Work in progress, incomplete

Personalized pricing disables rivals from softening competition[1]

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May 2019

Keywords: Spatial competition, personalized pricing, endogenous non-price variables

Abstract: Consumers leave increasingly more digital footprints, which improves firms' ability to practice personalized pricing (first-degree price discrimination) instead of uniform pricing. Other things equal, a dominant strategy for a firm is to use personalized pricing because it can then charge each consumer a price which equals that consumer's willingness to pay for the good. However, with personalized pricing firms compete fiercely for each single consumer. Therefore, an equilibrium with personalized pricing nonetheless constitutes a prisoner's dilemma for competing firms; they end up with lower profits than if they all used uniform pricing. Typically, though, imperfectly competitive firms have other strategic choice variables other than prices. For instance, it is well known that under uniform pricing each firm might differentiate its product from that of the rival in order to make the rival less aggressive. We show that this is not true under personalized pricing: Firms cannot use product differentiation or other non-price strategic variables as a tool

[1] In particular, we thank Greg Shaffer for very helpful comments and suggestions. Furthermore, we thank Arne Rogde Gramstad, Kenneth Fjell, Jarle Møen and seminar participants at University of Copenhagen, NHH Norwegian School of Economics and NORIO XI 2019, Stockholm School of Economics, for useful discussions.

to reduce the competitive pressure. Once we take this into account, the theory no longer predicts that it necessarily is a dominant strategy to use personalized pricing. Instead, it might be a dominant strategy to commit to using uniform pricing.

1 Introduction

Personalized pricing (first-degree price discrimination) was once the prevailing pricing method in the retail sector. Prior to the mid-nineteenth century, sellers in the U.S. and Western Europe negotiated on prices with each individual customer (Phillips, 2012; Wallheimer, 2018). It was not until the 1860s that we saw a shift towards the present pricing standard, uniform pricing. The establishment of the first department stores initiated the shift. Personalized pricing requires detailed information both about purchasing prices for each single good and about individual consumers' willingness to pay. It thus turned out to be an inefficient pricing method for department stores offering a wide variety of products and served a large number of customers.[2] Imposing one single fixed price on each good made the pricing task substantially less time consuming (Phillips, 2012, p.33).[3]

Today, personalized pricing is again on the agenda. Consumers leave digital footprints by downloading apps and visiting websites that are designed to collect individual data. In contrast to the early nineteenth century, sellers can now directly learn about consumers' willingness to pay. Moreover, Big Data and machine learning algorithms allow firms to come much closer to applying personalized pricing than before, for instance by inducing a shift from third-degree (group based pricing) to first-degree price discrimination. This

[2] Clerks used to adopt a "price code" system where information about prices written on the price-tags was understandable only for the clerks and not for the customers (Phillips, 2012, p.30). Hence, when stores grew larger, not only was negotiation more time consuming, but keeping track of all the codes became more cumbersome as well.

[3] Alexander T. Stewart, who established a dry-goods store in New York in 1826, was among the pioneers in using uniform prices. He is often credited as being the first to use the one-price-to-all-principle in the United States. Britannica describes Stewart in the following way (Alexander Turney Stewart, 2019): "Instead of haggling over prices with each individual customer, Stewart set standard prices on all his goods, which was an innovation in his time." The dry goods chain Macy's announced its one-price policy in 1858 (Resseguie, 1965), and the same policy was applied by John Wanamaker in Philadelphia some years later. In Western Europe, some Parisian stores had one-price-to-all-ads already in the 1830s (Wallheimer, 2018; Resseguie, 1965; Phillips, 2012).

reduces information costs significantly, and firms are often capable of practicing high-scale personalized pricing (see discussion e.g. by Choe et al., 2018, and Jullien et al., 2019). In Varian's (2010) terminology, "Instead of a 'one size fits all' model, the Web offers a 'market of one'.

With this development, will personalized pricing again become the standard pricing method in retail markets? Owing to textbook examples in ECO101, many relate personalized pricing to a monopolist seller who extracts all consumer surplus by charging each individual a price equal to her maximum willingness to pay for the good. Before the arrival of department stores 150 years ago, sellers were often local monopolists in their product lines (Jones, 1936, among others).[4] The advantage of using personalized pricing in such markets is well illustrated by the textbook example. However, in retail markets today, there are usually more than one seller; digitalization in itself increases the options consumers face through online sales. Therefore, using personalized pricing in such a market structure might lead firms to end up competing intensively for each and every consumer (a "market of one").[5] The seminal paper by Thisse and Vives (1988) shows that applying personalized pricing could be a prisoner's dilemma situation; each firm has incentives to unilaterally adopt personalized pricing even though joint profits would be higher if they all use uniform pricing.

Personalized pricing (or something close to it) is indeed observed to be practiced in certain industries, for instance by hotel and airline agencies (see, e.g., Mohammed, 2017). However, most firms set a fixed price for each product, even when they have access to large amounts of consumer data. Hence, for the time being, a widespread shift to personalized pricing in retail markets seems to be absent. In the same vein, it is interesting to note

[4] At that time, the general retail store in a region offering some product lines was often the only source of supply of goods people could not produce themselves in their homes. Further, special stores offering one product line were rare and usually found only in large cities (Jones, 1936, p.134).

[5] In their bestseller, written for a business audience, Shapiro and Varian (1998, pp. 40) gave the following warning: "If your online travel agency knows that you are interested in deep-sea fishing, and it knows that deep-sea fishermen like yourself are often wealthy, it may well want to sell you a high-priced hotel package. On the other hand, if the travel agency knows that you like snorkeling, and snorkelers prefer budget travel, then they can offer you a budget package. In these examples, the provider can design a package that is optimized for your interests and charge you accordingly. But be careful about those premium prices for deep-sea fishermen: even wealthy deep-sea fishermen can change travel agencies."

that despite the information revolution and huge advances in for instance supply side management and computer assisted design, firms do not seem to match their products according to each consumer's preferences to such an extent as one might expect.

The continued prevalence of uniform pricing may partly be due to privacy concerns and resistance from consumers who dislike information gathering and personalized pricing (see Acquisti et al., 2016, for a comprehensive survey). Consumers might also consider personalized pricing ("haggling") as "unfair", and prefer to buy from firms that commit to "one price for every man".

We abstract from these effects on the consumer side. Our focus is on strategic interactions between competing firms. In particular, we ask whether the prisoner's dilemma outcome from Thisse and Vives (1988) depends critically on their assumption that prices are firms' only choice variable. If firms also can make choices about for instance product differentiation or product customization, or other non-price variables, will they still have incentives to unilaterally adopt personalized pricing?

To approach these questions we consider competition between two firms located at each end of a Hotelling line.[6] At stage 0, each firm can commit to using uniform pricing (or alternatively, that a firm can renounce the possibility of using personalized pricing by for instance not collecting individual data[7]). At stage 1, the firms simultaneously choose the value of some non-price variable like product differentiation. At stage 2, they compete in prices. If a firm has not committed to uniform pricing at stage 0, it is free to choose between uniform pricing and personalized pricing at stage 2. Stages 0 and 2 of the game resemble Thisse and Vives (1988). However, we introduce an additional stage where firms make endogenous choices about a non-price variable.

A firm that uses personalized pricing seeks to maximize the profit margin it earns from each single consumer. If the firm is unable to attract a given consumer and earn a positive profit margin (for instance because of the competitive pressure), it can do no better than to offer the good to that consumer at a price equal to marginal costs. This is a robust result. Therefore, an important corollary is the following: If a firm faces competition from

[6] A recent example that literally fits into the spatial Hotelling framework is Staples which offered individual discounts based on the distance between the customers' location and the rival stores (Valentino-DeVries et al., 2012).

[7] See further discussion by Matsumura and Matsushima (2015).

a rival that uses personalized pricing, this firm's equilibrium prices reflect the fact that its consumers could alternatively have bought the rival's good at a price equal to marginal costs (Thisse and Vives, 1988; Lederer and Hurter,1986; and Bhaskar and To, 2004). This is true independently of the value and characteristics of any non-price variables the firm may employ (such as product customization, location or product differentiation). It is also true independently of whether the firm itself uses personalized pricing; it is not the firm's own pricing policy that matters in this respect. If the rival uses personalized pricing, this firm cannot use non-price variables as a tool to soften the rival's pricing behavior. To the best of our knowledge, the implications of this result has not yet been highlighted in the literature. This is the focus of the present paper.[8] In the spirit of Fudenberg and Tirole (1984) and Tirole (1988) we show that a firm's choice of whether to commit to uniform pricing at stage 0 is a choice of whether to give the rival strategic incentives to soften competition through non-price variables. This effect may invalidate the prisoner's dilemma outcome from Thisse and Vives (1988).

The rest of the paper proceeds as follows. Section 2 reviews related literature. In Section 3 we set up the basic model with the standard assumptions in a Hotelling framework. We first provide some general insights into how personalized pricing disables rivals to soften competition. Thereafter, we use endogenous firm-specific mismatch costs as an illustrative example to show how firms may prefer to commit to uniform pricing in order to avoid a low profit equilibrium. We extend the model in three ways in Section 4 by considering location incentives (an alternative non-price variable), a two-sided market and by opening up for partial multi-homing by consumers. Lastly, Section 5 concludes.

