Journal of Behavioral and Experimental Economics 107 (2023) 102109

Contents lists available at ScienceDirect

Journal of Behavioral and Experimental Economics

journal homepage: www.elsevier.com/locate/jbee

How does firms' cost structure affect their quality–price mix? An experimental analysis

Adriana Alventosa [a,*], Cesaltina Pacheco Pires [b], Sílvia Ferreira Jorge [c], Joana Pinho [d,e], Margarida Catalão-Lopes [f]

[a] ERI-CES, Universitat de València, Spain
[b] CEFAGE-UE, Departamento de Gestão, Universidade de Évora, Portugal
[c] GOVCOPP, DEGEIT, Universidade de Aveiro, Portugal
[d] Católica Porto Business School, Portugal
[e] CEGE, Católica Porto Business School, Universidade Católica Portuguesa, Portugal
[f] CEG-IST, Instituto Superior Técnico, Universidade de Lisboa, Portugal

A R T I C L E I N F O

JEL classification:
C91
D21
L22

Keywords:
Vertical product differentiation
Quality–price game
Cost structures
Experimental economics

A B S T R A C T

Experimental literature on product differentiation is scarce and mostly focused on horizontal product differentiation. This paper focuses on vertical product differentiation considering a quality-then-pricing duopoly game and exploring how firms' cost structure affects firms' decisions and market structure. Two scenarios are considered, differing in the way quality affects production costs: in the first, quality is costless, while, in the second, marginal production costs increase with quality. We explore the impacts on market coverage, qualities, product differentiation, prices, and intensity of competition (assessed by price-cost margins). Our experimental results confirm the (theoretically proved) need to endogenize the market structure, as a duopoly with full coverage emerges when quality is costless, but a duopoly with partial coverage emerges when quality is costly. We also find that quality differentiation is lower in the lab than what is theoretically predicted, and lower in the costless quality treatment. The intensity of competition is higher when quality is costly, as price-cost margins are lower in this case.

1. Introduction

In most markets, firms offer differentiated goods. Product differentiation may take several forms, from the color of the product to the level of corporate social responsibility of the firm producing the product, and it is a strategy that firms may use to soften price competition and gain market power. The economic literature distinguishes two types of product differentiation. Horizontal product differentiation (HPD) refers to situations where some consumers prefer one variety of the product while other consumers prefer another variety, i.e., there is no consensus among consumers about which variety is the best one (Hotelling, 1929). On the other side, vertical product differentiation (VPD) refers to situations where all consumers would prefer the same variety of the product if all varieties were priced the same, i.e., varieties differ in terms of quality (Gabszewicz & Thisse, 1979; Mussa & Rosen, 1978; Shaked & Sutton, 1982). As consumers usually have different preferences (e.g., willingness to pay or quality valuation), they do not all buy the same variety, even when one of the varieties has a higher quality.

Firms attempting to vertically differentiate their products may face different cost structures. For instance, a firm may need to make a large sunk investment cost, but subsequently, the marginal production cost may not depend on the product's quality. Alternatively, the firm may need a specialized workforce or more expensive inputs to make a higher-quality product, in which case the unitary cost increases with the quality level. Theoretical VPD literature shows that different types of firms' costs of quality improvement lead to different quality–price mix decisions.

The VPD literature is vast and addresses a wide range of issues. However, most contributions are theoretical and make simplistic assumptions regarding individuals' rationality. A standard assumption is that economic agents are unboundedly capable of managing all relevant information, calculating the equilibrium path, and implementing actions that maximize their objective functions. However, as it has extensively been evidenced by experimental contributions, these are strong assumptions and there are many forces driving individuals away from theoretical predictions. In this line, the VPD literature is going

* Correspondence to: Dep. de Análisis Económico (Universidad de Valencia), Av. de los Naranjos s/n, 46022, Valencia, Spain.
E-mail address: adriana.alventosa@uv.es (A. Alventosa).

https://doi.org/10.1016/j.socec.2023.102109
Received 2 October 2022; Received in revised form 25 September 2023; Accepted 25 September 2023
Available online 29 September 2023

through an enriching process by nurturing its theoretical models with behavioral insights observed in field and laboratory experiments. This paper aims to contribute to this enrichment process, by analyzing, theoretically and experimentally, how quality–price decisions depend on the production cost structure, considering two scenarios: the case where quality is costless (as in Wauthy, 1996), and the case where marginal production costs increase with quality (as in Pires, Jorge, Catalão-Lopes, Pinho, Garcês, & Alventosa, 2022).

