer behaviors.

Our research aims to answer the following questions:

- What is the optimal pricing strategy when consumers are forward-looking and are sensitive to network externality and loss aversion?
- What are the marketing implications of preannounced and responsive pricing regimes in this context?

The main results are as follows. First, the firm may employ different pricing schemes, including skimming, constant or penetration pricing strategies, of varying intensities, depending on the strength of forward- versus backward-looking behavior, and of consumers' psychological biases. In particular, while the reference-price effect and loss aversion call for skimming pricing strategy, the network externality and forward-looking behavior push towards a penetration pricing strategy. When consumers are loss averse, these conflicting forces may result in inertia, where a constant pricing strategy is optimal under certain conditions. Second, the monopolist may charge a high launch price if consumers are sufficiently sensitive to their price anchor. This can later favor the psychological surplus at the expense of no early adoption. Third, the presence of reference-dependent behavior, which might lead to a high launch price policy, could lead to a higher profit under responsive pricing than under posted prices. Papanastasiou and Savva (2017) also shows that, despite the popularity of preannounced pricing reported by the literature in the face of forward-looking consumers, preannounced pricing can be suboptimal in the presence of social learning. We, however, find that the presence of the reference-price effect can lead to such an outcome, which underscores the salience of accounting for nuances in consumer behavior.

The remainder of the paper is organized as follows: Section 2 reviews the relevant literature, and Section 3 describes the model. In Sections 4 and 5, we examine all considered scenarios when the firm adopts responsive pricing and preannounced pricing strategies, respectively. Section 6 compares the prices, demands, and profits of the two pricing strategies. Finally, we briefly conclude in Section 7.

2 Literature

Bass's seminal paper (Bass, 1969) initiated a large literature on the diffusion of new products and technologies.[2] The model applies to durable products and does not involve any decision variables. A number of studies have extended the framework to incorporate marketing-mix variables, especially price and advertising, in both a single-firm context and a competitive setup. Relative to our area of concern, we note that the price effect has been embedded through either the consumers adoption probability (Robinson and Lakhani, 1975; Dolan and Jeuland, 1981; Bass, 1980; Kalish, 1983; Breton et al., 1997) or the market potential (Horsky, 1990; Kalish, 1985); see Nair (2019) for a recent review on new product pricing. One main recommendation to the firm is to implement a skimming pricing strategy, unless consumers are highly affected by WoM communications. Zhang and Chiang (2020) incorporate reference price in market potential and assume a fixed adoption rate. If the firm is myopic, then a skimming pricing strategy is optimal. However, either penetration or skimming pricing strategies could be optimal for a farsighted monopolist.

Xie and Sirbu (1995) consider a market for a new product where consumers benefit from consumption externality. Through a numerical simulation, they show that when the externality is strong,

[2]In 2004, Bass (1969) was voted one of the ten most influential papers published in Management Science during the last fifty years.

the pricing trajectory is increasing in a market monopoly; however, under a duopoly, it is increasing, followed by a decreasing trend. Goldenberg et al. (2010) use both agent-based model and aggregate one to show that network externality has chilling effects on new product growth. However, their model does not show how the individual consumer behavior is related to network externality. Gabszewicz and Garcia (2008) suggest zero pricing in the initial periods for a monopolist who offers network goods to myopic consumers. Li and Zhang (2020) study how cross-group externality along with the reference-price effect influence pricing decisions in a one-shot game. Their single-stage setup assumes an exogenous reference price, which does not allow to examine how pricing strategy evolves over time. Bloch and Quérou (2013) tackle a similar problem while considering a network structure, where consumers care either about the local network externality or the aspiration reference price. In the latter model, it is implicitly assumed that consumers consider only transaction utility, by comparing the price they pay to the ones paid by their neighbors. In a similar vein, Duan and Feng (2021) study a static pricing problem, however, by integrating the network externality and the aspiration-based reference price into consumers's utility. Fainmesser and Galeotti (2015) extend Bloch and Quérou (2013) by relaxing the assumption of both the firm and consumers having full information about network effects to examine the value of information and its pricing implications.

We depart from this literature in two ways. First, we consider a dynamic two-period framework where both consumers and the firm are forward-looking. Second, we consider the standard internal reference price along with its asymmetric effect on consumers' choice in the presence of social influences. Put differently, the proposed model features the situation where consumers look both forward and backward during adoption occasions.

The notion of the reference price stems from adaptation-level theory (Helson, 1964) and prospect theory (Kahneman and Tversky, 1979), and it has found empirical generalizations (Kalyanaram and Winer, 1995) and extensions to other stimuli (Lattin and Roberts, 1988). Chen et al. (2020) considers a manufacturer-retailer supply chain to examine how the reference-price effect and consumers' forward-looking behavior affect pricing strategy in a centralized and a decentralized channel. While many studies have focused mainly on nondurable goods (see Mazumdar et al., 2005, for a review), the literature calls for study of the reference price's impact on consumer adoption behavior for a new product category (Lowengart, 2002; Mazumdar et al., 2005; Kalyanaram and Winer, 1995; Biswas and Sherrell, 1993) and to tie the findings on the nuances of consumer behavior to new product diffusion, and their significance for optimal marketing strategies (Nair, 2019; Peres et al., 2010). Prospect theory also proposes that backward-looking consumers are influenced by a psychological bias, known as loss aversion. Hu and Nasiry (2018) demonstrates that loss aversion is an individual phenomenon and that the aggregate market may not replicate consumers' micro-level behavior. Our study stands out from this literature by considering a product where both internal and external influences affect the consumer adoption dynamics.

Stokey (1979) and Besanko and Winston (1990) are among the early works on preannounced and responsive pricing strategies, respectively. Dasu and Tong (2010) examine both pricing approaches for a perishable product, while Papanastasiou and Savva (2017) do the same for a new product launch. The latter paper incorporates the social learning effect in a two-period adoption game and proposes that the monopolist is not generally better off with preannounced pricing. Huang et al. (2018) and Zhao et al. (2019) adopt a responsive pricing strategy in a similar time frame. Zhao et al. (2019) study the reference-price effect with and without price matching; however, the focus lies on how prices and the firm's profit vary based on market dynamics such as discount factor, intensity of the reference effect, or the ratio of myopic to strategic consumers. Jing (2011) and Chen and Jiang (2021) study the role of price commitment versus other pricing schemes, in order to determine conditions under which the ex-ante commitment is beneficial for the firm. Chen et al. (2020) adopt a responsive pricing strategy and consider the joint impact of the reference-price effect and forward-looking behavior in centralized and decentralized supply chains. Following the literature, we consider both responsive and preannounced pricing strategies, however, in a new framework, to see when each pricing scheme better serves the monopolist.

Our contributions are as follows. First, we contribute to the dynamic pricing literature by examining how monopoly pricing is formed when consumers look both backward and forward. While these two consumer behaviors are examined as standalone phenomena in the literature, we unify them to capture more intricate consumer behaviors in context of a new product launch. Arslan and Kachani (2011) explicitly suggest that the incorporation of forward-looking behavior in the context of the reference-price effect is useful, since consumers might be able to learn to anticipate future prices. Second, we explore the role of the firm's commitment in this context by considering both preannounced and responsive pricing strategies. Third, in line with prospect theory, since consumers have asymmetric reactions when they look backward, we contribute to this growing literature by studying how loss aversion impacts the results.

3 Model development

Consider a monopolist that launches a new product in a market composed of a unit-measure continuum of consumers who have a uniformly distributed private valuation $v \in [0,1]$. To capture the impact of buying time on pricing strategy, the formation of a reference price, and the effect of network externality in the most parsimonious way, we retain a two-period model. The firm's objective is to maximize its profit with respect to price. For ease of exposition, without loss of generality, we assume away discounting and production cost.

The consumer behaves strategically by choosing the adoption timing that maximizes her utility, which integrates three components: (i) an economic utility derived from consumption of the new product; (ii) a transaction utility measured by the difference between the current price and the (mental) reference price; and (iii) a network externality in the second period, measured by the first-period demand. The firm adopts either a responsive or a preannounced pricing strategy. For each pricing scheme, we study five scenarios:

B: Benchmark scenario, where only economic utility matters;

N: Network externality effect;

R: Reference price effect;

NR: Network externality and symmetric reference price effects;

NRL: Network externality and asymmetric reference price effect.

Remark 1. When the firm uses responsive pricing, the results in the five scenarios will be superscripted with RB, RN, RR, RNR, and $RNRL$; and with PB, PN, PR, PNR, and $PNRL$ when the firm implements preannounced pricing.

Denote by u_t, p_t and D_t the utility, price, and demand in period $t = 1, 2$, respectively. Let w be a positive parameter measuring the impact of the first-period demand on the second-period utility. In period 2, the reference price considered by consumers is the observed price p_1 in the first period. Let $\theta \in [0, 1]$, $\gamma \in [0, 1]$, and $\lambda \in [0, 1]$ be positive parameters, used to assess the impact of the reference price on second-period utility. Note that θ is used when the impact of the reference price is considered symmetric, regardless of whether it is a gain or a loss, whereas γ and λ are used when consumers encode the impact of the reference price as a gain or a loss, respectively, however, in an asymmetric way with $\lambda > \gamma$. Denote by $\delta \in (0, 1)$ the common discount factor to all consumers. Table 2 defines the consumer utility in each periods of the five scenarios. We make the following comments.