[8] DellaVigna and Gentzkow (2017) show that most U.S. retail chains use uniform pricing within stores. They consider three reasons as plausible explanations for this: Commitment to uniform pricing can soften competition, can be regarded as more fair from consumers' point of view, and can avoid imposing additional managerial decision-making costs. The first explanation is related to our findings. Further, technology improvements can reduce managerial costs related to offering more flexible prices, which might make it more difficult to commit to uniform pricing. However, we ask whether consumers within the same store face different prices for the same products rather than consumers across stores.

2 Literature review

Recent developments in information gathering technologies make it possible for firms to collect more accurate information about consumers' individual willingness to pay, and this increases firms' abilities to practice personalized pricing (first-degree price discrimination). While fully personalized pricing may still be unrealistic, prices based on detailed features of consumers are feasible. Varian (2019) actually argues that the distinction between first-degree and third-degree price discrimination is becoming vague. The (U.S.) Council of Economic Advisers (2015) states that "Big data is used to design products and services that deliver more value to the individual consumer" and "...encourages a shift from third-degree ...towards personalized pricing". Technological progress and improved data access therefore implies that personalized pricing and product customization are on the agenda as ever before. This is reflected in recent debates both in popular media (e.g. Tanner, 2014) and in academic literature (Valletti and Wu, 2016; Prüfer and Schottmüller, 2017; Rubinfeld and Gal, 2017; Choe et al., 2018; Jullien et al., 2019, among others).

Much attention has been devoted to size effects, where a firm with more consumers can collect more data and thereby create more accurate individual consumer information. However, firms may also buy access to data that allow for personalization of prices and products from third-party providers of data. Competition among such providers can be intensive; see discussion by Varian (2019). We do not focus on the process of collecting or buying information; we make the simplifying assumption that firms are able to practice personalized pricing unless they made an ex ante commitment not to do so.

In this respect, our study is closely related to Thisse and Vives (1988), who consider a two-stage game where each of two Hotelling firms can commit to uniform pricing before they compete in prices. For a firm that does not commit to uniform pricing in the first stage, it is optimal to use personalized pricing in the second stage. Thisse and Vives (1988) show that a prisoner's dilemma outcome emerges, where both firms in equilibrium use personalized pricing even though aggregate profits would be higher if they both had committed to uniform pricing.[9]

A firm that uses personalized pricing sets individual prices equal to marginal cost to its marginal consumer and to consumers served by the rival (Hurter and Lederer, 1985; Lederer

[9] Choudhary et al. (2005) extend Thisse and Vives (1988) to a set-up with vertically differentiated firms.

and Hurter, 1986; Thisse and Vives, 1988; Bhaskar and To, 2004). Previous studies assume either a fixed price policy, such that both firms per definition use personalized pricing (Hurter and Lederer, 1985; Lederer and Hurter, 1986; Bhaskar and To, 2004) or that all non-price variables are exogenous (Thisse and Vives, 1988). By combining these elements we show that a firm that uses personalized pricing disables rivals to soften competition. In the terminology of Fudenberg and Tirole (1984) and Tirole (1988), a firm's choice of whether to commit to uniform pricing is also a choice of whether to give the rival strategic incentives to soften competition. More precisely, if a firm uses personalized pricing, there will be no strategic effect of a rival's choice of non-price variables.

As an illustration, we consider firms' incentives to reduce the firm-specific mismatch costs, modelled as a firm-specific transportation cost in the Hotelling framework. Ferreira and Thisse (1996; inspired by the firm-specific transportation cost framework by Launhardt, 1885) and Hendel and de Figueiredo (1997) show that firms choose high mismatch costs in order to induce soft price competition. This is similar to our finding where both firms commit to uniform pricing; going for high mismatch costs induces soft pricing behavior from the rival. von Ungern-Sternberg (1988) assumes that mismatch costs and prices are determined simultaneously. This implies that there is no strategic interdependence between these two choice variables, and firms want to minimize mismatch costs. Consequently, von Ungern-Sternberg (1988) provides a benchmark that shows the outcome without a strategic effect under uniform pricing.

In an extension of the basic Hotelling model where firms are located at the extremes of the Hotelling line, we show that the location incentives for a firm using personalized prices depend crucially on the pricing policy of the rival. The firm we consider perceives a rival that charges all consumers the same price (uniform pricing) as relatively soft. This indicates that it will locate closer to a rival that uses uniform pricing than to a rival that uses personalized pricing. However, as noted above, the strategic effect – which generates maximum differentiation in the standard Hotelling model – does not exist if the rival uses personalized pricing. We show that for this reason, the firm will nonetheless locate closer to a rival that uses personalized pricing compared to one that uses uniform pricing.

Also Hurter and Lederer (1985), Lederer and Hurter (1986) and Bhaskar and To (2004) depart from the standard assumption of uniform pricing and analyze location incentives. However, they do not consider how the location incentives for a firm using personalized prices depend on the rival's price policy. Instead, they presuppose that both firms use personalized pricing, and find that the firms maximize profits by choosing locations that minimize consumers' average transportation costs. This implies that firms end up choosing the socially optimal locations.

There exist a few other studies that show how the prisoner's dilemma described above may not evolve under personalized pricing. Shaffer and Zhang (2002) show that a firm with a high quality product may benefit from personalized pricing through a higher market share. Closer to us is Matsumura and Matsushima (2015). The timing of the game in Matsumura and Matsushima (2015) resembles ours, where they consider cost-reducing effort as the non-price variable. They show that whereas it is always beneficial for the firm with a cost advantage to use personalized pricing, the high cost firm prefers to use uniform pricing if the ex ante cost difference between the two firms are sufficiently large. However, they focus mainly on size effects stemming from asymmetric costs and do not explicitly discuss the main point of the present paper: In general and regardless of size effects, if a firm uses personalized pricing, there is no strategic effect of a rival's choice of non-price variables.[10]

While fully personalized pricing may still be unrealistic in practice, prices based on detailed features of consumers are feasible. Consequently, the distinction between first-degree and third-degree price discrimination is becoming vague (Varian, 2019). Corts (1998) and Shaffer and Zhang (1995), among others, show that oligopolistic third-degree price discrimination can intensify competition and lower profits. As emphasized, we do not model the process of collecting more accurate consumer information. There is a large number of papers incorporating the process of collecting consumer information in a first-period in order to be able to price discriminate in later periods, so-called behavior-based price discrimination. The majority of these papers assume that firms use third-degree price discrimination in the second period. In such a framework, Fudenberg and Tirole (2000) find that a prisoner's dilemma situation occurs in equilibrium as more information about consumers' past purchases triggers aggressive competition (see also Villas-Boas, 1999). In contrast, Acquisti and Varian (2005) show that if firms can offer enhanced services to loyal consumers, their profits increase compared to uniform pricing in the second-period. Choe et al. (2018) extend Fudenberg and Tirole's (2000) framework to include asymmetric

[10] See also Anderson et al. (2015; 2016) who analyze targeting and the interplay with the advertising market.

consumer information and personalized pricing in the second period. The asymmetric information results in asymmetric equilibria where one firm sets more aggressive prices in the first period in order to gain market share, thereby being able to charge higher personalized prices to all loyal customers in the second period. Both firms are worse off when they are able to offer personalized prices compared to group-based pricing.

Our study also relates to the literature on product customization. Big data does not only put personalized pricing on the agenda, it also makes product customization a current topic as more information about consumer preferences is available. Dewan et al. (2000; 2003) and Bernhardt et al. (2007) consider costly customization. By contrast, we bypass any costs of customization in order to isolate the strategic effects on price. Syam et al. (2005) take a similar approach, though in a different context than ours. However, none of the above papers studies the choice of price policy in relation to product customization as we do.[11]

3 The model set-up

We consider competition between two firms that are located on a Hotelling line with length 1. Consumer tastes are uniformly distributed along the line. Throughout, we assume that both firms are active (market sharing) and that all consumers are served (market coverage). Further, for now we assume unit demand. Firms have constant marginal cost c. We consider two price schedules; personalized pricing and uniform pricing. If firm i uses personalized pricing (first-degree price discrimination), each consumer is offered the good at an individual price $p_i(x)$, where x is the consumer's location on the Hotelling line. If the firm uses uniform pricing, all consumers pay the same price $p_i(x) = p_i$ independently of location.

Thisse and Vives (1988) show that it is a dominant strategy for firms to choose personalized pricing rather than uniform pricing, but that this constitutes a prisoner's dilemma that reduces equilibrium profits. To demonstrate this as simply as possible, they abstract from any other choice variables for the firms. However, in imperfectly competitive markets firms typically also make decisions on for instance which quality level they should offer,

[11] See Stole (2007), Zhang (2009) and Fudenberg and Villas-Boas (2012) for literature surveys on personalized pricing (price discrimination) and competition.

whether they should differentiate their products from those of the rivals, and how much they should spend on advertising. In the following, we will label such decisions as non-price variables. A main contribution of the present paper is to show that once we allow firms to make decisions on non-price variables, it is no longer clear that it is a dominant strategy to choose personalized pricing. Indeed, it may instead be a dominant strategy to commit to uniform pricing.