We explore a two-stage game in which two firms first simultaneously choose the quality of their products and then simultaneously choose prices. Market coverage is an endogenous decision, meaning that whether all or a fraction of the consumers buy the good is determined by the quality–price combination that firms choose, rather than an exogenous assumption. We conclude that independently of the cost structure, in equilibrium, there is product differentiation, a result that is very general in the theoretical VPD literature. This is not surprising, since choosing the same quality level would make price competition very fierce and drive the profits of both firms down. As in Wauthy (1996), we conclude that under costless quality, in equilibrium, the high-quality firm chooses the highest possible quality level, as this increases the consumers' willingness to pay and has no impact on production costs. When quality is costly, setting the highest possible quality is no longer optimal, with the high-quality firm choosing an intermediate quality level. The low-quality firm chooses a lower (or equal) quality level when quality is costly than when it is costless. Thus, the average quality when quality is costless is higher than when quality is costly. Independently of the cost structure, the high-quality firm always sets a higher price than the low-quality firm (showing that in VPD the role of the firm is important in the price-game) and prices are higher in the costly scenario. As prices and margins may move in opposite directions, we look at the latter to evaluate the intensity of competition. Our model predicts that under both cost structures, the high-quality firm has higher price-cost margins than the low-quality firm. Moreover, the price-cost margins are almost always lower when quality is costly, as firms do not fully pass the costs increase to the consumers. However, when the difference in qualities is large, the low-quality firm may have a higher price-cost margin when quality is costly than when it is costless. Importantly, our model shows that the market coverage outcome depends on the cost structure: when quality is costless there is a duopoly with full coverage, whereas when quality is costly there is a duopoly with partial coverage.

Given the theoretical predictions, we make a set of hypotheses and conduct an experiment in the lab to explore how the two different cost structures affect market configuration, qualities, product differentiation, pricing, and intensity of competition, comparing theoretical predictions to lab findings. In the lab, overall, firms differentiate their products less than theoretically predicted and product differentiation is lower when quality is costless than when it is costly. Furthermore, the (average) observed qualities are lower and prices are higher (for given quality choices) when quality is costly than when it is costless. Observed prices increase with the level of product differentiation and are higher for the high-quality firm. Moreover, changes in the rival's quality have a negative impact on the high-quality price, but a positive impact on the low-quality price. In the lab, the high-quality firm gets a higher price-cost margin than the low-quality firm. Price-cost margins are lower when quality is costly, especially for the high-quality firm. Furthermore, as the number of rounds increases, the market configuration converges to a duopoly with full coverage when quality is costless, but to a duopoly with partial coverage when quality is costly. In sum, our experimental results corroborate most of our theoretical predictions and previous experimental literature on product differentiation. However, we emphasize the importance of: (i) the assumption regarding cost structure, (ii) considering the market structure as endogenous, and (iii) accounting for the asymmetry between the high and low-quality firms (namely when analyzing pricing decisions), in VPD experiments.

Below, we make a brief summary of the existing theoretical literature on VPD, in order to identify the most common assumptions and results, which allow us to rightly position our model. We then review the small experimental literature on VPD.

1.1. Theoretical literature on VPD

Starting with the works of Gabszewicz and Thisse (1979), Mussa and Rosen (1978), and Shaked and Sutton (1982), the theoretical literature on VPD is huge. Most of these works assume preferences à la Mussa and Rosen (1978), i.e., assume that consumers' utility increases linearly with quality and there is heterogeneity in the way consumers value quality. Moreover, they consider that firms decide the quality of their product before taking their price or quantity decisions. However, the existing literature differs on assumptions such as the timing of quality choices (sequential or simultaneous), the type of competition (Bertrand or Cournot), the type of costs of quality improvements, the distribution of consumers' valuation of quality, and whether the market is fully covered or not.[1] Still, the assumptions of a uniform distribution of consumer tastes, Bertrand competition and simultaneous quality choices are clearly dominant in the literature and are also assumed in our work.