1. In the first period, the only available piece of information is the price, which explains why the utility is the same in all scenarios. Whereas a myopic consumer would adopt the product in the first period if u_1 is positive, a strategic consumer compares her utilities in both periods and adopts at the period that yields the highest (positive) utility. If the utility is negative in both periods, then the consumer will not purchase the product.
2. In the second period, the utility varies across scenarios. In the benchmark scenario, the utility in period 2 depends only on the price. Network externality, which appears in 3 of the 5 scenarios, is

captured by the additional term wD_1. For instance, in the network externality scenario, we see that the result of the comparison of $u_1 = \nu - p_1$ to $u_2 = \delta(\nu - p_2 + wD_1)$ depends on the firm's pricing policy (p_1, p_2), the influence of first-period adopters, and on the degree of consumers' patience, captured by the discount rate.

3. As consumers do not have information on past prices in the first period, and in line with Nasiry and Popescu (2011), Zhao et al. (2019), and Chen et al. (2020), we assume that the reference price effect only appears in the second period. This effect is measured by the difference between p_1 and p_2 scaled by an appropriate parameter. In the third and fourth scenarios, independently of which price is higher, this impact is given by $\theta(p_1 - p_2)$, meaning that consumer reacts to gains ($p_1 > p_2$) or losses ($p_1 < p_2$) in the same way. In the last scenario, as suggested by prospect theory, where "losses loom larger than gains", we suppose that consumers react more strongly to losses compared to gains; hence our assumption that λ is larger than γ.
4. We assume that the utility function is additive in the three components. Such a functional form is widely adopted in the literature (e.g., Xie and Sirbu, 1995; Li and Zhang, 2020; Nasiry and Popescu, 2011).

Table 2: Consumer utility in each period in the five scenarios

	Period 1	Period 2
B	$u = \nu - p_1$	$u = \delta(\nu - p_2)$
N	$u = \nu - p_1$	$u = \delta(\nu - p_2 + wD_1)$
R	$u = \nu - p_1$	$u = \delta(\nu - p_2 + \theta(p_1 - p_2))$
NR	$u = \nu - p_1$	$u = \delta(\nu - p_2 + wD_1 + \gamma(p_1 - p_2))$
NRL	$u = \nu - p_1$	$u = \delta(\nu - p_2 + wD_1 + \gamma(p_1 - p_2)^+ - \lambda(p_2 - p_1)^+)$

4 Responsive pricing

Under responsive pricing, the sequence of events is as follows: First, the monopolist determines the price p_1 in period 1. Consumers subsequently compare their utilities across two periods and accordingly choose either to adopt in period 1, adopt in period 2, or leave the market. Since the demand D_1 and price p_2 are yet to be realized, consumers develop rational expectations on these values in order to predict their utility in period 2. In a rational expectation equilibrium, the predictions, here of D_1 and p_2, coincide with the realized ones. The demand D_1 is realized by the end of period 1. Second, the monopolist determines p_2 in the second period, and the remaining consumers choose to adopt or not, knowing the intrinsic psychological surplus and extrinsic social surplus.

To demonstrate our solution procedure, we show how a rational expectation equilibrium is obtained in the benchmark case. In this scenario, consumers adopt in period 1 if $\nu - p_1 \geq \delta(\nu - p_2)$. Suppose there exists a threshold τ such that all consumers with valuations $\nu \geq \tau$ adopt in the first period. Under the assumption that the new product valuation is uniformly distributed $\nu \in [0, 1]$, the demand in the first period would be $D_1 = (1 - \tau)$. Consequently, the remaining consumers in the second period would have valuations $\nu \in [0, \tau]$. A generic consumer in period 2 will adopt the new product if $u = \nu - p_2 > 0$, and the demand will be $\max(\tau - p_2, 0)$. The firm's optimization problem in period 2 can then be expressed as follows:

$$\max_{p_2} \pi_2 = p_2 D_2 = p_2(\tau - p_2). \tag{1}$$

The unique solution to this strictly concave optimization problem is $p_2^* = \frac{\tau}{2}$.

Next, we consider the firm's problem in the first period to determine p_1^*. In a rational expectation equilibrium, the consumers adopt the new product in the first period if, and only if, their utility in period 1 is nonnegative and higher than the one in period 2, that is, $\nu - p_1 \geq 0$ and $\nu - p_1 \geq \delta(\nu - p_2)$.

In particular, a consumer with valuation τ is indifferent between adopting in either period. Therefore, we have

$$\tau - p_1 = \delta(\tau - p_2), \tag{2}$$

and using $p_2^* = \frac{\tau}{2}$, we obtain the threshold τ as a function of p_1, that is,

$$\tau(p_1) = \begin{cases} \frac{2p_1}{2-\delta}, & \text{if } p_1 \leq \frac{2-\delta}{2} \\ 1, & \text{otherwise} \end{cases} \tag{3}$$

If $p_1 > \frac{2-\delta}{2}$, then no consumer adopts in the first period, and demand is only positive in the second period. If $p_1 \leq \frac{(2-\delta)}{2}$, then the overall firm's optimization problem becomes

$$\max_{p_1} \pi = \pi_1 + \pi_2^* = p_1(1 - \tau(p_1)) + \frac{(\tau(p_1))^2}{4}. \tag{4}$$

It is easy to verify that π is concave in p_1, and from the first-order optimality conditions, that the maximum is achieved at $p_1^* = \frac{(2-\delta)^2}{2(3-2\delta)}$. Clearly, we have $0 < p_1^* < \frac{2-\delta}{2} \leq 1$. Substituting for p_1^*, we get $\tau = \frac{2-\delta}{3-2\delta} < 1$, and $0 < p_1^* < \frac{2-\delta}{2} \leq 1$ and $0 < p_2 = \frac{2-\delta}{2(3-2\delta)} \leq 1$. The other results in the benchmark as well as in all other scenarios are given in the next proposition. We introduce the following notations, which are used throughout our analysis:

$$\begin{aligned}
w^\theta =& \frac{\delta^2 - 2(1-\delta)(1-\theta)}{2}, \qquad w_1^\gamma = \frac{\delta^2 - 2(1-\delta)(1-\gamma)}{2}, \qquad w_1^\lambda = \frac{\delta^2 - 2(1-\delta)(1-\lambda)}{2},\\
w_2^\gamma =& \frac{\delta(1-\delta) + \gamma(2-\delta^2) + \sqrt{(\delta(1-\delta) + \gamma(2-\delta^2))^2 + 8(1-\delta)(2-\delta)(1+\gamma)}}{4} > 0,\\
w_2^\lambda =& \frac{\delta(1-\delta) + \lambda(2-\delta^2) + \sqrt{(\delta(1-\delta) + \lambda(2-\delta^2))^2 + 8(1-\delta)(2-\delta)(1+\lambda)}}{4} > 0,\\
w^{RN} =& \frac{\delta(1-\delta) + \sqrt{\delta^2(1-\delta)^2 + 8(1-\delta)(2-\delta)}}{4} > 0,\\
w_1^{RNR} =& \frac{\delta(1-\delta) + \theta(2-\delta^2) + \sqrt{(\delta(1-\delta) + \theta(2-\delta^2))^2 + 8(1-\delta)(2-\delta)(1+\theta)}}{4} > 0,\\
\xi =& \frac{-8 + \delta(16 - \delta(6 + (4-\delta)\delta)) + \sqrt{((4 - \delta(4+\delta))(16 - \delta(48 + \delta(-44 + \delta(24 + \delta(-16 + \delta(4+\delta))))))}}{4\delta(2-\delta)(1-\delta)},\\
g(i) =& 2(1+i)((3 - 2\delta - i(1-\delta)^2) + w(2 + \delta(2 + \delta i))) - 2w^2 > 0, \quad i \in (\theta, \gamma, \lambda),\\
h(i) =& (1+i)((2-\delta)^2 + w(2 + \delta(2-\delta))) - 2w^2 > 0, \quad i \in (\theta, \gamma, \lambda),\\
k(i) =& (1+i)(2-\delta) + w(2 + \delta(1+2i)) > 0, \quad i \in (\theta, \gamma, \lambda),\\
l(i) =& 2(1 - i + w) - \delta(2 - i(2-\delta)) > 0, \quad i \in (\theta, \gamma, \lambda)\\
m(i) =& (1-\delta)(1+i)(3 + \delta - i(1-\delta)) + 2(1+\delta)(1+i)w - w^2 > 0, \quad i \in (\theta, \gamma, \lambda)\\
x^+ =& \max(x, 0).
\end{aligned}$$

Proposition 1. *If the firm adopts responsive pricing, then the optimal pricing strategies and the demands and profits in the five scenarios are those given in Tables 3 and 4, respectively.*

Proof. See Appendix. □

We note that the results in the benchmark scenario in Tables 3 and 4 are quite similar to those established in Proposition 1 in Huang et al. (2018) and Proposition 4 in Papanastasiou and Savva (2017). In these papers, the authors use the same benchmark, against which they compare the situation where consumers face anxiety or engage in social learning in their adoption decision, respectively. However, our focus is different from theirs, as we previously stated. In what follows, we highlight a series of results derived from Proposition 1.