To see the mechanisms at work, let n_0 and n_1 denote the level of the non-price variable chosen by firm 0 and 1 at stage 1 (for instance the location on the Hotelling line), and suppose first that both firms use uniform pricing (commit to uniform pricing at stage 0). The equilibrium prices at stage 2 will then be a function of non-price variables chosen at stage 1; $p_i = p_i(n_0, n_1)$, $i = 0, 1$. We can thus write the reduced-form profit level of firm i at stage 1 as

$$\pi_i = \pi_i(n_0, n_1, p_0(n_0, n_1), p_1(n_0, n_1)). \tag{1}$$

The first-order conditions at stage 1 is given by $d\pi_0/dn_0 = d\pi_1/dn_1 = 0$. Using the envelope theorem, we find that the total derivative of π_i with respect to n_i is

$$\frac{d\pi_i}{dn_i} = \frac{\partial \pi_i}{\partial n_i} + \underbrace{\frac{\partial \pi_i}{\partial p_j}}_{+} \frac{dp_j}{dn_i} \qquad (i \neq j), \tag{2}$$

where

$$\frac{dp_j}{dn_i} = \left(\frac{dp_j}{dp_i}\right)\left(\frac{dp_i}{dn_i}\right).$$

The first term on the right-hand side of (2) measures the change in firm i's profit when it increases n_i, holding the rival's price p_j fixed. This is the direct effect of changing n_i, and in equilibrium firm i would solve $\partial\pi_i/\partial n_i = 0$ if n_i was unobservable. Let $\hat{n}_i$ denote the solution to $\partial\pi_i/\partial n_i = 0$.

Since we have assumed that n_i is observable prior to the price decision in stage 2, p_j is a function of n_i if $dp_i/dn_i \neq 0$. Firm i thus has incentives to strategically affect the price charged by the rival through the level of the non-price variable n_i. This effect is captured by the second term on the right-hand side of (2). Suppose that $dp_i/dn_i > 0$. It then follows that firm i will set $n_i > \hat{n}_i$ because this induces the rival to increase its price too (given that prices are strategic complements, $dp_j/dp_i > 0$). In the terminology of Fudenberg and Tirole (1984), firm i chooses a "fat cat strategy"; it "overinvests" in the non-price variable to appear soft (it charges a higher price). In contrast, if the "investment" makes firm i tough (that is, $dp_i/dn_i < 0$), it "underinvests" in the non-price variable ($n_i < \hat{n}_i$) in order to make the rival set a relatively high price. This corresponds to a "puppy dog strategy" in the terminology of Fudenberg and Tirole.

Now, consider instead the case where firm j uses personalized pricing. As shown in the seminal contributions by Thisse and Vives (1988), Lederer and Hurter (1986) and Bhaskar and To (2004), a firm using personalized pricing will in equilibrium offer an individual price equal to the marginal cost to its "last" consumer as well as to consumers buying from the rival. Hence, at stage 2 firm j offers the price $p_j(\widehat{x}) = c$ towards all consumers served by firm i (independently of the value of the non-price variable that the firms have made at stage 1, n_0 and n_1). See Figure 1 for an illustration for the case where firm 0 uses personalized pricing.

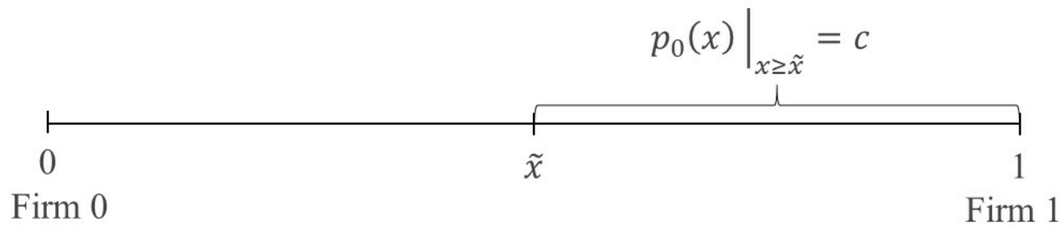

Figure 1: *Firm 0 uses personalized pricing.*

If firm i uses uniform pricing, its profit can be written as

$$\pi_i = \pi_i(n_0, n_1, p_i\left(n_0, n_1\right), p_j(\widehat{x})). \tag{3}$$

The total derivative of (3) is

$$\frac{d\pi_i}{dn_i} = \frac{\partial \pi_i}{\partial n_i} + \underbrace{\frac{\partial \pi_i}{\partial p_j\left(\widehat{x}\right)}}_{+}\frac{dp_j\left(\widehat{x}\right)}{dn_i},$$

where

$$\frac{dp_j(\widehat{x})}{dn_i} = 0.$$

Hence, the strategic effect is eliminated: When firm j uses personalized pricing, firm i cannot strategically affect firm j's pricing behavior, $p_j(\widehat{x}) = c$. It is straightforward to show that this is true also if firm i uses personalized pricing.

We can state:

Proposition 1: *Suppose that firm i's equilibrium price depends on the value of its non-price variable n_i.*

a) If firm j ($i \neq j$) uses uniform pricing, firm i will strategically choose a value of n_i that reduces the competitive pressure.

b) If firm j uses personalized pricing, firm i is unable to use n_i strategically.

Proposition 1 indicates that firm j may find it optimal to commit to using uniform pricing because this induces the rival to make strategic choices that reduce the competitive pressure. If so, the prisoner's dilemma outcome identified by Thisse and Vives (1988) may cease to exist. Below, we will set up a specific model to verify that this might be the case.

3.1 An example: Endogenous firm-specific mismatch costs

To get more insight into possible implications of using non-price variables strategically, we add more structure to the model. Let the location of firm $i = 0, 1$ be given by x_i, and assume that $x_0 = 0$ for firm 0 and $x_1 = 1$ for firm 1 (so that they are located at each end of the Hotelling line). The consumer utility of buying from firm i for a consumer located at x is

$$u_i(x) = v_i - m_i |x - x_i| - p_i(x), \tag{4}$$

where $v_i > 0$ is the intrinsic value value of good i. A higher quality of good i increases the value of v_i. The second term in (4) captures the idea that consumers in general do not find any of the goods to be a perfect fit; the perceived mismatch costs (transportation costs) associated with good i for a consumer located at x is $m_i |x - x_i|$, where $m_i > 0$.[12] The

[12] This modelling of a firm-specific mismatch cost is equivalent to the one used by Ferreira and Thisse (1996), who build on Launhardt (1885).

smaller is m_i, the greater is the number of consumers who is willing to buy good i, other things equal. One can think of the variable m_i as an inverse measure of the market size for firm i (it is straightforward to show that p_i is independent of m_i and output decreasing in m_i if firm i is a monopolist that does not serve the whole market).

The location of the consumer who is indifferent between the offers from firm 0 and 1, denoted by $\tilde{x}$, is found by setting $u_0(\tilde{x}) = u_1(\tilde{x})$:

$$D_i = \frac{(v_i - v_j) + m_j + p_j(\tilde{x}) - p_i(\tilde{x})}{m_i + m_j}. \tag{5}$$

Evidently, demand for good i is decreasing in own mismatch costs, $\partial D_i / \partial m_i = -D_i/(m_i + m_j) < 0$, and increasing in the rival's mismatch costs, $\partial D_i / \partial m_j = (1 - D_i)/(m_i + m_j) > 0$. Note that this set-up resembles the traditional Hotelling model, with the exception that we open up for the possibility that $m_0 \neq m_1$.

In the following, we let mismatch costs be the non-price variable that the firms can influence the size of, such that $n_i = m_i$. Since we do not consider other non-price variables in the basic model, we henceforth set $v_0 = v_1 = v$, and will show that with endogenous mismatch costs, it might be optimal for firms to renounce the possibility of using personalized prices.[13] Therefore, the three-stage game is as follows: At stage 0, each firm commits to uniform pricing if this is individually profitable. Then, at stage 1, the firms simultaneously decide on mismatch levels. We assume that m_i is bounded by $m_i \in [\underline{m}, \overline{m}]$. At stage 2, the firms compete in consumer prices. If firm i has not made any commitment at stage 0, it is free to choose between using uniform pricing and personalized pricing at stage 2.

An advantage of using endogenous firm-specific mismatch costs as an example of a strategic non-price variable is that it provides clear-cut benchmarks: If $m_0 = m_1 = m$, we have Hotelling's (1929) conventional transportation cost interpretation (where the variable m is typically labelled t). When both firms use uniform pricing, we arrive at the well-know result that both firms charge the equilibrium prices $p^{UP-UP} = c + m$ and that profits equal $\pi^{UP-UP} = m/2$. If both firms use personalized pricing, on the other hand, a firm is able to charge price equal to $c + m$ only towards consumers that find the goods to be a perfect fit; $p_0(0) = c + m$ and $p_1(1) = c + m$. For all other consumers, the individual

[13] Firms may for instance have to invest in data collection and design more flexible pricing technologies to be able to use personalized pricing. However, we abstract from such issues in order to highlight strategic considerations.

price is lower when both firms use personalized pricing compared to when both use uniform pricing (Thisse and Vives, 1988; Bhaskar and To, 2004). Profits fall to one half of the profit under uniform pricing, such that $\pi^{PP-PP} = m/4$.

Below, we first assume that one of the two firms, which we label firm k, has committed to uniform pricing, and analyze what effect this commitment might have on pricing and choice of mismatch costs. We consider both the case where the rival uses uniform pricing and where it uses personalized pricing. Then we perform the same analysis if firm k has made no price policy commitment. Since the firms are intrinsically symmetric, we will, without loss of generality, let $k = 0$.