Regarding the costs of quality improvement, many of the initial VPD models assumed nil costs (Choi & Shin, 1992; Gabszewicz & Thisse, 1979; Tirole, 1988; Wauthy, 1996). Fixed or investment quality costs, such as R&D or advertising activities performed to improve quality, have been considered by authors such as García-Gallego and Georgantzís (2009), Lambertini (1999), Niem (2019) and Shaked and Sutton (1982). Marginal production costs increasing with quality, which happens when higher quality requires more expensive inputs, have been assumed by Lambertini (1996), Mussa and Rosen (1978), Pires et al. (2022), Schmidt (2006) and Schubert (2017). It is interesting to note that, under price competition, regardless of the cost of quality assumptions, firms always differentiate their qualities in equilibrium, because that softens price competition. Moreover, in equilibrium the high-quality firm always charges a higher price (because the high-quality product is more valued by consumers).[2] However, the quality levels depend a lot on the cost assumptions. For instance, with nil quality cost the high-quality firm always chooses the highest possible quality, a result which does not hold with costly quality. The vast majority of the existing studies either assumes partial market coverage (Aoki & Prusa, 1996; Benassi, Chirco, & Colombo, 2006; Lambertini & Tampieri, 2012; Motta, 1993) or full market coverage (Crampes & Hollander, 1995; Schmidt, 2006; Schubert, 2017). On the contrary, Liao (2008), Pires et al. (2022) and Wauthy (1996) determine endogenously market coverage, considering nil quality cost, quadratic investment quality costs, and marginal production costs that depend quadratically on quality, respectively. These works show that whether the market is partially covered or not depends on the distribution of the consumers' preferences. If there is high heterogeneity in the way consumers value quality, there is partial market coverage; on the contrary, if consumers' preferences are similar, price competition will be fiercer even if firms differentiate quality more, and the market will be fully covered.[3]

1.2. Experimental literature on VPD

While the theoretical literature on VPD is extremely vast, there are very few experimental studies testing VPD models in the lab. Moreover,

[1] For a summary of the main assumptions used in previous theoretical VPD models, see the table on page 56 of Jorge, Pires, Catalão-Lopes, Carrilho-Nunes, and Alventosa (2022).

[2] With simultaneous quality choices, typically there are two asymmetric subgame perfect Nash equilibrium where the roles (being high-quality or low-quality) of the two firms are reversed.

[3] In addition, these works show that there are different types of full coverage equilibria, depending on whether the equilibrium in the price game is such that the low-quality firm has an interior solution or a corner solution, and that there is a discontinuity in the transition from the uncovered to the covered market.

the existing experiments rarely consider endogenous quality and price choices, as studied in the majority of the theoretical VPD models.

Mangani (2002) is the first experimental study exploring the relationship between quality differentiation and price competition.[4] Assuming exogenous qualities, the author considers treatments where quality differentiation is maximal and others where it is minimal, concluding that collusion is likely to occur with low differentiation, but disappears with maximal differentiation (as price competition is relaxed).[5]

Burgmeier (2012) performs a laboratory experiment to study how the number of entrants in a market influences the decision of an incumbent firm, which sells a premium-quality good, to offer a product with lesser quality and lower price ("fighter brand") to deter entry. In the experiment, the incumbent and the entrant decide sequentially the quality (profit-maximizing prices are calculated by the computer). When there is only one potential entrant, the incumbent accommodates the entry and coordinates with the entrant, so that relative profits are balanced. By contrast, with two potential entrants, the incumbent may deviate from the equilibrium prediction by reducing the entrants' profits to the minimum to deter entry. According to the author, this shift in subjects' behavior is due to the increased difficulty of reciprocating as the number of participants increases.

These few exceptions in the experimental literature dealing with VPD address either the quality or the price decision and not both decisions in the same game. To the best of our knowledge, the two previous experimental works on firms' strategic behavior concerning the quality–price mix are Alventosa, Pinho, Jorge, and Catalão-Lopes (2023) and Amaldoss and Shin (2011). Amaldoss and Shin (2011) consider two market segments: the "low-end", composed of consumers who have low valuations for quality, and the "high-end", composed of consumers who value quality more. Preferences are uniformly distributed for each of these segments. Firms first choose qualities (simultaneously or sequentially) and then simultaneously choose prices. Admitting marginal production costs that increase quadratically on the quality level, the authors investigate how the relative size of the "low-end" market influences the quality–price choices. The sequential choice model predicts that, for an intermediate size of the "low-end" market, the leader chooses a low-quality product and has a higher profit than the follower. The sequential model is tested experimentally, by varying the size of the "low-end" market. The experimental results are qualitatively aligned with the theoretical predictions. However, the follower's quality is less differentiated from the leader's quality than the theory predicts, which may be explained by an anchoring effect. In contrast, prices seem not to respond as much as they should to the rival's quality, reflecting adjustment and egocentric biases. The current paper differs from Amaldoss and Shin (2011) by testing a model of simultaneous quality choices followed by simultaneous price choices as in Alventosa et al. (2023), where the authors explore, theoretically and experimentally, the impact of heterogeneity in consumers' preferences on firms' decisions. Alventosa et al. (2023) find less vertical product differentiation in the lab than theoretically predicted, especially when the heterogeneity in consumers' preferences is high. Alventosa et al. (2023) and Amaldoss and Shin (2011) present a demand-side approach, whereas the current paper focus on a supply-side approach, assessing how different cost structures affect the quality–price mix decisions and the resulting market structure.