Table 3: Responsive pricing strategies

Scenarios	Pricing strategies
RB	$(p_1^{RB}, p_2^{RB}) = (\frac{(2-\delta)^2}{2(3-2\delta)}, \frac{(2-\delta)}{2(3-2\delta)})$
RN	$(p_1^{RN}, p_2^{RN}) = (\frac{(2-\delta)^2+w(2-\delta(2-\delta))-2w^2}{2(3-w)(1+w)-4\delta(1-w)}, \frac{(2-\delta)+w(2+\delta)}{2(3-w)(1+w)-4\delta(1-w)})$
RR	$(p_1^{RR}, p_2^{RR}) = \begin{cases} (1, \frac{1}{2}), & \text{if } \theta > \frac{2(1-\delta)}{2(1-\delta)+\delta^2} \\ (\frac{(2-\delta)^2}{2(3-2\delta-\theta(1-\delta)^2)}, \frac{(2-\delta)}{2(3-2\delta-\theta(1-\delta)^2)}), & \text{if } \theta \leq \frac{2(1-\delta)}{2(1-\delta)+\delta^2} \end{cases}$
RNR	$(p_1^{RNR}, p_2^{RNR}) = \begin{cases} (1, \frac{1}{2}) & \text{if } w \leq w^\theta \\ (\frac{h(\theta)}{g(\theta)}, \frac{k(\theta)}{g(\theta)}) & \text{if } w > w^\theta \end{cases}$
RNRL	$(p_1^{RNRL,\gamma}, p_2^{RNRL,\gamma}) = \begin{cases} \begin{cases} (1, \frac{1}{2}) & 0 < w \leq w_1^{\gamma+} \\ (\frac{h(\gamma)}{g(\gamma)}, \frac{k(\gamma)}{g(\gamma)}) & w_1^{\gamma+} < w \leq \min\{w_2^\gamma, 1\} \end{cases}, & \text{if } \lambda > \gamma \geq \xi^+ \\ (1, \frac{1}{2}) \quad 0 < w \leq \min\{w_2^\gamma, 1\}, & \text{if } \gamma < \lambda < \xi^+ \end{cases}$ $(p_1^{RNRL,\lambda}, p_2^{RNRL,\lambda}) = \begin{cases} (\frac{h(\lambda)}{g(\lambda)}, \frac{k(\lambda)}{g(\lambda)}) \quad \min\{w_2^\lambda, 1\} \leq w < 1, & \text{if } \lambda > \gamma \geq \xi^+ \\ \begin{cases} (\frac{1}{2}, \frac{1}{2}) & \min\{w_2^\lambda, 1\} \leq w < w_1^\lambda \\ (\frac{h(\lambda)}{g(\lambda)}, \frac{k(\lambda)}{g(\lambda)}) & w_1^\lambda < w \leq 1 \end{cases}, & \text{if } \gamma < \lambda < \xi^+ \end{cases}$ $(p_1^{RNRL}, p_2^{RNRL}) = \begin{cases} (\frac{1}{2}, \frac{1}{2}) \quad \min\{w_2^\gamma, 1\} < w < \min\{w_2^\lambda, 1\}, & \text{if } \lambda > \gamma \geq \xi^+ \\ (\frac{1}{2}, \frac{1}{2}) \quad \min\{w_2^\gamma, 1\} < w < \min\{w_2^\lambda, 1\}, & \text{if } \gamma < \lambda < \xi^+ \end{cases}$

Result 1. *In the benchmark scenario, the firm adopts a skimming pricing strategy, and the demand is increasing over time.*

In the absence of WoM and learning-by-doing effects, it is optimal to first sell the product to consumers having a high willingness to pay, and next decrease the price to reach other market segments. This result is in line with the literature; see, e.g., Kalish (1983); Krishnan et al. (1999).

Result 2. *In the presence of network externality:*

1. *If*

$$w > w^{RN} = f(\delta) = \frac{\delta(1-\delta) + \sqrt{\delta^2(1-\delta)^2 + 8(1-\delta)(2-\delta)}}{4},$$

then it is optimal to implement a penetration pricing strategy; otherwise skimming pricing is optimal,

2. *The market penetration of a new product is higher than in the benchmark scenario, i.e.,* $D^{RN} = D_1^{RN} + D_2^{RN} > D^{RB} = D_1^{RB} + D_2^{RB}$*, because* $D^{RN} - D^{RB} = \frac{w(4(1+w)-\delta(7-4\delta+3w))}{2(3-2\delta)((3-w)(1+w)-2\delta(1-w))} > 0$.

Clearly, the pricing strategy depends critically on the intensity of social influences. When this intensity is strong enough, then it is optimal to start with a low price to stimulate early adoption and benefit from a high externality effect in the second period. Otherwise, it is optimal to follow a skimming pricing strategy, for the same reason as in the benchmark scenario. As compared to the benchmark, the price is lower in the first period for all admissible parameter values, which results in higher demand. Even a small social effect is worth exploiting. Therefore, the aggregate demand would be higher than in the benchmark scenario, and the marginal difference is increasing with respect to the degree of social influences.

Table 4: Demands and profit under responsive pricing

Scenarios	Demands and profit
RB	$(D_1^{RB}, D_2^{RB}, \pi^{RB}) = (\frac{(1-\delta)}{(3-2\delta)}, \frac{(2-\delta)}{2(3-2\delta)}, \frac{(2-\delta)^2}{4(3-2\delta)})$
RN	$(D_1^{RN}, D_2^{RN}, \pi^{RN}) = (\frac{1-\delta+w}{(3-w)(1+w)-2\delta(1-w)}, \frac{(2-\delta)+w(2+\delta)}{2(3-w)(1+w)-4\delta(1-w)}, \frac{(2-\delta)^2+4w}{4(3-w)(1+w)-8\delta(1-w)})$
RR	$(D_1^{RR}, D_2^{RR}, \pi^{RR}) = \begin{cases} (0, \frac{1+\theta}{2}, \frac{1+\theta}{4}), & \text{if } \theta > \frac{2(1-\delta)}{2(1-\delta)+\delta^2} \\ (\frac{2(1-\delta)-\gamma(2-\delta(2-\delta))}{2(3-2\delta-\theta(1-\delta)^2)}, \frac{(2-\delta)}{2(3-2\delta-\theta(1-\delta)^2)}, \frac{(2-\delta)^2}{4(3-2\delta-\theta(1-\delta)^2)}) & \text{if } \theta \leq \frac{2(1-\delta)}{2(1-\delta)+\delta^2} \end{cases}$
RNR	$(D_1^{RNR}, D_2^{RNR}, \pi^{RNR}) = \begin{cases} (0, \frac{1+\theta}{2}, \frac{1+\theta}{4}) & \text{if } w \leq w^\theta \\ (\frac{(1+\theta)l(\theta)}{g(\theta)}, \frac{(1+\theta)k(\theta)}{g(\theta)}, \frac{((1+\theta)(2-\delta)^2+4w)}{2g(\theta)}) & \text{if } w > w^\theta \end{cases}$
RNRL	$(D_1^{RNRL,\gamma}, D_2^{RNRL,\gamma}, \pi^{RNRL,\gamma}) = \begin{cases} \begin{cases} (0, \frac{1+\gamma}{2}, \frac{1+\gamma}{4}) & 0 < w \leq w_1^{\gamma+} \\ (\frac{(1+\gamma)l(\gamma)}{g(\gamma)}, \frac{(1+\gamma)k(\gamma)}{g(\gamma)}, \frac{(1+\gamma)(2-\delta)^2+4w}{2g(\gamma)}) & w_1^{\gamma+} < w \leq \min\{w_2^\gamma, 1\} \end{cases}, & \text{if } \lambda > \gamma \geq \xi^+ \\ (1, \frac{1}{2}) \quad 0 < w \leq \min\{w_2^\gamma, 1\}, & \text{if } \gamma < \lambda < \xi^+ \end{cases}$
	$(D_1^{RNRL,\lambda}, D_2^{RNRL,\lambda}, \pi^{RNRL,\lambda}) = \begin{cases} (\frac{(1+\lambda)l(\lambda)}{g(\lambda)}, \frac{(1+\lambda)k(\lambda)}{g(\lambda)}, \frac{(1+\lambda)(2-\delta)^2+4w}{2(g(\lambda))}) \quad \min\{w_2^\lambda, 1\} \leq w < 1, & \text{if } \lambda > \gamma \geq \xi^+ \\ \begin{cases} (\frac{1}{2}, \frac{1}{2}) & \min\{w_2^\lambda, 1\} \leq w < w_1^\lambda \\ (\frac{h(\lambda)}{g(\lambda)}, \frac{k(\lambda)}{g(\lambda)}) & w_1^\lambda < w \leq 1 \end{cases}, & \text{if } \gamma < \lambda < \xi^+ \end{cases}$
	$(D_1^{RNRL}, D_2^{RNRL}, \pi^{RNRL}) = \begin{cases} (\frac{1-\delta}{2(1-\delta+\delta w)}, \frac{w}{2(1-\delta+\delta w)}, \frac{1-\delta+w}{2(1-\delta+\delta w)}) \quad \min\{w_2^\gamma, 1\} < w < \min\{w_2^\lambda, 1\}, & \text{if } \lambda > \gamma \geq \xi^+ \\ (0, \frac{1}{2}, \frac{1}{4}) \quad \min\{w_2^\gamma, 1\} < w < \min\{w_2^\lambda, 1\}, & \text{if } \gamma < \lambda < \xi^+ \end{cases}$

Remark 2. The set of values that satisfy the condition $w > f(\delta)$ is not empty. Indeed, we have $f(\delta) \in [0,1]$, with $f(0) = 1$, $f(1) = 0$, and $f'(\delta) < 0$. If consumers are perfectly farsighted, i.e., $\delta = 1$, then the condition is always satisfied.

Result 3. *In the presence of the reference-price effect:*

1. *The firm adopts a skimming pricing strategy,*
2. *The market penetration of a new product is higher than in the benchmark scenario i.e.,* $D^{RR} = D_1^{RR} + D_2^{RR} > D^{RB} = D_1^{RB} + D_2^{RB}$, *because*

$$D^{RR} - D^{RB} = \begin{cases} \frac{3\theta-1+12\delta\theta}{6-4\delta} > 0, & \textit{if } p_1 = 1 \textit{ (high launch price);} \\ \frac{\theta(2-\delta)^2(1-\delta)}{2(3-2\delta)(3-2\delta+\theta(1-\delta)^2)} > 0, & \textit{otherwise.} \end{cases}$$

The presence of a reference price in the second-period demand leads the firm to adopt a skimming pricing strategy. In both periods, the price is higher in this scenario than in the benchmark scenario. The firm achieves a dual benefit from this behavior. First, it allows,in period 1, to target consumers with a high utility for the product, as in the benchmark scenario. Second, it provides a psychological surplus to consumers in the second period, which is measured by $\theta(p_1 - p_2)$. Consequently, consumers adopt the product in larger numbers than in the benchmark scenario. Interestingly, if the marginal impact of the reference price is beyond a certain threshold, that is, $\theta > \frac{2(1-\delta)}{2(1-\delta)+\delta^2}$, then it is optimal to set a maximum price in period 1, that is, $p_1 = 1$, which leads to zero demand in that period. The rationale for such action is to maximize the reference-price effect on the second-period demand. We refer to this situation as *a high launch price*. Additionally, as consumers become more forward-looking, i.e., $\delta \to 1$, it would be easier to satisfy the above condition, which means that the firm would be able to charge aggressive skimming prices even when consumers are not strongly backward-looking. Besides, the firm is able to capture a higher market penetration than in the benchmark scenario.