3.1.1 Firm 0 has committed to uniform pricing

Pricing (stage 2) Using backward induction, we first analyze the firms' pricing decisions (stage 2). At this stage the firms' product characteristics (mismatch costs) and price policies (whether they have committed to uniform pricing) are predetermined.

If firm 0 at stage 0 has committed to uniform pricing, it will solve the following maximization problem:

$$\max_{p_0} \pi_0^{UP-R} = (p_0 - c)D_0^{UP-R}, \text{ where } R\epsilon\{UP, PP\}. \tag{6}$$

Throughout, the first part of the superscript indicates the firm's own price strategy (uniform pricing, abbreviated to UP, in this case), while the second part indicates the rival's price strategy (where R is UP or PP, where the latter stands for personalized pricing).

Suppose first that also firm 1 has committed to uniform pricing. Setting $p_i(x) = p_i$ and $p_j(x) = p_j$ into equation (5) it follows that the perceived demand for firm $i = 0, 1$ equals:

$$D_i^{UP-UP} = \frac{m_j - (p_i - p_j)}{m_i + m_j} \tag{7}$$

By solving (6) we now find that prices are strategic complements, and that the reaction functions are given by

$$p_i(p_j) = \frac{c + p_j}{2} + \frac{m_j}{2}. \tag{8}$$

A higher value of m_j means that the competitive pressure for firm i's marginal consumers falls. This explains why $\partial p_i(p_j)/\partial m_j > 0$. In contrast, we see that $\partial p_i(p_j)/\partial m_i = 0$; firm i's optimal price does not depend directly on its own choice of mismatch costs. The reason for this is that a higher value of m_i reduces the number of consumers who prefers good i, but does not affect the optimal price towards its remaining consumers, all else equal. However, since an increase in m_i increases the rival's price, we nonetheless find that each firm's (potential) equilibrium price is increasing both in its own and the rival's mismatch costs, albeit most in the latter. More precisely, solving (8) for the two firms' prices simultaneously, we have

$$p_i^{UP-UP} = c + \frac{m_i + 2m_j}{3}, \tag{9}$$

proving that $\partial p_i^{UP-UP}/\partial m_j > \partial p_i^{UP-UP}/\partial m_i > 0$.

Inserting for (7) and (9) into (6) yields

$$\pi_i^{UP-UP} = \frac{(m_i + 2m_j)^2}{9(m_i + m_j)}, \tag{10}$$

from which it follows that $\partial \pi_i^{UP-UP}/\partial m_j > \partial \pi_i^{UP-UP}/\partial m_i > 0$. Since higher mismatch cost softens competition when both firms use uniform pricing, it leads to higher profits.

Suppose next that only firm 0 has committed to uniform pricing. Firm 1 is then free to choose between uniform pricing and personalized pricing at the stage 2, but it will clearly select the latter. The reason for this is that with personalized pricing, it can charge a price from each consumer which is infinitesimally lower than that of firm 0 and become these consumers' preferred supplier (and this will be the optimal pricing strategy towards all consumers who thereby generates a non-negative profit). No other price schedule can possibly yield a higher profit for firm 1. Following Thisse and Vives (1988), we thus assume that when only firm 0 has made a price policy commitment, it will act as a Stackelberg leader at stage 2.[14] Inserting $p_1^{PP}(\tilde{x}) = c$ into (5), it follows that firm 0's demand becomes

$$\tilde{x} = D_0^{UP-PP} = \frac{m_1 - (p_0 - c)}{m_0 + m_1}.$$

By solving the maximization problem in (6) we then find

$$p_0^{UP-PP} = c + \frac{m_1}{2}. \tag{11}$$

[14] If firms set prices simultaneously when one of them has committed to uniform pricing and the other uses personalized pricing, then we must solve for mixed strategies. See Thisse and Vives (1988, 1992).

Equation (11) is firm 0's equilibrium price as well as its reaction function. The latter follows because the rival always charges a price equal to marginal costs for its last consumer and for all consumers served by firm 0 (so that $p_1(x) = c$ for $x \in [0, \tilde{x}]$).

Profit of firm 0 can now be written as

$$\pi_0^{UP-PP} = \frac{m_1^2}{4(m_0 + m_1)}. \tag{12}$$

Firm 1 sells to all consumers in the interval $[\tilde{x}, 1]$, and these consumers are charged prices which ensure that $u_1(x) \geq u_0(x)$. In equilibrium this constraint is binding, and from equation (4) we find that $p_1(x) = c + \frac{m_1}{2} + m_0 x - m_1(1 - x)$ for $x \in [\tilde{x}, 1]$. Profit for firm 1 thus equals

$$\pi_1^{PP-UP} = \int_{\tilde{x}}^{1} (p_1(x) - c)\, dx = \frac{(2m_0 + m_1)^2}{8(m_0 + m_1)}. \tag{13}$$

Choice of mismatch costs (stage 1) Let us now turn to firm 0's choice of mismatch costs (stage 1). With no effect on our qualitative results, we assume that the firm can costlessly choose any mismatch level it wants within the boundaries $[\underline{m}, \overline{m}]$.

By assumption, firm 0 has committed to uniform pricing. If the rival has made the same commitment (recall that it will not use uniform pricing at stage 2 unless it has committed to do so), we know from equations (9) and (10) that equilibrium prices and profits are increasing in each firm's level of mismatch costs. It thus follows that firm 0 will set $m_0 = \overline{m}$ (and firm 1 will likewise set $m_1 = \overline{m}$).

In the terminology of Fudenberg and Tirole (1984) and Tirole (1988), cf. section 3.1, firm 0 uses a puppy dog strategy if the rival uses uniform pricing: it "underprovides" reductions in the mismatch level on its own good in order to induce a more soft response from the rival. This is similar to the findings in Ferreira and Thisse (1996) and Hendel and de Figueiredo (1997).

In contrast, if the rival uses personalized pricing, we know from Proposition 1 that a change in firm 0's mismatch costs does not affect firm 1's pricing behavior towards its marginal consumer or any of the consumers served by firm 0; it always sets $p_1^{PP}(x)\big|_{x \leq \tilde{x}} = c$. Consequently, as the strategic effect is eliminated, firm 0 does not need to worry about any aggressive response from the rival if it reduces the perceived mismatch costs associated with the good it offers. Since a reduction in own mismatch costs raises its market share

$(\partial D_0^{UP-PP}/\partial m_0 < 0)$, firm 0 thus maximizes profits by setting $m_0 = \underline{m}$. Formally, this follows because equation (12) implies:

$$\frac{\partial \pi_0^{UP-PP}}{\partial m_0} = -\frac{m_1^2}{4\left(m_0 + m_1\right)^2} < 0.$$

To summarize the results so far:

Lemma 1: *Suppose that firm 0 has committed to uniform pricing, and that the rival*

(a) uses uniform pricing. Then firm 0 chooses to maximize mismatch costs associated with its own good (sets $m_0^{UP-UP} = \overline{m}$*).*

(b) uses personalized pricing. Then firm 0 chooses to minimize mismatch costs associated with its own good (sets $m_0^{UP-PP} = \underline{m}$*).*

3.1.2 Firm 0 has not committed to uniform pricing

Pricing (stage 2) Suppose that firm 1 has committed to uniform pricing, while firm 0 has made no commitment. Then we know from the analysis above that firm 0 will use personalized pricing. Due to the intrinsic symmetry of the firms, we can switch subscripts in equation (13) and deduce that the profit level of firm 0 now equals

$$\pi_0^{PP-UP} = \int_0^{\tilde{x}} \left(p_0(x) - c\right) dx = \frac{\left(m_0 + 2m_1\right)^2}{8\left(m_0 + m_1\right)}. \tag{14}$$

From equations (11) and (12) it likewise follows that

$$p_1^{UP-PP} = c + \frac{m_0}{2} \text{ and} \tag{15}$$

$$\pi_1^{UP-PP} = \frac{m_0^2}{4\left(m_0 + m_1\right)}. \tag{16}$$

Suppose instead that neither of the firms have committed to uniform pricing. In this case both firms will use personalized pricing.[15] Each of them will consequently set price equal to marginal cost for its last consumer ($x = \tilde{x}$) and for all consumers served by the rival (Thisse and Vives, 1988). Hence, inserting $p_0^{PP}(\tilde{x}) = p_1^{PP}(\tilde{x}) = c$ into (5) yields

[15] In equation (18) below we find that $\pi_i^{PP-PP} = \frac{m_j^2}{2(m_i+m_j)}$. Since $\pi_i^{PP-PP} - \pi_i^{UP-PP} = \frac{m_j^2}{2(m_i+m_j)} - \frac{m_j^2}{4(m_i+m_j)} = \frac{m_j^2}{4(m_i+m_j)} > 0$ and $\pi_i^{PP-UP} - \pi_i^{UP-UP} = \frac{(2m_j+m_i)^2}{8(m_0+m_1)} - \frac{(2m_j+m_i)^2}{9(m_0+m_1)} = \frac{1}{72}\frac{(2m_j+m_i)^2}{m_0+m_1} > 0$ it follows that firm i will use personalized pricing whatever the price policy of the rival. Thus, it is a dominant strategy at stage 2 to choose personalized pricing for a firm that has not made any other commitment.

$$\tilde{x} = D_0^{PP-PP} = \frac{m_1}{m_0 + m_1}. \tag{17}$$

Equivalently, $D_1^{PP-PP} = 1 - \tilde{x} = \frac{m_0}{m_0+m_1}$.[16]