Although in a less direct way, our work can also be related to the HPD experimental literature.[6] The first experiment considering endogenous location-then-price choices is Camacho-Cuena, García-Gallego, Georgantzís, and Sabater-Grande (2005). The study concludes that sellers with higher flexibility in changing locations differentiate significantly more their products and set higher prices than those with low flexibility. Barreda-Tarrazona, García-Gallego, Georgantzís, Andaluz-Funcia, and Gil-Sanz (2011) also find that the higher the degree of product differentiation, the higher the prices. Another important result of Barreda-Tarrazona et al. (2011) is that differentiation is lower in the lab than theoretically expected.[7] Xefteris, Barreda-Tarrazona, García-Gallego, and Georgantzís (2023) also consider location and price choices assuming three possible locations. They compare the results when location and price are simultaneously chosen with the (more common) location-then-price setup. Although the equilibria involve mixed strategies, the observed behavior is not consistent with mixed-strategies play. Moreover, when prices are chosen after locations are known, closer locations lead to lower prices, which is consistent with the idea that differentiation softens price competition. Finally, there is some coordination in monopoly pricing in both settings.

Our paper contributes to the experimental literature on how quality and price choices are interconnected and how these choices influence the market structure. Our conclusions are aligned with the existing product differentiation experimental evidence. In particular, we also find lower quality differentiation than theoretically expected (as obtained by Amaldoss & Shin, 2011 under VPD, and by Barreda-Tarrazona et al., 2011 under HPD). However, our results also reveal the importance of the assumptions regarding costs, namely for the observed market coverage, as we obtain full market coverage under nil costs, but partial market coverage when marginal costs are increasing with quality. Moreover, we show that when quality is costly, average market qualities are lower but quality differentiation is higher. Concerning pricing, we observe that prices increase with quality differentiation and are always higher for the high-quality firm. Prices of a firm are increasing with its own quality and also sensitive to the rival's quality, but the impact on price of the rival's quality is positive for the low-quality firm and is negative for the high-quality firm. Furthermore, when quality is costly, market prices are higher but the intensity of competition (measured by the price-cost margins) tends to be fiercer given that these prices must cover the higher quality costs too.

The rest of this paper is organized as follows. Section 2 describes the theoretical framework and derives the theoretical predictions. Section 3 describes the experiment and its procedures. Section 4 presents the hypotheses. Section 5 describes and discusses the experimental results.

[4] Regarding quality, one of the first topics to be experimentally analyzed was the information disclosure and the emergence of "lemons" (i.e., low-quality products trying to disguise as high-quality products, taking advantage of information asymmetries). In this line, full information yields more efficient exchanges, but "lemons" occur and prevail (Holt & Sherman, 1990; Lynch, Miller, Plott, & Porter, 1984). This literature is focused on private information disclosure, whereas our focus is on VPD competition.

[5] Another related line of research tests if corporate social responsibility can be understood as a source of vertical product differentiation. Rode, Hogarth, and Le Menestrel (2008) and Vasileiou and Georgantzís (2015) provide experimental work in this line. Rode et al. (2008) consider a triopoly where one of the firms offers an ethically produced good, firms decide prices, and consumers decide whom they want to buy from. In Vasileiou and Georgantzís (2015) experiment, firms invest in an energy-saving public good, set prices, and consumers decide whom to buy from. Both works are especially focused on consumers' choices, revealing that consumers are willing to pay more for ethically produced goods and for goods produced by energy-saving manufacturers. However, Vasileiou and Georgantzís (2015) also show that the price increase does not compensate for the increased energy-saving costs.

[6] The experimental literature on HPD is more extensive than on VPD. Some works consider fixed prices and endogenous location choices and study the effect of non-binding communication (Brown-Kruse, Cronshaw, & Schenk, 1993; Brown-Kruse & Schenk, 2000) and the number of firms in the market (Collins & Sherstyuk, 2000; Huck, Müller, & Vriend, 2002). Other works consider fixed locations and endogenous prices (Orzen & Sefton, 2008; Selten & Apesteguia, 2005). Only the works mentioned in the text consider endogenous location-then-price choices.