Result 4. *In the presence of network externality and a symmetric reference-price effect:*

1. *If*

$$w > \max\{w^\theta, \min\{w_1^{RNR}, 1\}\},$$

   then the firm implements a penetration pricing strategy; otherwise, skimming pricing would be the optimal choice.

2. *If $w > w^\theta$, then market penetration under RNR is greater than the benchmark. For $w \leq w^\theta$, however, it is greater if $\theta > \frac{1-\delta}{3-2\delta}$.*

The above results shed light on how internal influences with reference-price effect can accelerate or decelerate the penetration of new product. The market penetration is higher under RNR in the presence of strong social influences. When this is not the case and when the reference-price effect is not prominent, then fewer consumers may end up adopting in the RNR scenario compared to the benchmark, especially if consumers are less farsighted. Moreover, the extent of penetration pricing is less, compared to the RN scenario, because $\max\{w^\theta, \min\{w_1^{RNR}, 1\}\} > w^{RN}$, which signals that this pricing strategy is not favorable in the presence of backward-looking behavior.

Result 5. *In the presence of network externality and an asymmetric reference-price effect, the pricing strategy is as follows:*

$$\text{if } \begin{cases} 0 < w \leq \min\{w_2^\gamma, 1\}, & \text{then price skimming is optimal,} \\ \max\{w_1^\lambda, \min\{w_2^\lambda, 1\}\} \leq w \leq 1, & \text{then price penetration is optimal,} \\ \min\{w_2^\gamma, 1\} < w < \min\{w_2^\lambda, 1\}, & \text{then constant pricing is optimal.} \end{cases}$$

The literature reports, that depending on the magnitude of the initial reference point, the firm can adopt a penetration, constant, or skimming pricing strategy. Our result generalizes to forward-looking consumers the similar result obtained in the literature with reference-dependent loss-averse myopic consumers (see, for example, Popescu and Wu, 2007, Theorem 4). However, the optimal pricing strategy depends on the whole dynamics of consumer adoption behavior, including social influences and the intensity of backward-looking behavior. If we had assumed that there is an initial reference point in the launch period too, then the choice of pricing strategy would additionally depend on the initial reference price. The main takeaway is that the firm takes into account the whole dynamics of consumers' adoption behaviors in pricing decision, and not solely their initial reference point.

To summarize, the monopoly pricing and market penetration of new products depend critically on the social influences, forward-backward-looking behavior, and whether consumers are loss averse. For instance, the monopolist's pricing strategy can change from a very aggressive skimming pricing strategy in the RR case to constant or penetration pricing in the $RNRL$ case, highlighting the impact of the interplay between the asymmetric reference-price effects and social influences.

5 Preannounced pricing

In this section, we examine the role of commitment in the firm's pricing strategy. The firm preannounces the full price path at the launch period, and consumers make their decisions accordingly. This pricing regime has been shown to be effective, that is, leading to higher outcomes, when consumers are forward-looking (Aviv and Pazgal, 2008).

As in the previous section, we illustrate the solution approach using the simplest benchmark case. First, the firm preannounces the prices p_1 and p_2. Given this information, consumers with valuations higher than a threshold τ adopt in the first period, whereas the remaining consumers may adopt in period 2. This threshold is defined by

$$\tau(p_1,p_2) = \begin{cases} p_1, & \text{if} \quad p_1 \le p_2, \\ \frac{p_1-\delta p_2}{1-\delta}, & \text{if} \quad p_1 > p_2 \quad \text{and} \quad p_1 - \delta p_2 \le 1-\delta, \\ 1, & \text{if} \quad p_1 > p_2 \quad \text{and} \quad p_1 - \delta p_2 > 1-\delta. \end{cases} \tag{5}$$

The firm determines its pricing strategy by optimizing its total profit, i.e.,

$$\max_{p_1,p_2} \pi = p_1 D_1 + p_2 D_2 = p_1(1-\tau(p_1,p_2)) + p_2(\tau(p_1,p_2) - p_2). \tag{6}$$

It is easy to verify that $\tau(p_1,p_2) = \frac{p_1-\delta p_2}{1-\delta}$ maximizes the firm's profit, whereas $\tau(p_1,p_2) = p_1$ and $\tau(p_1,p_2) = 1$ yield suboptimal solutions. The following proposition shows the equilibrium solution for all cases.

Proposition 2. *If the firm adopts preannounced pricing, then the optimal pricing strategies and the demands and profits in the five scenarios are those given in Tables 5 and 6, respectively.*

The benchmark case in Proposition 2 is similar to Proposition 1 in Papanastasiou and Savva (2017). Next, we give a series of results that have some managerial implications in relation to the firm's and consumers' decisions.

Result 6. *In the benchmark scenario, the firm adopts a skimming pricing strategy, and the demand rate is the same in both periods.*

Table 5: Preannounced pricing strategies

Scenarios	Pricing strategies	
PB	$(p_1^{PB}, p_2^{PB}) = (\frac{2}{3+\delta}, \frac{1+\delta}{3+\delta})$	
PN	$(p_1^{PN}, p_2^{PN}) = (\frac{2-w}{3+w-\delta}, \frac{1+\delta}{3+w-\delta})$	
PR	$(p_1^{PR}, p_2^{PR}) = (\frac{2}{3+\delta-\theta(1-\delta)}, \frac{(1+\delta)}{3+\delta-\theta(1-\delta)})$	
PNR	$(p_1^{PNR}, p_2^{PNR}) = (\frac{2(1-\delta)(1+\theta)+(1+\delta)(1+\theta)w-w^2}{m(\theta)}, \frac{(1-\delta^2)(1+\theta)+(1+\delta+2\delta\theta)w}{m(\theta)})$	
PNRL	$(p_1^{PNRL,\gamma}, p_2^{PNRL,\gamma}) = (\frac{2(1-\delta)(1+\gamma)+(1+\delta)(1+\gamma)w-w^2}{m(\gamma)}, \frac{(1-\delta^2)(1+\gamma)+(1+\delta+2\delta\gamma)w}{m(\gamma)})$,	if $0 < w \le \min\{(1+\gamma)(1-\delta), 1\}$
	$(p_1^{PNRL,\lambda}, p_2^{PNRL,\lambda}) = (\frac{2(1-\delta)(1+\lambda)+(1+\delta)(1+\lambda)w-w^2}{m(\lambda)}, \frac{(1-\delta^2)(1+\lambda)+(1+\delta+2\delta\lambda)w}{m(\lambda)})$,	if $\min\{(1+\lambda)(1-\delta), 1\} \le w < 1$
	$(p_1^{PNRL}, p_2^{PNRL}) = (\frac{1}{2}, \frac{1}{2})$,	if $\min\{w(1+\gamma)(1-\delta), 1\} < w < \min\{(1+\lambda)(1-\delta), 1\}$

Result 6 is similar to Proposition 1 in Papanastasiou and Savva (2017), suggesting that the firm is better off with skimming pricing strategies.

Result 7. *In the presence of network externality, if $w > 1-\delta$, the firm adopts a penetration pricing strategy; otherwise, it is better off with skimming pricing strategy.*

Table 6: Demands and profit under preannounced pricing

Scenarios	Demands and profit
PB	$(D_1^{PB}, D_2^{PB}, \pi^{PB}) = (\frac{1}{3+\delta}, \frac{1}{3+\delta}, \frac{1}{3+\delta})$
PN	$(D_1^{PN}, D_2^{PN}, \pi^{PN}) = (\frac{1}{3+w-\delta}, \frac{1}{3+w-\delta}, \frac{1}{3+w-\delta})$
PR	$(D_1^{PR}, D_2^{PR}, \pi^{PR}) = (\frac{(1-\theta)}{3+\delta-\theta(1-\delta)}, \frac{(1+\theta)}{3+\delta-\theta(1-\delta)}, \frac{1}{3+\delta-\theta(1-\delta)})$
PNR	$(D_1^{PNR}, D_2^{PNR}, \pi^{PNR}) = (\frac{(1+\theta)((1-\delta)(1-\theta)+w)}{m(\theta)}, \frac{(1+\theta)((1-\delta)(1+\theta)+w)}{m(\theta)}, \frac{(1+\theta)(1-\delta+w)}{m(\theta)})$
PNRL	$(D_1^{PNRL,\gamma}, D_2^{PNRL,\gamma}, \pi^{PNRL,\gamma}) = (\frac{(1+\gamma)((1-\delta)(1-\gamma)+w)}{m(\gamma)}, \frac{(1+\gamma)((1-\delta)(1+\gamma)+w)}{m(\gamma)}, \frac{(1+\gamma)(1+w-\delta)}{m(\gamma)})$, if $0 < w \leq \min\{(1+\gamma)(1-\delta), 1\}$
	$(D_1^{PNRL,\lambda}, D_2^{PNRL,\lambda}, \pi^{PNRL,\lambda}) = (\frac{(1+\lambda)((1-\delta)(1-\lambda)+w)}{m(\lambda)}, \frac{(1+\lambda)((1-\delta)(1+\lambda)+w)}{m(\lambda)}, \frac{(1+\lambda)(1+w-\delta)}{m(\gamma)})$, if $\min\{(1+\lambda)(1-\delta), 1\} \leq w < 1$
	$(D_1^{PNRL}, D_2^{PNRL}, \pi^{PNRL}) = (\frac{1-\delta}{2(1-\delta+\delta w)}, \frac{w}{2(1-\delta+\delta w)}, \frac{(w-\delta+1)}{(4(\delta w-\delta+1))})$, if $\min\{w(1+\gamma)(1-\delta), 1\} < w < \min\{(1+\lambda)(1-\delta), 1\}$

The above result is intuitive. Indeed, if the network effect is high enough, then the firm should capitalize on it and initially offer the product at a low price and then increase it. Note that the more strategic (or farsighted) the consumer is, i.e., the higher the value of δ, then the easier it is to satisfy the inequality in the statement. In particular, if we let $\delta \to 1$, then a penetration strategy would be the only possible result.