Profit to firm i is then[17]

$$\pi_i^{PP-PP} = \frac{m_j^2}{2(m_i + m_j)}. \tag{18}$$

Choice of mismatch costs (stage 1) Now, consider firm 0's incentives to reduce mismatch costs when it uses personalized pricing. Assume first that firm 1 uses uniform pricing. The discussion above then indicates that firm 0 will choose high mismatch costs, because this makes firm 1 soft. This is confirmed by differentiating equation (14) with respect to m_0:

$$\frac{\partial \pi_0^{PP-UP}}{\partial m_0} = \frac{(m_0 + 2m_1)\, m_0}{8(m_0 + m_1)^2} > 0.$$

If firm 1 instead uses personalized pricing, it sets $p_1^{PP}(x) = c$ towards its marginal consumer. We again know from Proposition 1 that firm 0 then is unable to make its rival softer through choosing high mismatch costs. It is therefore unambiguously beneficial for firm 0 to reduce mismatch costs, because this will increase the size of its market. Formally, from equation (18), we have

$$\frac{\partial \pi_0^{PP-PP}}{\partial m_0} = -\frac{m_1^2}{2(m_0 + m_1)^2} < 0.$$

We can state:

Lemma 2: *Suppose that firm 0 uses personalized pricing, and that the rival*

(a) uses uniform pricing. Then firm 0 chooses to maximize mismatch costs associated with its own good (sets $m_0^{PP-UP} = \overline{m}$).

[16] It is straightforward to show that if firm 0 uses personalized pricing it will sell less if the rival uses personalized pricing than if the rival uses uniform pricing ($D_0^{PP-PP} < D_0^{PP-UP}$). The reason for this is that the rival sets a lower price towards its marginal consumer in the former case ($p_1^{PP}(\tilde{x}) = c < p_1^{UP-PP} = c + m_0/2$).

[17] We have $\pi_0^{PP-PP} = \int_0^{\tilde{x}} [p_0(x) - c]\, dx = \frac{m_1^2}{2(m_0+m_1)}$ and $\pi_1^{PP-PP} = \int_{\tilde{x}}^1 [p_1(x) - c]\, dx = \frac{m_0^2}{2(m_0+m_1)}$.

(b) uses personalized pricing. Then firm 0 chooses to minimize mismatch costs associated with its own good (sets $m_0^{PP-PP} = \underline{m}$).

Lemma 2 resembles Lemma 1. Each firm takes into account the fact that if the rival uses uniform pricing, then a reduction of its own mismatch costs triggers an aggressive price response from the rival. If the rival uses personalized pricing, on the other hand, a firm which decreases its mismatch costs will observe higher sales without having to reduce its price. A corrollary that follows from Proposition 1, Lemma 1 and Lemma 2 is thus:

Corollary 1: *Firm i's incentives to reduce the mismatch costs of its product is independent of whether it uses uniform prices or not. It chooses to reduce mismatch costs if and only if the rival uses personalized pricing.*

Corollary 1 highlights the fact that choosing personalized pricing comes at a cost; it gives your rival incentives to tailor its good to each consumer's preferences (reduce mismatch costs). The driving force is as in Proposition 1; personalized pricing disables rivals to soften competition. Therefore, if a firm uses personalized pricing, the rival has no incentives to increase its mismatch costs. On the contrary, it will minimize mismatch costs.[18]

3.1.3 The choice of whether to commit to uniform pricing

Using the results that firm i sets $m_i = \underline{m}$ (minimum mismatch costs) if the rival uses personalized pricing and $m_i = \overline{m}$ if the rival uses uniform pricing, we can apply equations (10) and (18) to express profit if both firms use either uniform pricing or personalized pricing as respectively[19]

$$\pi_i^{UP-UP} = \frac{\overline{m}}{2} \text{ and } \pi_i^{PP-PP} = \frac{\underline{m}}{4}. \tag{19}$$

[18] Note that even though a reduction in mismatch costs is individually profitable, the firms would be better off if they could make a (joint) commitment to abstain from it. To see this, assume $m_1 = m_2 = m$. Equation (18) is then simplified to $\pi_i^{PP-PP}\big|_{m_i=m_j=m} = m/4$, which is strictly increasing in m.

[19] Note that if the mismatch costs are sufficiently convex in the per unit of distance on the Hotelling line, firms' profits are higher when both firms use personalized pricing compared to the case where both firms use uniform pricing. If $m_0 = m_1 = m$, and $m\left(|x - x_i|\right)^{\alpha}$, we have the prisoner's dilemma shown by Thisse and Vives (1988) as long as α is below approximately 5 (see Bhaskar and To, 2004). We have intentionally assumed $\alpha = 1$ in order to focus on how firms may choose to commit to uniform pricing to avoid the prisoner's dilemma described by Thisse and Vives (1988).

If one and only one of the firms has committed to uniform pricing, we likewise find from equations (12) and (13) that

$$\pi_i^{PP-UP} = \frac{(\overline{m} + 2\underline{m})^2}{8(\underline{m} + \overline{m})} \text{ and } \pi_i^{UP-PP} = \frac{\overline{m}^2}{4(\underline{m} + \overline{m})}. \tag{20}$$

Let $\alpha \equiv \overline{m}/\underline{m} \geq 1$ define the ratio between maximum and minimum mismatch costs, and suppose that firm j has committed to uniform pricing.[20] Should firm i do the same? If it does, firm j will choose high mismatch costs (soft behavior). Equations (19) and (20) yield

$$\pi_i^{UP-UP} - \pi_i^{PP-UP} = \frac{3\alpha^2 - 4}{8(1+\alpha)}\underline{m} < 0 \text{ if } \alpha < \alpha_{crit} = \sqrt{4/3} \approx 1.1547. \tag{21}$$

Thus, it is not a Nash equilibrium for both firms to choose uniform pricing if the ratio between maximum and minimum mismatch costs is below a critical value, $\alpha < \alpha_{crit}$. The reason for this is that the gain from committing to uniform pricing and making the rival soft is then low compared to the gain from charging each consumer according to her willingness to pay for the good (personalized pricing). On the other hand, if $\alpha > \alpha_{crit}$, we see that $\pi_i^{UP-UP} - \pi_i^{PP-UP} > 0$. Then, neither firm will regret committing to uniform pricing, because each of them has much to gain from having a soft rival.

What should firm i do if the rival has not committed to uniform pricing (which implies that it will use personalized pricing)? Using equations (19) and (20) we find

$$\pi_i^{UP-PP} - \pi_i^{PP-PP} = \frac{\alpha(\alpha-1) - 1}{4(\alpha+1)}\underline{m} > 0 \text{ if } \alpha > \alpha^{crit} = \frac{1}{2}\sqrt{5} + \frac{1}{2} \approx 1.618. \tag{22}$$

Hence, it is profitable for firm i to commit to uniform pricing even if the rival uses personalized pricing if $\alpha > \alpha^{crit}$. Again, the intuition is that the larger is the ratio between maximum and minimum mismatch costs, the more valuable it is to commit to uniform pricing in order to make the rival soft. The reason why $\alpha^{crit} > \alpha_{crit}$ is that the loss in market share from using uniform pricing is greater when the rival chooses personalized pricing than when it uses uniform pricing.

Inspection of (21) and (22) reveals that there does not exist any equilibrium where one firm commits to uniform pricing and the other does not,[21] so we can state

Proposition 2: *Equilibrium constellations:*

[20] If $\alpha = 1$ we arrive at Thisse and Vives' (1988) model framework.

[21] This might change if the firms are ex ante asymmetric.

(i) If $\alpha < \alpha_{crit}$, there is a unique equilibrium where both firms choose not to commit to uniform pricing.

(ii) If $\alpha > \alpha^{crit}$, there is a unique equilibrium where both firms choose to commit to uniform pricing.

(iii) If $\alpha_{crit} \leq \alpha < \alpha^{crit}$, there are multiple equilibria, where both firms choose to commit to uniform pricing or both firms choose not to commit to uniform pricing.

In sharp contrast to Thisse and Vives (1988), we thus find that it is not necessarily true that firms unambiguously will choose to not commit to uniform pricing (which would be a prisoner's dilemma). Quite the opposite; once we open up for endogenous mismatch costs, a strategy of not committing to uniform pricing might not even constitute a Nash equilibrium. This is true if the span between the lowest and the highest level of mismatch costs is sufficiently large. The threat that the rival will tailor its product as closely as possible to each consumer's preferences may discipline firms and induce them to stick to uniform pricing.

4 Extensions

4.1 Location as non-price variable

In this section, we extend the model to consider location incentives. Location is a non-price variable, and it is interesting to examine the insights from Proposition 1 on firms' location. The maximal differentiation principle from d'Aspremont et al. (1979) implies that firms using uniform pricing choose to locate at the extremes of the Hotelling line in order to soften competition. Under the assumption that both firms are using personalized pricing, Hurter and Lederer (1985), Lederer and Hurter (1986) and Bhaskar and To (2004) find that firms locate so as to minimize social costs. Our focus is different; we ask how the location incentives for a firm using personalized prices (firm 0) depend on whether the rival (firm 1) uses personalized prices or a uniform price. To highlight the location incentives we set $m_0 = m_1 = m$. We will not carry out a full-fledged location analysis. Technically, the way we have modelled mismatch costs corresponds to linear transportation costs. It is well known that this is unsuited for analyzing endogenous location when firms use uniform pricing (see e.g. d'Aspremont et al., 1979). Instead, we take firm 1's location as given and examine firm 0's location choice.