[7] Most contributions on experimental HPD assume rational consumers, with pure selfish preferences, who are uniformly located along the line. On the contrary, Barreda-Tarrazona et al. (2011) and Camacho-Cuena et al. (2005) considered real consumers.

Section 6 sums up the main findings and concludes, discussing possible future research lines. Appendix A presents the payoff matrices and describes in further detail the computation of the subgame-perfect Pareto-dominant Nash equilibria of the game. Finally, Appendix B provides the instructions distributed to subjects at the beginning of the experiment.

2. Theoretical framework

2.1. Basic model and parameters

Consider a duopoly where firm $i \in \{1, 2\}$ produces a good of quality k_i that sells at price p_i. Without loss of generality, let firm 2 be the firm that produces the highest quality good ($k_2 \geq k_1$).[8] Consumers in the market value quality positively but are heterogeneous in their quality valuation. The utility that a consumer, identified by his/her taste parameter θ, obtains from purchasing the good from firm $i \in \{1, 2\}$ is:

$$U_i(\theta) = \theta k_i - p_i, \quad (1)$$

where $\theta > 0$ captures the consumer's quality valuation (assumed to be independent of the identity of the firm that sells the good). This parameter is uniformly distributed across $\left[\underline{\theta}, \overline{\theta}\right]$, with density $f(\theta) = \frac{1}{\overline{\theta}-\underline{\theta}}$. As $k_2 \geq k_1$, for equal prices ($p_1 = p_2$) all consumers prefer to buy good 2, i.e., the two goods are vertically differentiated.

Demand is perfectly inelastic: each consumer buys, at most, one unit of the good. Thus, consumer θ decides whether to buy the good and, if so, from which firm to buy it. If a consumer does not buy the good from any firm, he/she gets a reservation utility, which we normalize to zero. As a result, consumer θ prefers not buying any good than buying the good from firm $i \in \{1, 2\}$ if and only if:

$$U_i(\theta) \leq 0 \;\Leftrightarrow\; \theta \leq \frac{p_i}{k_i} \equiv \hat{\theta}_i.$$

Consumers with $\theta < \min\{\hat{\theta}_1, \hat{\theta}_2\}$ prefer not to buy from any firm, i.e., to stay out of the market. If only one of the firms provides consumer θ with a positive utility, he/she will buy from that firm. If both firms provide him/her with a positive utility, the consumer buys the good giving him/her the highest utility. Given the qualities and the prices of the two firms, consumer θ is indifferent between buying from firm 1 and firm 2 if and only if:

$$U_1(\theta) = U_2(\theta) \;\Leftrightarrow\; \theta k_1 - p_1 = \theta k_2 - p_2 \Leftrightarrow\; \theta = \frac{p_2 - p_1}{k_2 - k_1} \equiv \tilde{\theta}.$$

Any consumer with quality valuation $\theta < \tilde{\theta}$ prefers to buy the good from firm 1, while any consumer with $\theta > \tilde{\theta}$ prefers to buy the good from firm 2.[9]

Firms play a two-stage game with complete information with the following timing: in the first stage, firms simultaneously and independently choose the quality of their goods; in the second stage, after observing qualities, firms simultaneously and independently choose prices. The objective of firm $i \in \{1, 2\}$ is to maximize its individual profit, given by:

$$\pi_i = p_i q_i - C(k_i, q_i), \quad (2)$$

where q_i is the quantity sold, and $C(k_i, q_i)$ is the total cost function, which may depend on the quality of the good, k_i, and the quantity sold, q_i. We consider two different specifications for the production cost function: (i) the case where quality is costless, $C(k_i, q_i) = 0$ (Wauthy, 1996); and (ii) the case where marginal production costs are constant and increase quadratically with the quality level, $C(k_i, q_i) = ck_i^2 q_i$ (Pires et al., 2022).[10] We will refer to the first scenario as the "no (quality) cost" (NC) scenario; and to the second scenario as the "quality cost" (QC) scenario.

Depending on the firms' decisions, all consumers may purchase the good (full market coverage), or at least one consumer may not purchase the good (partial market coverage). Furthermore, only one firm may be active in the market (monopoly) or both may be active (duopoly). Thus, 5 market configurations may appear: duopoly with full coverage (DFC), duopoly with partial coverage (DPC), monopoly with full coverage (MFC), monopoly with partial coverage (MPC), and no market (NM).[11] As pointed out by Pires et al. (2022) and Wauthy (1996), restricting the analysis to specific market configurations, in terms of market coverage or structure, is a strong and potentially unrealistic assumption.