Result 8. *In the presence of the reference-price effect, the firm adopts a skimming pricing strategy.*

This result is the mirror of the previous case. As the second-period utility (and demand) is increasing in the first-period price, it is in the best interest of the firm to adopt a skimming pricing strategy. With such a strategy, in period 1, the firm sells at a high price to consumers having a large valuation of the product, and it attracts a higher demand in the second period with the positive effect of the reference price.

Comparing the benchmark and the reference-price scenarios, we can highlight the following features: (i) In both scenarios, the firm implements a skimming pricing strategy ($p_1^{PB} > p_2^{PB}$ and $p_1^{PR} > p_2^{PR}$). (ii) The firm charges higher prices in both periods when consumers consider a reference price ($p_1^{PR} > p_1^{PB}$ and $p_2^{PR} > p_2^{PB}$), with $\frac{p_1^{PB}}{p_2^{PB}} = \frac{p_1^{PR}}{p_2^{PR}}$, that is, the ratios of the first-period price to the second-period price are equal in both scenarios; (iii) The relative profits are equal to the relative prices, i.e., $\frac{\pi^{PB}}{\pi^{PR}} = \frac{p_1^{PB}}{p_1^{PR}} = \frac{p_2^{PB}}{p_2^{PR}}$.

Result 9. *In the presence of network externality and a symmetric reference-price effect, if $w < \min\{(1+\theta)(1-\delta), 1\}$, then the firm adopts a skimming pricing strategy; otherwise, penetration pricing is the optimal choice.*

The choice of the pricing strategy depends on the interplay between the network externality, the reference price, and the consumer's farsightedness parameters. The short interpretation is that if the marginal network effect w is too small, then the firm is better off to start with a high price to benefit from the psychological surplus in the second period. Note that, as by definition $w \in (0, 1)$, if $(1+\theta)(1-\delta) > 1$, which is equivalent to $\delta < \frac{\theta}{1+\theta}$, then the inequality in the statement of the result becomes $w < 1$ and is always satisfied. Put differently, if consumers are a little farsighted, then a skimming strategy is the right choice for the firm. On the other hand, if consumers are perfectly farsighted ($\delta \to 1$), then the condition, which becomes $w < \min\{0, 1\}$, cannot be met, and penetration pricing is optimal.

Result 10. *In the presence of network externality and asymmetric reference-price effect, the pricing strategy is as follows:*

1.

$$\text{if } \begin{cases} 0 < w \le \min\{(1+\gamma)(1-\delta), 1\}, & \textit{then price skimming is optimal,} \\ \min\{(1+\gamma)(1-\delta), 1\} < w < \min\{(1+\lambda)(1-\delta), 1\}, & \textit{then constant pricing is optimal,} \\ \min\{(1+\lambda)(1-\delta), 1\} \le w < 1, & \textit{then price penetration is optimal.} \end{cases}$$

2. *Loss aversion reduces the extent of the penetration pricing strategy since*

$$\min\{(1+\lambda)(1-\delta), 1\} > \min\{(1+\theta)(1-\delta), 1\}.$$

As in the previous result, the choice of a pricing strategy depends on all parameters involved in the second-period demand function. A few differences are worth highlighting. First, constant prices can be optimal under some conditions, which was not the case before. Second, the firm's pricing strategy depends on the relative importance of the psychological surplus and social influence. Indeed, the firm skims when social externality is weak, which amplifies the positive reference-price effect, whereas it adopts a penetration pricing policy when the social influence is strong. Constant pricing is the optimal choice when neither externality nor the reference-price effect prevail. Moreover, when the loss-aversion effect is high, a penetration pricing strategy becomes less appealing and the firm may end up adopting constant pricing if social externality does not counterbalance the negative reference-price effect.

6 Comparison

In this section, we characterize the conditions under which the firm is better off choosing a preannounced pricing strategy (respectively, responsive pricing strategy), and check if this choice is the one preferred by consumers. The detailed results are provided in the Appendix.

Result 11. *For all admissible parameter values, a preannounced pricing strategy in the benchmark scenario leads to higher prices and a higher profit, and to lower market penetration than does responsive pricing, that is,*

$$p_1^{PB} > p_1^{RB}, \quad p_2^{PB} > p_2^{RB}, \quad \pi^{PB} > \pi^{RB}, \quad D^{PB} < D^{RB}.$$

Result 12. *For all admissible parameter values, in the presence of network externality, a preannounced pricing strategy leads to higher prices and a higher profit, and to lower market penetration than does responsive pricing, that is,*

$$p_1^{PN} > p_1^{RN}, \quad p_2^{PN} > p_2^{RN}, \quad \pi^{PN} > \pi^{RN}, \quad D^{PN} < D^{RN}.$$

The recommendation from Results 11–12 is clear: the firm is better off implementing a preannounced pricing strategy in both considered scenarios. This choice does not suit consumers because prices are higher in both periods and demand is lower. In the benchmark scenario, we already obtained that, under both pricing strategies, price skimming is the optimal choice. Result 11 replicates what has been obtained in, e.g., Aviv and Pazgal (2008) or Papanastasiou and Savva (2017) in the absence of social learning, namely, that preannounced pricing is the right strategy when consumers are strategic. Result 12 is telling us that the logic remains unaltered if we add in network externality.

Result 13. *In the presence of the reference-price effect, if* $\theta > \frac{2(1-\delta)}{2(1-\delta)+\delta^2}$*, then a preannounced pricing strategy leads to lower prices, demand, and profit than does responsive pricing, i.e.,*

$$p_1^{PR} < p_1^{RR}, \quad p_2^{PR} < p_2^{RR}, \quad D^{PR} < D^{RR}, \quad \pi^{PR} < \pi^{RR};$$

otherwise, we have

$$p_1^{PR} > p_1^{RR}, \quad p_2^{PR} > p_2^{RR}, \quad D^{PR} < D^{RR}, \quad \pi^{PR} > \pi^{RR}.$$

Recall that when $\theta > \frac{2(1-\delta)}{2(1-\delta)+\delta^2}$, it is optimal to set $p_1^{RR} = 1$ (high launch price). Under this condition, responsive pricing leads to higher prices and profit; otherwise, preannounced pricing is more profitable. Interestingly, in both situations, the total demand is higher under responsive pricing, which is due to the big psychological boost $\theta(1-p_2)$ given to demand in the second period under responsive pricing. Note that the inequality $\theta > \frac{2(1-\delta)}{2(1-\delta)+\delta^2}$ is always satisfied when consumers are fully farsighted ($\delta = 1$), and never when they are myopic ($\delta = 0$). If the marginal impact of the reference price is low enough, that is, $\theta < \frac{2(1-\delta)}{2(1-\delta)+\delta^2}$, then the firm should implement preannounced pricing.

To save on notation, let

$$X = (1+\theta)(\delta^2(1+\theta)^2 + (1-\theta+w)^2 - 2\delta(1+w+\theta(\theta+w)))$$

Result 14. *In the presence of network externality and a symmetric reference-price effect, the results compare as follows:*

- *If $w \leq w^\theta$, then*

$$\begin{aligned} p_1^{PNR} &< p_1^{RNR}, \quad p_2^{PNR} \begin{cases} < p_2^{RNR}, & \text{if } w < (1-\delta)(1+\theta), \\ > p_2^{RNR}, & \text{otherwise,} \end{cases} \\ D^{PNR} &\lesseqgtr D^{RNR}, \text{ for } X \lesseqgtr 0, \\ \pi^{PNR} &\lesseqgtr \pi^{RNR}, \text{ for } X \lesseqgtr 0. \end{aligned}$$

- *If $w > w^\theta$, then*

$$\begin{aligned} p_1^{PNR} &> p_1^{RNR}, \quad p_2^{PNR} > p_2^{RNR}, \\ D^{PNR} &< D^{RNR}, \\ \pi^{PNR} &> \pi^{RNR}. \end{aligned}$$

In this comparison, we note that the reference price and the network externality play in opposite directions in the first period. In particular, if the reference price has a big enough effect on demand in the second period, then it is tempting to set the (responsive) price at the highest level in the first period to boost the psychological surplus in the second period, and hence the demand. On the other hand, a high impact of the network externality constitutes an incentive to launch the product at a low price to maximize the benefit of social influences in the second period.

Result 14 suggests that the monopolist is better off with a preannounced pricing strategy if it does not adopt a high launch price under responsive pricing; otherwise, the firm's profit under posted pricing might be dominated, depending on the market dynamics. Figures 1 and 2 illustrate the difference between PNR and RNR in terms of market penetration and profit, respectively, under $\delta = 0.9$. These figures reinforce the analytical results, that market penetration is smaller with committed pricing but leads to a higher profit. The exception happens only under a high launch price of responsive pricing for certain values. As consumers become more myopic, i.e., $\delta \to 0$, the whole area becomes consistent with our formal result, i.e., $D^{PNR} < D^{RNR}$ and $\pi^{PRN} > \pi^{RNR}$.