Suppose that firm 1 is located at $x_1 \in \left(\frac{1}{2}, 1\right]$ and firm 0 at some point x_0 to the left of firm 1, as shown in Figure 2.

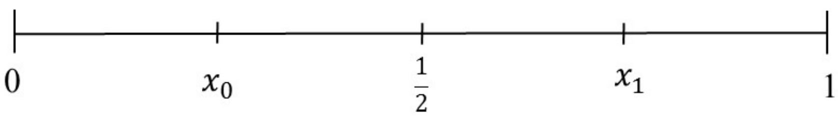

Figure 2: *Location incentives.*

The net utility of buying good 0 for a consumer located (weakly) to the right of x_0 is $u_0^{x \geq x_0}(x) = v - m\,(x - x_0) - p_0(x)$, while the net utility of buying good 1 for a consumer to the left of x_1 equals $u_1^{x \leq x_1}(x) = v - m(x_1 - x) - p_1(x)$. Using the fact that firm 0 charges $p_0^{PP}(x) = c$ from the consumer who is indifferent between good 0 and good 1, we find from $u_0^{x \geq x_0}(\tilde{x}) = u_1^{x \leq x_1}(\tilde{x})$ the demand facing firm 0

$$D_0 = \tilde{x} = \frac{x_0 + x_1}{2} + \frac{p_1(\tilde{x}) - c}{2m}.$$

Firm 0 maximizes profit by choosing $p_0(x)$ such that $u_0^{x \geq x_0} = u_1^{x \leq x_1}$ for all consumers between x_0 and $\tilde{x}$. This means that

$$p_0^{x \in [x_0, \tilde{x}]}(x) = p_1(x) + m\,(x_0 - x) - m\,(x - x_1) \text{ for } x \in [x_0, \tilde{x}]\,. \tag{23}$$

For consumers located between 0 and x_0 the net utility of buying good 0 is $u_0^{x < x_0} = v - m\,(x_0 - x) - p_0(x)$. In this area firm 0 optimally sets $p_0(x)$ such that $u_0^{x < x_0} = u_1^{x \leq x_1}$, yielding prices

$$p_0^{x \in [0, x_0]}(x) = p_1(x) - m\,(x_0 - x) - m\,(x - x_1) \text{ for } x \in [0, x_0]\,.$$

Profit for firm 0 is thus

$$\pi_0^{PP-R} = \int_0^{x_0} \left(p_0^{x \in [0, x_0]}(x) - c \right) dx + \int_{x_0}^{\tilde{x}} \left(p_0^{x \in [x_0, \tilde{x}]}(x) - c \right) dx,$$

which can be rewritten as

$$\pi_0^{PP-R} = x_0 \left(-c + p_1(x) + m\,(x_1 - x_0)\right) + \frac{\left(-c + p_1(x) + m\,(x_1 - x_0)\right)^2}{4m}. \tag{24}$$

As above, firms decide on the non-price variable (location) prior to price competition. Recall that we take firm 1′s location as given, such that only firm 0 chooses location. We solve the game through backward induction. After solving for the price competition between the firms, the first-order condition with respect to the non-price variable is given by (cf. section 3.1)

$$\frac{d\pi_0^{PP-R}}{dx_0} = \frac{\partial\pi_0^{PP-R}}{\partial x_0} + \frac{\partial\pi_0^{PP-R}}{\partial p_1}\frac{dp_1}{dx_0} = 0. \tag{25}$$

In order to evaluate the term $\frac{\partial\pi_0^{PP-R}}{\partial p_1}$, we use equation (24) to obtain

$$\frac{\partial\pi_0^{PP-R}}{\partial p_1} = \frac{-c + p_1(x) + m\,(x_0 + x_1)}{2m} > 0, \tag{26}$$

which is unambiguously positive since $p_1(x) \geq c$. We can now examine how the first-order condition of firm 0's location problem depends on firm 1's choice between uniform and personalized pricing.

If firm 1 uses personalized pricing, it will offer its good at a price equal to marginal cost for consumers located in $x \in [x_0, \tilde{x}]$. Inserting $p_1^{PP}(x) = c$ in equation (24) we then find

$$\pi_0^{PP-PP} = x_0 m\,(x_1 - x_0) + \frac{m\,(x_1 - x_0)^2}{4}. \tag{27}$$

Since $p_1^{PP}(x) = c$ in $x \in [0, \tilde{x}]$, firm 0 cannot affect the price that firm 1 charges consumers in this area, that is, $\frac{dp_1}{dx_0} = 0$. Therefore, the total derivative in equation (25) reduces to $\frac{d\pi_0^{PP-PP}}{dx_0} = \frac{\partial\pi_0^{PP-PP}}{\partial x_0}$. This resembles Proposition 1; only the market expansion (direct) effect of firm 0's choice of location on profit remains when firm 1 uses personalized pricing. From (27) we find

$$\frac{d\pi_0^{PP-PP}}{dx_0} = \frac{\partial\pi_0^{PP-PP}}{\partial x_0} = m\,(x_1 - 2x_0) - \frac{1}{2}m\,(x_1 - x_0) = \frac{m\,(x_1 - 3x_0)}{2}.$$

Consequently, solving (25) for firm 0's location yields $x_0^{PP-PP} = \frac{1}{3}x_1$.[22]

If instead firm 1 uses uniform pricing, it solves $p_1 = \arg\max \pi_1^{UP-PP}$, where $\pi_1^{UP-PP} = (p_1 - c)\,(1 - D_0)$. This gives the price

$$p_1 = \frac{2\,(c + m) - m\,(x_0 + x_1)}{2}. \tag{28}$$

[22] Due to symmetry ($x_0 = 1 - x_1$) the equilibrium location in this case would be $x_0 = \frac{1}{4}$ and $x_1 = \frac{3}{4}$. See also Bhaskar and To (2004).

Firm 0 faces relatively soft (potential) competition when firm 1 uses uniform pricing. Other things equal, the firm will therefore expand demand more if it locates closer to a rival using uniform pricing compared to a rival using personalized pricing. Therefore, we should expect firm 0 to locate closer to its rival when the rival uses uniform pricing. To confirm this, note that

$$\frac{\partial \pi_0^{PP-UP}}{\partial x_0} = \frac{-c + p_1 - 3mx_0 + mx_1}{2} = \frac{m\left(2 - 7x_0 + x_1\right)}{4}.$$

Since

$$\frac{\partial \pi_0^{PP-UP}}{\partial x_0} - \frac{\partial \pi_0^{PP-PP}}{\partial x_0} = \frac{m\left(2 - x_0 - x_1\right)}{4} > 0,$$

taking only the demand expansion effect into account thus indicates that $x_0^{PP-UP} > x_0^{PP-PP} = \frac{1}{3}x_1$.

However, from equation (28), $\frac{dp_1}{dx_0} = -\frac{1}{2}m$, hence one drawback of moving closer to firm 1 is that firm 1 will respond by setting a lower uniform price. Inserting for (28) into (26) we find that the strategic effect is equal to $\left(\frac{\partial \pi_0}{\partial p_1}\frac{dp_1}{dx_0}\right)^{PP-UP} = -\frac{(2+x_0+x_1)m}{8} < 0$, which encourages firm 0 to locate further away from the rival. Adding the demand expansion effect and the strategic effect yields

$$\frac{d\pi_0^{PP-UP}}{dx_0} = \frac{m\left(2 - 15x_0 + x_1\right)}{8}.$$

The first-order condition then implies that $x_0^{PP-UP} = \frac{1}{15}x_1 + \frac{2}{15}$. Since $x_0^{PP-UP} - x_0^{PP-PP} = -\frac{2(2x_1-1)}{15} < 0$, firm 0 will locate further away from firm 1 if firm 1 uses uniform pricing than if firm 1 uses personalized pricing. As an example, suppose that $x_1 = 0.75$. Then we would have $x_0 = 0.25$ if firm 1 use personalized pricing, while we would have $x_0 \approx 0.18$ if firm 1 uses uniform pricing.

One implication of personalized pricing by the rival on a firm's location incentives is therefore that the firm does not need to consider any strategic response from the rival following the firm's choice of location; only the market expansion effect on profit remains. In contrast, if the rival uses uniform pricing, the strategic effect induces the firm to differentiate more away from the rival in order to soften price competition. Hence, even though the firm considers a rival which uses uniform pricing as relatively soft compared to a rival which uses personalized pricing, it will nonetheless locate closer to a rival using personalized pricing since the rival will not respond by lowering prices. Since firm 0 by assumption uses personalized pricing, the result is purely driven by firm 1's choice of price policy.

Consequently, if both firms use personalized pricing, they will locate relatively close to each other. This resembles Hurter and Lederer (1985), Lederer and Hurter (1986) and Bhaskar and To (2004), who find that firms locate so as to minimize social costs. The reason is that the direct effect implies that firms try to minimize the average mismatch costs (transportation costs), which resembles the choice of a social planner that maximizes total welfare. However, since Hurter and Lederer (1985), Lederer and Hurter (1986) and Bhaskar and To (2004) assume that both firms use personalized pricing, they do not uncover the fact that the driving force is whether the rival uses using personalized pricing (and not the firm's own price policy).