As one of our main goals is to test in the lab the impact of different cost structures on the market outcome, in the experiment (explained in further detail in the following section) we assume $\underline{\theta} = 0.3$ and $\overline{\theta} = 1.2$. This parameter calibration implies different equilibrium market coverage under the two cost assumptions.[12] More precisely, as shown by Pires et al. (2022) and Wauthy (1996), for these parameter values, both firms operate in the (subgame-perfect Nash) equilibrium. However, under nil costs (NC), the market is fully covered (see case 3 on page 351 of Wauthy, 1996), whereas with increasing marginal costs (QC) the market is partially covered (see case 1 in Proposition 6 of Pires et al., 2022). In addition, quality differentiation ($k_2 - k_1$) is higher under the nil costs assumption; and, for given quality choices, prices are higher with costly quality (due to the higher marginal costs). Finally, under both cost assumptions, for a given market coverage, we expect higher prices when quality differentiation is higher.

To implement the model in the lab, we assume $c = 0.1$ and consider a discrete set of consumers[13] and a discrete set of firms' choices. The set of consumers is $\mathcal{J} = \{1, 2, 3, \ldots, 10\}$, and the quality valuation of consumer j is $\theta_j = 0.3+0.1(j-1)$, for $j \in \mathcal{J}$. Thus, consumers are ranked in a way that a consumer indexed with a higher value for j values more the quality, i.e., $\theta_1 < \theta_2 < \cdots < \theta_{10}$ (note that $\theta_1 = \underline{\theta} = 0.3$ and $\theta_{10} = \overline{\theta} = 1.2$). In addition, we also discretize the set of firms' choices (as Luini & Mangani, 2000; Vasileiou & Georgantzís, 2015, among others). Firms must choose a quality level from $\mathcal{K} = \{2.5, 3, 3.5, \ldots, 6.5\}$, and a price from $\mathcal{P} = \{0.5, 1, 1.5, \ldots, 4.5\}$. Note that when quality is costly (QC), firms may make positive profits even if they set the highest quality level (6.5) or may make losses even if they set the lowest quality level (2.5).[14]

---

[8] This assumption is without loss of generality, as qualities are exogenous in the price game and, in the quality game, we are just denoting by firm 2 the one with higher quality (Wauthy, 1996).

[9] Whenever a consumer is indifferent between buying from one firm or the other, he/she buys from any firm with a probability of 0.5. Similarly, whenever a consumer is indifferent between buying or not the good, he/she buys with a probability of 0.5.

[10] Nil production costs were standard in the early VPD literature and drive widely known theoretical results. Increasing marginal production costs is becoming more common in recent VPD literature.

[11] The "No Market" scenario corresponds to the case where, given the quality–price choices, no firm gets a positive demand.

[12] To compare with the contributions of Pires et al. (2022) and Wauthy (1996), notice that this parameters' choice implies that $\frac{\overline{\theta}}{\underline{\theta}} = 4$ and $\underline{\theta} = \frac{1}{3}\left(\overline{\theta} - \underline{\theta}\right)$.

[13] In their experiments, Holt and Sherman (1990), Luini and Mangani (2000), Lynch et al. (1984), and Vasileiou and Georgantzís (2015) also considered a discrete set of consumers.

[14] In the QC scenario, if a firm chooses the highest quality level, its marginal cost is $0.1 \times (6.5)^2 = 4.225$. Thus, the firm makes losses for any price $p_i < 4.5$ and profits for $p_i \geq 4.5$. By contrast, if a firm sets the lowest possible quality, its marginal cost is 0.625, so the firm makes losses for $p_i < 1$ and profits for $p_i \geq 1$. When quality is costless (NC), firms make no losses regardless of the quality–price combination, as production costs are nil.