Recall that the $RNRL$ equilibrium result is expressed in different cases depending on the value of w, γ and λ. This makes the comparison between $PNRL$ and $RNRL$ very complicated because the parameter space is divided into 8 regions with $RNRL$ and into 3 regions with $PNRL$. To illustrate, we compare for two cases where consumers are loss neutral and loss averse, respectively. Let us suppose that $0 < w < \min(\max(w_1^\lambda, 0), \min(w_2^\gamma, 1), \min((1+\gamma)(1-\delta), 1))$. One can easily find that

$$p_1^{PNRL,\gamma} < p_1^{RNRL,\gamma}, \qquad p_2^{PNRL,\gamma} \lesseqgtr p_2^{RNRL,\gamma} \qquad \text{for} \quad w \lesseqgtr \min((1-\delta)(1+\gamma), 1)$$

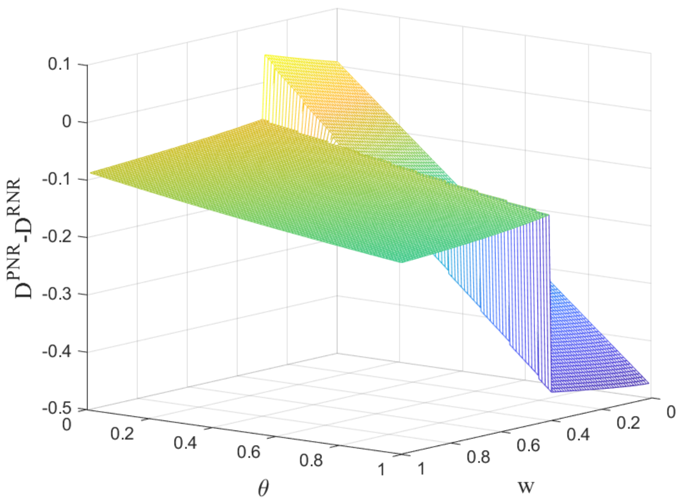

Figure 1: Market penetration difference between PNR and RNR

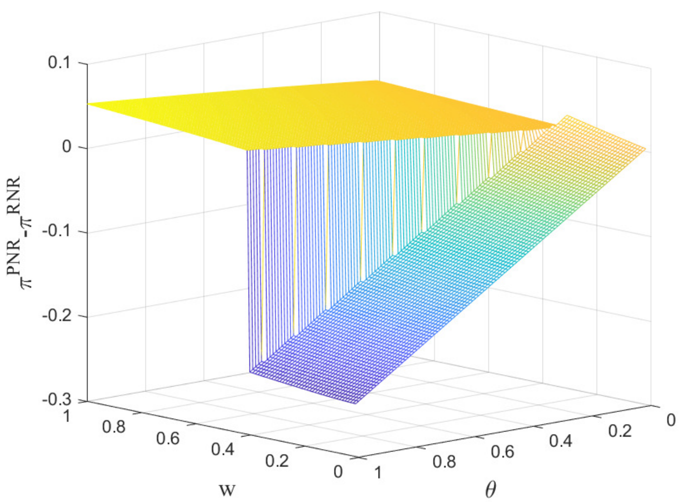

Figure 2: Profit difference between PNR and RNR

$$D^{PNRL,\gamma} \lesseqgtr D^{RNRL,\gamma} \quad \text{for} \quad X \lesseqgtr 0, \qquad \pi^{PNRL,\gamma} \lesseqgtr \pi^{RNRL,\gamma} \qquad \text{for} \quad X \lesseqgtr 0.$$

Similarly, let us suppose that $\max(w_1^\lambda, \min(w_2^\lambda, 1), \min((1+\lambda)(1-\delta), 1)) < w < 1$, which implies that we are in the region where loss-aversion results apply in both the $PNRL$ and $RNRL$ scenarios. It can be easily shown that

$$p_1^{PNRL,\lambda} > p_1^{RNRL,\lambda}, \quad p_2^{PNRL,\lambda} > p_2^{RNRL,\lambda}, \quad D^{PNRL,\lambda} < D^{RNRL,\lambda}, \quad \pi^{PNRL,\lambda} > \pi^{RNRL,\lambda}.$$

As we can see in the latter case, preannounced pricing leads to higher profits for the firm, but consumer would have preferred responsive pricing. Outside these specific cases, not much can be stated from the comparison of $PNRL$ and $RNRL$ scenarios.

7 Conclusion

This research is concerned with monopoly pricing for a new product when consumers look both forward and backward in the presence of social influences and loss aversion. We characterized and compared the results for two possible pricing schemes, namely, responsive and preannounced pricing. We adopt a rational expectation equilibrium between the firm and consumers to determine the prices, the demand rates, and the monopolist's performance. For both pricing strategies, we explore how the results vary with different consumer behaviors.

We find that the pricing regimes and the rate of new product demand depend heavily on the underlying consumer behaviors. When social influences are absent, the firm adopts a skimming pricing strategy; however, its intensity depends on the degree to which consumers tend to look backward. For instance, when consumers are highly sensitive to the reference price, the firm may adopt a skimming pricing strategy. When this happens, the monopolist may be better off avoiding committed pricing, which is usually called for in the literature for forward-looking consumers. In the presence of externality, the penetration or constant pricing strategy can be the optimal choice under certain conditions. We suggest that marketers should be aware that skimming pricing is preferable in the presence of backward-looking behavior and loss aversion, whereas penetration pricing is a better choice when strategic consumers are prone to social influences. We also generalize the conditional pricing strategy composed of penetration, constant, and skimming pricing strategies in the literature to reference-dependent loss-averse forward-looking consumers. We show that the type of pricing regime depends on the whole dynamics of consumer adoption behaviors rather than just the initial reference point.

The current study can be extended by considering more sophisticated consumers. For instance, one can consider a mixed population of myopic and forward-looking behaviors and also account for other reference price mechanisms e.g. peak-end anchoring, as proposed by Nasiry and Popescu (2011). Another avenue for future research is to study a fully dynamic multi-period diffusion model to examine how the evolving reference-price effect goes hand in hand with the new product diffusion mechanism over time. This is particularly important since the literature suggests that behavioral regularities, such as loss aversion, are more prevalent in durables (Neumann and Böckenholt, 2014) and the aggregate diffusion rate does not necessarily inherit such regularities from individual-level behavior (Hu and Nasiry, 2018).

Appendix

Proof of Proposition 1. We demonstrate the proof of Proposition 1 using backward induction similar to the proof of previously described benchmark case in order to obtain the equilibrium results.

- **Proof of RNR.** We show the proof of the network externality and reference-price effect case, i.e., RNR, which also incorporates the proof of RN. Thus, we do not provide an exclusive proof for the RN case in order to avoid repetition.

  The firm's problem in period 2 is $\max_{p_2} \pi_2 = p_2 D_2 = p_2(\tau - p_2 + \theta(p_1 - p_2) + wD_1)$. Using the first-order conditions, one can obtain $p_2 = \frac{\tau(1-w)+\theta p_1 + w}{2(\theta+2)}$. The indifference equation, i.e., $\tau - p_1 = \delta(\tau - p_2 + \theta(p_1 - p_2) + w(1-\tau))$ yields

$$\tau(p_1) = \begin{cases} \frac{p_1(2+\delta\theta)+\delta w}{2-\delta+\delta w}, & \text{if } p_1 \leq \frac{2-\delta}{2+\delta\theta} \\ 1, & \text{otherwise} \end{cases} \tag{A.1}$$

  Under the assumption of $p_1 \leq \frac{2-\delta}{2+\delta\theta}$, the firm's problem is as follows:

$$\max_{p_1} \pi = \quad p_1(1-\tau(p_1)) + \pi_2^{RNR} = p_1(1-\tau(p_1)) + \frac{(\tau(p_1)(1-w)+\theta p_1 + w)^2}{4(1+\theta)} \tag{A.2}$$

Solving the above optimization problem yields the solution described in Tables 3 and 4. One may note that $p_1^{RNR} \leq \frac{2-\delta}{2+\delta\theta}$ holds only if $w \geq w^{\theta}$. Therefore, we can obtain equilibrium solutions for both cases, i.e., $p_1^{RNR} \leq \frac{2-\delta}{2+\delta\theta}$ and $p_1^{RNR} > \frac{2-\delta}{2+\delta\theta}$, as described in Proposition 1. For the RN case, $p_1^{RN} \leq \frac{2-\delta}{2}$ holds, and since π is a concave function of p_1, the solution in Tables 3 and 4 is the global optimal one.