We then reach the following:

Proposition 3: *Suppose firms are symmetric ($m_0 = m_1 = m$). Then, a firm will locate closer to a rival which uses personalized pricing compared to a rival which uses uniform pricing. The effect stems from the rival using personalized pricing, not from a firm's own decision on pricing policy.*

4.2 The mixed blessing of accessing a two-sided market

In this section, we modify the model to consider a two-sided market. One example of firms or platforms in this context is newspapers, which attract readers as well as advertisers. Another example is search engines, serving users and advertisers. Suppose firms have two sources of revenue; they charge users for their consumption, as in the main model. In addition, they charge advertisers for providing them with the users' attention. To keep the framework simple, we assume that consumers are indifferent to ad levels. Hence, their utility is unaffected by the advertisement side of the market.

If firm i uses uniform pricing in the user market, it charges each user a subscription fee p_i. Further, as in Anderson et al. (2018), we assume that the firm earns b per user in the advertising market. Its profit is therefore $\pi_i^{UP-R} = (p_i + b - c)D_i$.

First, suppose both firms use uniform pricing in the user market. Solving $\partial\pi_i^{UP-UP}/\partial p_i = 0$, $i = 1, 2$, we find

$$p_i = c - b + \frac{m_i + 2m_j}{3}.$$

Compared to the main model, the user price is in this case b units lower. This is because the possibility of selling the users' attention to advertisers intensifies firm rivalry to such an extent that they compete away advertising revenue. This so-called see-saw effect is well-known from the media economics literature (see e.g. Armstrong, 2006). Total profit for firm i is thus equal to

$$\pi_i^{UP-UP} = \frac{(m_i + 2m_j)^2}{9(m_i + m_j)},$$

which is the same expression as in the main model, cf. equation (10).

Assume instead that firm i uses personalized pricing in the user market. Since this requires relatively disaggregated market data, it is reasonable to assume that the firm has acquired (weakly) more information about each individual user than it would under uniform pricing. Such individualized information could be valuable for the firm when it approaches the advertising market. To capture this, assume that firm i which uses personalized pricing can charge an ad premium $\delta \geq 0$ for each user.

In order to see the implications of the ad price premium, suppose that firm 1 uses personalized pricing, while firm 0 has committed to uniform pricing. A user located in x is now worth $p_1(x) + b + \delta - c$ to firm 1, which is δ units more than if it instead used uniform pricing. This hurts firm 0 in two ways. First, demand for good 0 falls, since the rival finds it profitable to capture more users with personalized pricing than with uniform pricing. More precisely, the location of firm 1's marginal consumer is now implicitly given by $p_1^{PP}(\tilde{x}) = c - b - \delta$, where $\tilde{x}$ evidently is decreasing in δ. Second, since firm 1 is now willing to offer its good at a price equal to $c - b - \delta$ to all consumers served by the rival, the perceived willingness to pay for good 0 falls (firm 0's demand curve shifts δ units downward). Firm 0's profit maximizing price is therefore strictly decreasing in δ. Formally, inserting for $p_1^{PP}(\tilde{x})$ into (5) and maximizing $\pi_0 = (p_0 + b - c)\, D_0^{UP-PP}$ with respect to p_0 yields

$$\tilde{x} = D_0^{UP-PP} = \frac{m_1 - \delta}{2(m_0 + m_1)} \text{ and } p_0^{UP-PP} = c - b + \frac{m_1 - \delta}{2}. \tag{29}$$

Note that firm 0 will have positive sales only if $m_1 > \delta$. To ensure that this is always the case, we assume that $\underline{m} > \delta$. From (29) we then find that the profit level of firm 0 equals

$$\pi_0^{UP-PP} = \frac{(m_1 - \delta)^2}{4(m_0 + m_1)}, \quad \frac{\partial \pi_0^{UP-PP}}{\partial \delta} = -\frac{1}{2}\frac{m_1 - \delta}{m_0 + m_1} < 0.$$

We derive firm 1's optimal price from equation (4) by setting $u_0 = u_1$. This yields $p_1(x) = c - b + \frac{m_1 - \delta}{2} + m_0 x - m_1(1 - x)$. The fact that firm 0's optimal price falls when firm 1 uses personalized pricing forces firm 1 to reduce its price even towards consumers in its own turf. However, since firm 1 sells more and makes a higher profit per user the greater is δ, its profit level is nonetheless unambiguously increasing in δ :

$$\pi_1^{PP-UP} = \int_{\tilde{x}}^{1} \left((p_1(x) + b + \delta - c) \right) dx = \frac{(2m_0 + m_1 + \delta)^2}{8\,(m_0 + m_1)}. \tag{30}$$

Finally, it is straightforward to show that if both firms use personalized pricing, the see-saw effect once again implies that they compete away advertising revenue. Their profit level is thus the same as they would have been in the one-sided market, cf. equation (18):

$$\pi_i^{PP-PP} = \frac{m_j^2}{2\,(m_i + m_j)}.$$

As in the main model, each firm chooses to maximize mismatch costs ($\overline{m}$) if the rival uses uniform pricing and minimize mismatch costs ($\underline{m}$) if the rival uses personalized pricing. Profits can then be expressed as

$$\begin{aligned} \pi_i^{UP-UP} &= \frac{\overline{m}}{2},\ \pi_i^{PP-PP} = \frac{\underline{m}}{4} \\ \pi_i^{UP-PP} &= \frac{(\overline{m} - \delta)^2}{4\,(\underline{m} + \overline{m})},\ \pi_i^{PP-UP} = \frac{(2\underline{m} + \overline{m} + \delta)^2}{8\,(\underline{m} + \overline{m})}. \end{aligned} \tag{31}$$

From (31) it follows that $d\left(\pi_i^{UP-UP} - \pi_i^{PP-UP}\right)/d\delta < 0$ and $d\left(\pi_i^{UP-PP} - \pi_i^{PP-PP}\right)/d\delta < 0$. This implies that firm i is more incentivized to use personalized pricing the greater δ is. We can thus state:

Proposition 4: *Suppose that each firm has more individual reader data if it uses personalized pricing than if it uses uniform pricing in the user market. Suppose further that this generates a premium in the advertising market. The greater is the premium, the greater are each firm's individual incentives to use personalized pricing, which can lead them to end up in the low-profit equilibrium with personalized pricing.*

Profits are the same under a two-sided market and a one-sided market when firms use the same price policy due to the see-saw effect. However, the ad-price premium makes firms more incentivized to unilaterally adopt personalized pricing in a two-sided market compared to a one-sided market. Therefore, firms might prefer a one-sided market if a two-sided market induces switching to personalized pricing.

We restrict prices offered to the marginal consumer and consumers served by the rival to be non-negative, $p_i^{PP}(\tilde{x}) = c - b - \delta$. Liu and Serfes (2013) show when prices are restricted to be non-negative that if firms' marginal cost is relatively low and the cross-group externalities relatively strong, profits can be higher with personalized prices compared to uniform prices. Strong network externalities give firms incentives to set low prices regardless of price policy, however, since personalized prices intensify competition further, prices fall until they reach the binding floor of zero. Due to this, the total profits with uniform prices might be lower than total profits under personalized pricing because uniform prices depend on the network externalities while the personalized prices do not since prices are restricted to be non-negative. In the present setup, we will reach a similar outcome with a relatively strong network effect b such that the price offered to the marginal consumer and consumers served by the rival $p_1^{PP}(\tilde{x}) = c - b - \delta \geq 0$ is binding.

4.3 Multihoming consumers

Traditionally, consumers are restricted to buy at most one of the two goods that are offered in standard Hotelling models (which means that $D_0 + D_1 \leq 1$). We now relax this assumption by allowing consumers to buy one unit from each firm (multi-purchasing). We follow the concept of incremental pricing by Anderson et al. (2017) and Kim and Serfes (2006). The net utility of buying only good i is still given by equation (4), $u_i(x) = v - m_i |x - x_i| - p_i(x)$, while the value of buying good i in addition to good j (its incremental value) equals

$$u_{ji} = \theta [v - m_i |x - x_i|] - p_i(x), \tag{32}$$

where the parameter $\theta \in [0, 1]$. If $\theta < 1$, the incremental value of each good is smaller than its stand-alone value, for instance due to overlap in the goods' area of use.[23]

Let x_{10} denote the consumer who is indifferent between buying only good 1 and buying both goods. The location of this consumer is found by solving $u_1 = u_1 + u_{10}$. This yields

$$x_{10} = \frac{\theta v - p_0(x)}{\theta m_0}. \tag{33}$$

Note that x_{10} depends only on firm 0's price and mismatch cost, not on the rival's price

[23]Foros, Kind and Wyndham (2019) provide an alternative utility formulation that illustrates that the outcome does not depend on consumers having a first and a second choice. However, their analysis does not consider personalized pricing and endogenous mismatch costs.

and mismatch cost: The attractiveness of buying good 0 in addition to good 1 only hinges on the net utility offered by good 0.