2.2. Theoretical predictions

As firms play a two-stage game, we use backward induction to solve the (discrete) model. First, we solve the second stage of the game, by finding, for all possible quality pairs (k_1, k_2), the prices that maximize individual profits, $\left(p_1^{**}(k_1, k_2), p_2^{**}(k_1, k_2)\right)$. Then, to solve the first stage of the game, we plug these prices in the profit functions, given in (2), and find the equilibrium qualities, (k_1^*, k_2^*). If $k_1^* \neq k_2^*$, the equilibrium prices are $(p_1^*, p_2^*) = \left(p_1^{**}(k_1^*, k_2^*), p_2^{**}(k_1^*, k_2^*)\right)$.[15]

If, in the first stage, firms choose the same quality level, $k_1^* = k_2^*$, they engage in fierce price competition in the second stage of the game and set prices as close as possible to marginal costs (as they are producing homogeneous goods and competing in prices – Bertrand paradox). If quality is costless (NC), this means that the equilibrium prices are the lowest possible, regardless of k_i for $i \in \{1, 2\}$ (as marginal costs are null in this case). If quality is costly (QC), both firms choose the price in $\mathcal{P}$ that is the closest to $c(k_i^*)^2$.

Proposition 1 (*Subgame-perfect Pareto-dominant Nash equilibria*)**.** *Assuming $k_2 \geq k_1$:*

1. *If quality is costless (NC), there is 1 subgame-perfect Pareto dominant Nash equilibrium in pure strategies with both firms active in the market and all consumers served (Duopoly with Full Coverage). On-the-equilibrium-path, the vectors of individual qualities (k_i), prices (p_i), price-cost margins (μ_i),*[16] *the number of consumers served (q_i), and profits (π_i) are:*[17]

k_1^{NC}	k_2^{NC}	p_1^{NC}	p_2^{NC}	μ_1^{NC}	μ_2^{NC}	q_1^{NC}	q_2^{NC}	π_1^{NC}	π_2^{NC}
3.5	6.5	1	2.5	1	2.5	2.5	7.5	2.5	18.75

2. *If quality is costly (QC), there are 2 subgame-perfect Pareto dominant Nash equilibria in pure strategies with both firms active in the market and 3 consumers not purchasing any good (Duopoly with Partial Coverage).*[18] *On-the-equilibrium-path:*[19]

	k_1^{QC}	k_2^{QC}	p_1^{QC}	p_2^{QC}	μ_1^{QC}	μ_2^{QC}	q_1^{QC}	q_2^{QC}	π_1^{QC}	π_2^{QC}
i	3	5	1.5	3.5	0.6	1	4.5	2.5	2.7	2.5
ii	3.5	5.5	2	4	0.775	0.975	4.5	2.5	3.4875	2.4375

Proof. See Appendix A. □

Proposition 1 characterizes the equilibria if firm 2 is the firm selling the highest quality good ($k_2 \geq k_1$). We would get symmetric equilibria in the case $k_1 \geq k_2$ (with the players' roles reversed). Thus, if we removed this assumption, the number of equilibria would double in both cases. Notice further that, when quality is costless (NC), the high-quality firm profits significantly more than the low-quality firm. As shown later on, this feature of the equilibrium in the NC case exacerbates the coordination problem subjects have to deal with in the lab. Indeed, when implementing this scenario in the lab, we observe that subjects choose the (same) highest quality level and set the (same) lowest possible price in many markets (i.e., do not play in accordance with theoretical predictions).

Proposition 1 also reveals that there exists quality differentiation in equilibria. As in Wauthy (1996), when quality is costless, the high-quality firm chooses the highest possible quality level, $k_2^{NC} = 6.5$, in equilibrium. This allows the firm to attract more consumers without incurring higher marginal production costs (as they are independent of the quality choice). However, when quality is costly (QC), firms face a trade-off: they want to choose a higher quality level to increase the consumers' willingness to pay, but they are aware that this implies higher marginal production costs. As a result, in equilibrium, the high-quality firm no longer sets the highest possible quality, $k_2^{QC} < 6.5$. The low-quality firm never chooses the same quality level as the high-quality firm (to avoid head-to-head competition), but quality differentiation is higher in the NC scenario.

Regardless of the cost structure, the model predicts that the high-quality firm sets a higher price than the low-quality firm ($p_2^s > p_1^s$, for $s \in \{NC, QC\}$) both on-the-equilibrium path and off-the-equilibrium path.[20] This is due to the fact that consumers are willing to pay more for the high-quality good (under both cost assumptions) and higher quality implies higher marginal production costs (when quality is costly). Moreover, for given qualities (k_1, k_2), prices are higher in QC than in NC and are increasing with the level of quality differentiation $(k_2 - k_1)$.