- **Proof of RR.** We show the proof for the reference-price effect only, i.e., RR. Using a backward induction approach, we optimize the monopolist's profit function in period 2. That is:

$$\max_{p_2} \pi = p_2(\tau - p_2 + \theta(p_1 - p_2)) \tag{A.3}$$

This yields $p_2 = \frac{\tau+\theta p_1}{2(\theta+1)}$. Using the indifference equation $\tau - p_1 = \delta(\tau - p_2 + \theta(p_1 - p_2))$, one can obtain

$$\tau(p_1) = \begin{cases} \frac{p_1(2+\delta\theta)}{2-\delta}, & \text{if } p_1 \leq \frac{2-\delta}{2+\delta\theta} \\ 1, & \text{otherwise} \end{cases} \tag{A.4}$$

Under the assumption of $p_1 \leq \frac{2-\delta}{2+\delta\theta}$, the firm's problem may be expressed as follows:

$$\max_{p_1} \pi = \quad p_1(1 - \tau(p_1)) + \pi_2^{RR} = p_1(1 - \tau(p_1)) + \frac{(\tau(p_1)\theta p_1)^2}{4(1+\theta)} \tag{A.5}$$

We can use the first-order conditions to obtain $p_1 = \frac{(2-\delta)^2}{2(3-2\delta-\theta(1-\delta)^2)}$. The condition $p_1 \leq \frac{2-\delta}{2+\delta\theta}$ holds if $\theta \leq \frac{2(1-\delta)}{2(1-\delta)+\delta^2}$, which implies $\tau(p_1) = \frac{p_1(2+\delta\theta)}{2-\delta}$; otherwise $\tau(p_1) = 1$. However, when $p_1 > \frac{2-\delta}{2+\delta\theta}$, then $\tau = 1$ and the firm's problem is $\pi = \pi_2 = p_2(1 - p_2 + \theta(p_1 - p_2))$ whereby the first-order conditions give $p_2 = \frac{1}{2}$. Since π is an increasing linear function with respect to p_1, we can obtain $p_1 = 1$. For each case, the equilibrium outcome can be found in Proposition 1.

- **Proof of RNRL**. Finally, we provide the proof for the $RNRL$ case. A similar approach can be used here. However, the consumers react to the reference-price effect asymmetrically, depending on whether they receive gains or losses. That means the firm's problem in period 2 can be expressed as follows:

$$\max_{p_2} \pi_2 = p_2 D_2 = p_2(\tau - p_2 + \gamma(p_1 - p_2)^+ + \lambda(p_1 - p_2)^- + wD_1) \tag{A.6}$$

The above-mentioned firm's problem is not smooth. We can transform this problem into two smooth subproblems:

$$\max_{p_2} \pi_2^{\gamma} = p_2 D_2 = p_2(\tau - p_2 + \gamma(p_1 - p_2) + wD_1) \tag{A.7}$$

$$\max_{p_2} \pi_2^{\lambda} = p_2 D_2 = p_2(\tau - p_2 + \lambda(p_1 - p_2) + wD_1) \tag{A.8}$$

Solving these subproblems yields $p_2^{\gamma} = \frac{\tau+\gamma}{2(1+\gamma)}$ and $p_2^{\lambda} = \frac{\tau+\lambda}{2(1+\lambda)}$. From the indifference equation for each subproblem, we also have

$$\tau^{\gamma}(p_1) = \begin{cases} \frac{p_1(2+\delta\gamma)+\delta w}{2-\delta+\delta w}, & \text{if } p_1 \leq \frac{2-\delta}{2+\delta\gamma} \\ 1, & \text{otherwise} \end{cases} \tag{A.9}$$

$$\tau^{\lambda}(p_1) = \begin{cases} \frac{p_1(2+\delta\lambda)+\delta w}{2-\delta+\delta w}, & \text{if } p_1 \leq \frac{2-\delta}{2+\delta\lambda} \\ 1, & \text{otherwise} \end{cases} \tag{A.10}$$

Under the assumption of $p_1 \leq \frac{2-\delta}{2+\delta\gamma}$ and $p_1 \leq \frac{2-\delta}{2+\delta\lambda}$, the two subproblems, namely, the gain subproblem and the loss subproblem, can be expressed as follows:

$$\max_{p_1} \pi^{\gamma} = p_1(1 - \tau^{\gamma}(p_1)) + \frac{(\tau^{\gamma}(p_1)(1-w) + \gamma p_1 + w)^2}{4(1+\gamma)} \tag{A.11}$$

$$\max_{p_1} \pi^\lambda = p_1(1-\tau^\lambda(p_1)) + \frac{(\tau^\lambda(p_1)(1-w)+\lambda p_1 + w)^2}{4(1+\lambda)} \tag{A.12}$$

It suffices to use the first-order conditions for each subproblem to determine p_1^γ and p_1^λ. One may note that when $0 \le w \le \min\{w_2^\gamma, 1\}$, then the equilibrium solution from the gain subproblem holds whereas the one from the loss subproblem is true for $\min\{w_2^\lambda, 1\} \le w \le 1$. Let's assume that $\lambda > \gamma \ge \max(\xi, 0)$ which ensures that $w_2^\gamma > w_1^\gamma$ and $w_2^\lambda > w_1^\lambda$. Consequently, if $0 \le w \le \max\{w_1^\gamma, 0\}$, then $p_1^{RNRL,\gamma} > \frac{(2-\delta)}{(2+\delta\gamma)}$; however, when $\max\{w_1^\gamma, 0\} < w < \min\{w_2^\gamma, 1\}$, then $p_1^{RNRL,\gamma} < \frac{(2-\delta)}{(2+\delta\gamma)}$ and the equilibrium can be found in Proposition 1 for both cases.

Furthermore, when $\min\{w_2^\lambda, 1\} < w < 1$, the equilibrium outcome can be derived from the loss subproblem. Particularly, $p_1^{RNRL,\lambda} < \frac{(2-\delta)}{(2+\delta\lambda)}$ holds if $\max\{w_1^\lambda, 0\} < w$. Given that $\max\{w_1^\lambda, 0\} < \min\{w_2^\lambda, 1\}$, one can see that, only this case, i.e., $p_1^{RNRL,\lambda} < \frac{(2-\delta)}{(2+\delta\lambda)}$ can describe the equilibrium outcome under loss aversion. When $\min\{w_2^\gamma, 1\} < w < \min\{w_2^\lambda, 1\}$, the firm adopts a constant pricing strategy. We can follow a similar backward induction approach. More specifically, the firm's problem in the second period is $\pi = pD_2 = p(\tau - p + wD_1)$, where $p = p_2 = p_1$. By applying the first-order conditions, we will have $p = \frac{1+\tau(1-w)}{2}$. The indifference equation, i.e., $\tau - p = \delta(\tau - p + w(1-\tau))$, leads to $\tau(p) = \frac{p(1-\delta)+\delta w}{1-\delta(1-w)}$. Thus, the firm's optimization problem under this case can be as follows:

$$p = \frac{\tau(1-\delta(1-w)) - \delta w}{1-\delta} \tag{A.13}$$

Therefore the firm's problem can take the following form:

$$\max_{\tau} \pi^{RNRL} = \quad p(1-\tau(p)) + p(\tau(p) - p + w(1-\tau(p))) \tag{A.14}$$

By solving the above-mentioned optimization problem, we can obtain the equilibrium results described in Proposition 1, which hold only when $\min\{w_2^\gamma, 1\} < w < \min\{w_2^\lambda, 1\}$.

Now if $\gamma < \lambda < \max(\xi, 0)$, then $w_1^\gamma > w_2^\gamma$ and $w_1^\lambda > w_2^\lambda$. In this case, the solution can be characterized under $RNRL(\lambda > \gamma \ge \max(\xi, 0))$. This means that for $0 < w < \min(w_2^\gamma)$, the inequality $p_1^{RNRL,\gamma} > \frac{(2-\delta)}{(2+\delta\gamma)}$ holds, and the corresponding solution prevails. When $\min(w_2^\gamma, 1) < w < \min(w_2^\lambda, 1)$, the constant pricing will be the optimal strategy, as in previous case. For $\min(w_2^\lambda, 1) < w < w_1^\lambda$, we need to solve the following problem:

$$\begin{aligned} \max_{p_1,p_2} \pi^{RNRL} = \quad & p_2(1-p_2+\lambda(p_1-p_2)) \\ \text{subject to:} \quad & p_1 - p_2 < 0 \\ & -p_1 \le 0 \\ & -p_2 \le 0 \end{aligned} \tag{A.15}$$

Given that the above function is concave with respect to p_1 and p_2 and the constraints are convex, we can utilize $K.K.T.$ conditions to determine the optimal solution:

1. $\nabla \pi^{RNRL}(p_1,p_2) = \nabla \sum_{i=1}^{3} \alpha_i g_i(p_1,p_2)$

$$(\lambda p_2, 1-2(1+\lambda)p_2+\lambda p_1) = \alpha_1(1,-1) + \alpha_2(-1,0) + \alpha_3(0,-1)$$

$$\Rightarrow \quad \begin{cases} \lambda p_2 = \alpha_1 - \alpha_2 \\ 1-2(1+\lambda)p_2 + \lambda p_1 = -\alpha_1 - \alpha_3 \end{cases}$$

2. $\alpha_i g_i(p_1,p_2) = 0 \quad i = 1, ..., 3$:

$$\alpha_1(p_1 - p_2) = 0,$$
$$\alpha_2(-p_1) = 0,$$
$$\alpha_3(-p_2) = 0.$$

3. $g_i(p_1, p_2) \leq 0$

$$\begin{aligned} p_1 - p_2 &\leq 0, \\ -p_1 &\leq 0, \\ -p_2 &\leq 0. \end{aligned}$$

4. $\alpha_1, \alpha_2, \alpha_3 \geq 0$

The above conditions are necessary and sufficient conditions for a solution to be deemed a global maximizer given the concavity of the objective function and the convexity of the constraints. One can see that $\alpha_1 = \frac{\lambda}{2}, \alpha_2 = \alpha_3 = 0, p_1 = \frac{1}{2}$ and $p_2 = \frac{1}{2}$ would satisfy the aforementioned conditions, and hence, a constant pricing policy is optimal for this case too. Finally, for $w_1^{\lambda} < w < 1$, the equilibrium solution from the loss problem holds where $p_1^{RNRL,\lambda} < \frac{2-\delta}{2+\delta\lambda}$. □

Proof of Proposition 2. As in proof of the benchmark case, a similar approach can be used. One can use the indifference equation to compute the valuation threshold based on p_1 and p_2. Consequently, we can replace τ with its equivalent to rewrite the monopolist's profit function as a function of prices in periods 1 and 2. Next, it suffices to use first-order conditions with respect to p_1 and p_2 to determine the equilibrium results for each case, given the concavity of the profit function.