The location of the consumer who is indifferent between buying only good 0 and buying both goods is likewise given by

$$x_{01} = 1 - \frac{\theta v - p_1(x)}{\theta m_1}. \tag{34}$$

We will analyze a market structure with partial multihoming. This means that some consumers buy both goods ($D_0 + D_1 > 1$), but none of the goods are sold to all consumers ($D_i < 1$). This market outcome is illustrated in Figure 3.[24] Demand for firm i's good and the distribution of singlehoming (SHC) and multihoming (MHC) consumers are (where x_i is firm i's location)

$$D_i = \underbrace{|x_{ij} - x_i|}_{\text{SHC}} + \underbrace{|x_{ji} - x_{ij}|}_{\text{MHC}} = |x_{ji} - x_i|\,. \tag{35}$$

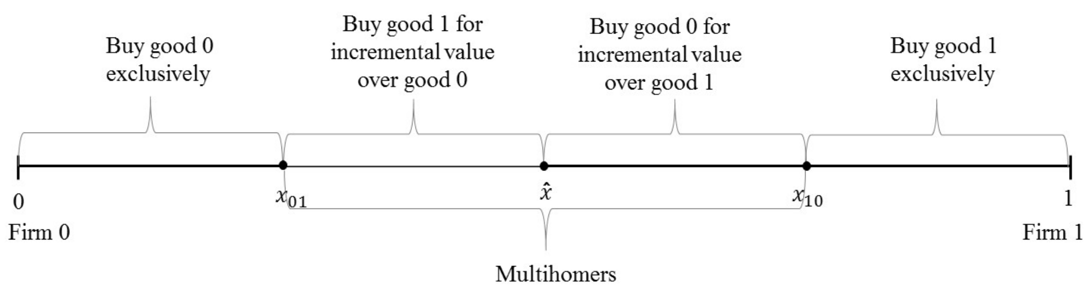

Figure 3: *Market outcome with partial multihoming.*

Hence, total demand for good 0 is $D_0 = x_{10}$, total demand for good 1 is $D_1 = 1 - x_{01}$, and the number of multihomers is given by $(x_{10} - x_{01})$.

Let us first consider the outcome when firm 0 uses uniform pricing.[25] Its profit level is

[24] Since the line has length 1, consumers located at $x < 1/2$ are closer to firm 0 and therefore have good 0 as their most preferable good. Likewise, consumers located at $x > 1/2$ are closer to firm 1 and have good 1 as their most preferable good. Hence, it follows that $\hat{x} = 1/2$. This implies that multihoming consumers to the left of $\hat{x}$ buy good 1 for its incremental value over good 0, while multihoming consumers to the right of $\hat{x}$ buy good 0 for its incremental value over good 1.

[25] It is beyond the scope of the present paper to provide a complete analysis of possible singlehoming and multihoming equilibria and their stability; we limit our attention to consider candidate equilibria with partial multihoming. See the appendix in Anderson et al. (2017) for a comprehensive analysis of deviation incentives.

then given by $\pi_0 = (p_0 - c)D_0$. Since $D_0 = x_{10}$ is independent of p_1 and m_1, the profit maximizing price and profitability of good 0 are independent of whether firm 1 uses uniform or personalized pricing:

$$p_0^{UP-R} = \frac{c + v\theta}{2} \quad (36)$$

$$\pi_0^{UP-R} = \frac{(v\theta - c)^2}{4\theta m_0}. \quad (37)$$

Inserting (36) into (33) we find that demand equals

$$D_0^{UP-R} = \frac{v\theta - c}{2\theta m_0}. \quad (38)$$

From (37) we note that firm 0 chooses to minimize own mismatch costs whatever the price policy of the rival.

Let us now assume that firm 0 uses personalized pricing. For reasons that become clear below, we assume that personalized pricing involves an extra marginal cost equal to $\phi > 0$. In equilibrium firm 0 then charges $p_0^{PP-R}(x) = v - m_0 x$ towards its exclusive (singlehoming) consumers, $p_0^{PP-R}(x) = \theta (v - m_0 x)$ towards multihoming consumers, and $p_0^{PP-R}(x) = c + \phi$ towards its marginal consumer (and those served by the rival). Thus, the smaller the mismatch costs are, the higher price can firm 0 charge each of its consumers.

Inserting that $p_0^{PP-R}(\tilde{x}) = c + \phi$ into equation (33) yields

$$D_0^{PP-R} = \frac{\theta v - (c + \phi)}{\theta m_0},$$

which shows that firm 0's total sales are decreasing in m_0. By reducing mismatch costs, the firm will therefore both be able to charge a higher price and sell more since the number of exclusive consumers for firm 0 is independent of m_0, cf. equation (34). Hence, also in this case, the firm minimizes its own mismatch costs independently of which price policy the rival uses. If firm 1 also uses personalized pricing, firm 0's equilibrium profit is

$$\begin{aligned}\pi_0^{PP-PP} &= \int_0^{x_{01}} (v - \underline{m}x - c - \phi)\, dx + \int_{x_{01}}^{x_{10}} (\theta (v - \underline{m}x) - c - \phi)\, dx \\ &= \frac{2(v - c - \phi) - \underline{m}x_{01}}{2} x_{01} + \frac{(2(v\theta - c - \phi) - \theta \underline{m}(x_{01} + x_{10}))}{2} (x_{10} - x_{01}),\end{aligned}$$

where $x_{10} = \frac{\theta v - (c+\phi)}{\theta \underline{m}}$ and $x_{01} = 1 - \frac{\theta v - (c+\phi)}{\theta \underline{m}}$.

From the above discussion, if consumers multihome, firms cannot affect the rival's price policy through its choice of mismatch costs. We can state:

Proposition 5: *Each firm will minimize mismatch costs, independently of which price policy the rival uses, if some consumers multihome.*

As noted above, x_{10} only depends on firm 0's price and mismatch cost, thus firm 0's total demand is independent of the rival's actions. On the other hand, since x_{01} only depends on firm 1's price and mismatch cost, firm 1 can by its actions affect firm 0's demand composition. Specifically, a reduction in m_1 expands firm 1's demand by turning some of firm 0's exclusive consumers into multihomers. If firm 0 uses uniform pricing, the demand composition does not matter for its profit since singlehomers and multihomers are charged the same price. However, if firm 0 uses personalized pricing, a reduction in m_1 hurts firm 0 because a multihomer is only worth θ of a singlehomer. Further, from Proposition 5, we know that firms are incentivized to minimize their mismatch costs independently of what the rival does. We then reach the following:

Corollary 2: *Assume some, but not all, consumers are multihoming. If firm i uses uniform pricing, it is not affected by the rival's choice of uniform pricing or personalized pricing. In contrast, if firm i uses personalized pricing, it is better off if the rival uses uniform pricing.*

Note that the ratio of total demand under uniform pricing and personalized pricing is

$$\frac{D^{PP-PP}}{D^{UP-UP}} = 2(1 - \frac{\phi}{v\theta - c}).$$

If $\phi = 0$, the demand is twice as large with personalized pricing than with uniform pricing, which means that the market is not covered with uniform pricing.[26] Therefore, we assume an extra marginal cost $\phi > 0$ with personalized pricing to avoid this issue.

5 Concluding remarks

Before the arrival of department stores 150 years ago, personalized pricing where sellers negotiated prices with each single consumer was the common pricing method. Today,

[26] Partial multihoming implies that the total demand is strictly less than 2.

consumer information is increasingly available through digital footprints, which allow firms to more carefully learn each consumer's willingness to pay. Therefore, it is not unlikely that personalized pricing might make a comeback as sellers' preferred pricing policy. A robust theoretical result is the following: In a competitive environment, a firm that uses personalized pricing finds it optimal to set individual prices equal to marginal cost towards all consumers who buy from the rival (Thisse and Vives, 1988; Lederer and Hurter,1986). For this reason, we show that if a firm applies personalized pricing, the firm's price policy choice disables rivals from softening competition through making decisions on product differentiation, customization or other non-price decisions. Therefore, the opportunity costs of applying personalized pricing might be high. Due to this, the existence of endogenous non-price variables might make choosing uniform pricing firms' dominant strategy. This result is in sharp contrast to Thisse and Vives (1988), where firms end up in a low-profit equilibrium with personalized pricing.

The literature on oligopolistic personalized pricing provides robust predictions in one-shot games. In particular, the Nash equilibrium individual prices are equal to the marginal cost for all consumers buying from rivals. Will prices set by learning algorithms reach these equilibrium prices? Pricing algorithms can enhance effective practice of personalized pricing by quickly learning consumer information through rich data on for instance consumers' clickstream activity (Harrington, 2018). Many firms already rely on automated pricing programs rather than human agents to set prices (Calvano et al., 2018). Due to this, a recent policy concern is whether pricing algorithms can independently adapt pricing rules that yield collusive outcomes through learning (see Harrington, 2018; Calvano et al., 2018; 2019a; 2019b, among others). Recent studies suggest that algorithms indeed can learn to collude. For instance, Calvano et al. (2018) show how simple algorithms learn to play sophisticated collusive pricing strategies. However, these studies rely on experiments on simulated markets and assume firms set uniform prices. The UK Competition and Markets Authority (2018) argue that both explicit and tacit collusion are less likely under personalized pricing than under uniform pricing since reaching focal points for each individual consumer can be difficult. Further, personalized pricing makes monitoring of rivals' prices more difficult, which makes collusion challenging (Harrington, 2018). A possible task for future research is therefore to investigate whether autonomous learning algorithms programmed to set personalized prices will reach an optimal individual price equal to the marginal cost towards the marginal consumer.

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