To avoid repetition, we demonstrate the proof of the last case i.e., externality and asymmetric reference-price effect where others can be shown quite similarly. The monopolist's problem can be expressed as follows:

$$\max_{p_1,p_2} \pi = p_1(1-\tau) + p_2(\tau - p_2 + \gamma(p_1 - p_2)^+ + \lambda(p_1 - p_2)^- + w(1-\tau)) \tag{A.16}$$

Since the problem is not smooth, we can divide it into the two following subproblems:

$$\max_{p_1,p_2} \pi^{\gamma} = p_1(1-\tau) + p_2(\tau - p_2 + \gamma(p_1 - p_2) + w(1-\tau)) \tag{A.17}$$

$$\max_{p_1,p_2} \pi^{\lambda} = p_1(1-\tau) + p_2(\tau - p_2 + \lambda(p_1 - p_2) + w(1-\tau)) \tag{A.18}$$

Using indifference equation, τ^{γ} and τ^{λ} cab be obtained:

$$\tau^{\gamma}(p_1,p_2) = \begin{cases} \frac{p_1(1+\delta\gamma)-\delta p_2(1+\gamma)+\delta w}{1-\delta+\delta w}, & \text{if } p_1(1+\delta\gamma) - \delta p_2(1+\gamma) \leq 1-\delta \\ 1, & \text{otherwise} \end{cases} \tag{A.19}$$

$$\tau^{\lambda}(p_1,p_2) = \begin{cases} \frac{p_1(1+\delta\lambda)-\delta p_2(1+\lambda)+\delta w}{1-\delta+\delta w}, & \text{if } p_1(1+\delta\lambda) - \delta p_2(1+\lambda) \leq 1-\delta \\ 1, & \text{otherwise} \end{cases} \tag{A.20}$$

Replacing τ with τ^{γ} and τ^{λ} for the gain and loss subproblems, respectively, and using first-order conditions, we can determine the equilibrium outcome given the concavity of π^{γ} and π^{λ}. Note that $p_1^{PNRL,\gamma}(1+\delta\gamma) - \delta p_2^{PNRL,\gamma}(1+\gamma) \leq 1-\delta$ and $p_1^{PNRL,\lambda}(1+\delta\lambda) - \delta p_2^{PNRL,\lambda}(1+\lambda) \leq 1-\delta$ hold and the equilibrium is derived from the gain subproblem when $0 < w < \min\{(1+\gamma)(1-\delta), 1\}$, and from the loss subproblem when $\min\{(1+\lambda)(1-\delta), 1\} < w < 1$. However, for $\min\{(1+\gamma)(1-\delta), 1\} < w < \min\{(1+\lambda)(1-\delta), 1\}$, the firm adopts a constant pricing strategy. The indifference equation is

$$\tau(p) = \begin{cases} \frac{p(1+\delta\gamma)-\delta p(1+\lambda)+\delta w}{1-\delta+\delta w}, & \text{if } p(1+\delta\gamma) - \delta p(1+\gamma) \leq 1-\delta \\ 1, & \text{otherwise} \end{cases} \tag{A.21}$$

The results in this case can be obtained by considering the following optimization problem:

$$\max_{p} \pi = p(1-\tau(p)) + p(\tau(p) - p + w(1-\tau(p))) \tag{A.22}$$

where τ may be replaced with $\tau(p) = \frac{p(1+\delta\gamma)-\delta p(1+\lambda)+\delta w}{1-\delta+\delta w}$. Note that $p^{PNRL}(1+\delta\gamma)-\delta p^{PNRL}(1+\gamma) \leq 1-\delta$ holds. Hence, the equilibrium can be obtained in this case too, as shown in Tables 5 and 6. □

Proof of Results 1–10. The proposed properties in Results 1–10 can be directly obtained from the equilibrium outcomes in Propositions 1–2. □

Proof of Result 11. We can easily obtain

$$\begin{aligned}
p_1^{PB} - p_1^{RB} &= \frac{(1-\delta)\delta^2}{2(3+\delta)(3-2\delta)} > 0, \\
p_2^{PB} - p_2^{RB} &= \frac{3(1-\delta)\delta}{2(3+\delta)(3-2\delta)} > 0, \\
\pi^{PB} - \pi^{RB} &= \frac{(1-\delta)\delta^2}{4(3+\delta)(3-2\delta)} > 0, \\
D^{PB} - D^{RB} &= \frac{-3\delta(1-\delta)}{2(3+\delta)(3-2\delta)} < 0.
\end{aligned}$$

□

Proof of Result 12. Similarly, we can obtain

$$\begin{aligned}
p_1^{PN} - p_1^{RN} &= \frac{\delta^2(1+w(2-w)-\delta(1-w))}{2(3+\delta-w)((3-w)(1+w)-2\delta(1-w))} > 0, \\
p_2^{PN} - p_2^{RN} &= \frac{\delta(3(1-\delta(1-w))+w(2-w))}{2(3+\delta-w)((3-w)(1+w)-2\delta(1-w))} > 0, \\
\pi^{PN} - \pi^{RN} &= \frac{\delta^2(1-\delta+w)}{4(3+\delta-w)((3-w)(1+w)-2\delta(1-w))} > 0, \\
D^{PN} - D^{RN} &= \frac{-\delta(3-w)(1+w-\delta)}{2(3+\delta-w)((3-w)(1+w)-2\delta(1-w))} < 0.
\end{aligned}$$

□

Proof of Result 13.

- If $\theta > \frac{2(1-\delta)}{2(1-\delta)+\delta^2}$:

$$\begin{aligned}
p_1^{PR} - p_1^{RR} &= \frac{-(1+\delta-\gamma(1-\delta))}{3+\delta-\gamma(1-\delta)} < 0 \\
p_2^{PR} - p_2^{RR} &= \frac{-(1-\delta(1-\gamma)-\gamma)}{2(3+\delta-\gamma(1-\delta))} < 0, \\
D^{PR} - D^{RR} &= \frac{-1-3\delta-\gamma(3+\delta)+\gamma(1-\delta)(1+\gamma)}{2(3+\delta-\gamma(1-\delta))} < 0, \\
\pi^{PR} - \pi^{RR} &= \frac{-2-3\delta-\gamma(3+\delta)+\gamma(1-\delta)(1+\gamma)}{4(3+\delta-\gamma(1-\delta))} < 0
\end{aligned}$$

- Otherwise:

$$\begin{aligned}
p_1^{PR} - p_1^{RR} &= \frac{\delta^2(1-\delta)(1+\gamma)}{2(3+\delta-\gamma(1-\delta))(3-2\delta+\gamma(1-\delta)^2)} > 0, \\
p_2^{PR} - p_2^{RR} &= \frac{(1-\delta)\delta(3-\gamma(1-2\delta))}{2(3+\delta-\gamma(1-\delta))(3-2\delta+\gamma(1-\delta)^2)} > 0,
\end{aligned}$$

$$D^{PR} - D^{RR} = \frac{-\delta(1-\delta)(1+\gamma)(3-\gamma(1-\delta))}{2(3+\delta-\gamma(1-\delta))(3-2\delta+\gamma(1-\delta)^2)} < 0,$$
$$\pi^{PR} - \pi^{RR} = \frac{\delta^2(1-\delta)(1+\gamma)}{4(3+\delta-\gamma(1-\delta))(3-2\delta+\gamma(1-\delta)^2)} > 0.$$

□

Proof of Result 14.

- If $w \leq w^\theta$:

$$p_1^{PNR} - p_1^{RNR} = \frac{-((1+\theta)(1-\delta^2-(1-\delta)^2\theta+(1+\delta)w))}{m(\theta)} < 0,$$
$$p_2^{PNR} - p_2^{RNR} = \frac{-((1-\delta)(1-\theta)+w)(w-(1-\delta)(1+\theta))}{2m(\theta)} = \begin{cases} < 0, & \text{if} \quad w < (1-\delta)(1+\theta) \\ > 0, & \text{Otherwise} \end{cases}$$
$$D^{PNR} - D^{RNR} = \frac{(1+\theta)(\delta^2(1+\theta)^2+(1-\theta+w)^2-2\delta(1+w+\theta(\theta+w)))}{2m(\theta)} \lesseqgtr 0,$$
$$\pi^{PNR} - \pi^{RNR} = \frac{(1+\theta)(\delta^2(1+\theta)^2+(1-\theta+w)^2-2\delta(1+w+\theta(\theta+w)))}{4m(\theta)} \lesseqgtr 0.$$

- Otherwise:

$$p_1^{PNR} - p_1^{RNR} = \frac{(\delta^2(1+\theta)((1-\delta)(1+\theta)+(1+2\theta)w)(1+\theta-\delta(1+\theta)(1-w)+(2+\theta)w-w^2))}{m(\theta)g(\theta)} > 0,$$
$$p_2^{PNR} - p_2^{RNR} = \frac{\delta((1-\delta)(1+\theta)+(1+2\theta)w)((1-\delta)(1+\theta)(3-(1-2\delta)\theta)+(1+\theta)(2+\delta(3+2\delta\theta))w-w^2)}{m(\theta)g(\theta)} > 0,$$
$$D^{PNR} - D^{RNR} = -\frac{\delta((1-\delta)(1+\theta)+(1+2\theta)w)((1-\delta)(1+\theta)(3-(1-\delta)\theta)+(2+\delta+2\theta)w-w^2)}{m(\theta)g(\theta)} < 0,$$
$$\pi^{PNR} - \pi^{RNR} = \frac{(\delta^2(1+\theta)(1+\theta-\delta(1+\theta)+w+2\theta w)^2)}{2m(\theta)g(\theta)} > 0.$$

□

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