When quality is costless (NC), prices are good indicators of the intensity of competition in the market. However, when quality is costly (QC), a higher price can be the consequence of producing a higher-quality good (which implies a higher marginal cost) and not necessarily be an indicator of softer price competition. In this case, the price-cost margins are better indicators. Independently of the cost structure, the high-quality firm gets higher margins than the low-quality firm on-the-equilibrium path (Proposition 1) and off-the-equilibrium path.[21] When comparing the intensity of competition across the two cost scenarios, we conclude that on-the-equilibrium path (Proposition 1), competition is fiercer in the QC scenario, as both firms get lower price-cost margins ($\mu_i^{QC} < \mu_i^{NC}$ for $i \in \{1, 2\}$). Off-the-equilibrium path, the high-quality firm gets a lower margin in the QC scenario than in the NC scenario, but the same does not always apply to the low-quality firm. When the two firms sell highly differentiated goods, the low-quality firm may have a lower price-cost margin in the NC scenario than in the QC scenario (the opposite of what happens to the high-quality firm). The reason is that, in this case, the high-quality firm has high marginal costs and hence charges a high price. Since prices are strategic complements, the equilibrium price of the low-quality firm is higher and more than compensates for the production costs (absent in the NC case). As a result, the low-cost firm gets a higher price-cost margin in QC than in NC.

To conclude, it should be highlighted that our results, obtained in a discrete VPD model, corroborate most of the existing results in the literature (for continuous VPD models). The only exception concerns the profits' ranking in the QC case. More precisely, Pires et al. (2022) obtained that, when quality is costly, the high-quality firm profits more than the low-quality firm, while we obtained the opposite result (Proposition 1). This divergence may be explained by the fact that under QC the difference in the two firms' profits is low (both in Pires et al., 2022, and in our setup).

[15] To reduce the number of equilibria, we apply an equilibrium refinement in both stages of the game, by eliminating the Pareto-dominated equilibria.

[16] As, in this scenario, firms have no costs, the price-cost margin trivially coincides with the price, $p_i = \mu_i$.

[17] It is straightforward to see that, for these qualities and prices, the consumer $\theta_3 = 0.5$ has the same utility if buying from firm 1 or firm 2. Thus, he/she will buy from one of the firms with a probability of 0.5. This is why firm 1 (resp. firm 2) may serve 2 or 3 consumers (resp. 8 or 7 consumers) with a probability of 0.5 in equilibrium.

[18] In both equilibria, the consumer $\theta_8 = 1$ is indifferent between buying the good from firm 1 or firm 2. This is why firm 1 (resp. firm 2) may serve 4 or 5 consumers (resp. 3 or 2 consumers) with a probability of 0.5 in equilibrium.

[19] As total production costs in this scenario are $C(k_i, q_i) = 0.1{k_i}^2 q_i$, it follows that $\mu_i = p_i - 0.1{k_i}^2$.

[20] The conclusions regarding the off-the-equilibrium path are based on the analysis of the second-stage Nash equilibrium prices, for all possible (k_1, k_2), presented in Tables 7 and 9 in Appendix A.

[21] See Table 10 in Appendix A.

3. Experimental design

We designed an experiment where subjects played the role of sellers in a market with 2 sellers and 10 virtual buyers. Buyers were heterogeneous in the way they valued the quality of the good and their utility function was given by (1). We implemented a between-subjects design, so each subject participated in one and only one session and treatment. Each session was composed of 15 periods,[22] where subjects choose, in each period, the characteristics of their products in two stages:

Quality stage — The two sellers simultaneously choose the quality of their products, among the following possibilities:

2.5 | 3 | 3.5 | 4 | 4.5 | 5 | 5.5 | 6 | 6.5

Price stage — The two sellers observe both quality choices and simultaneously choose the price of their products, among the following possibilities:

0.5 | 1 | 1.5 | 2 | 2.5 | 3 | 3.5 | 4 | 4.5

After the two subjects choose their prices, the 10 (virtual) buyers were automatically allocated to a seller (if getting a positive utility from at least one seller).[23] At this point, subjects observed the two qualities offered in the market, the prices set, how many buyers bought from each seller, their profits in that round, and their accumulated profits up to that round. Then, subjects were randomly rematched with another seller in the room and played another round (up to the end of the 15 rounds).

The experiment was programmed in oTree (Chen, Schonger, & Wickens, 2016) and implemented at the Behavioural and Experimental Lab in Economics and Management (BELEM@UA), at the University of Aveiro, between February and March 2020. Following the model presented in Section 2, we considered two treatments just differing in the specification of the total cost function:

- *No Costs (NC) treatment* , where $C(k_i, q_i) = 0$.
- *Quality Costs (QC) treatment* , where $C(k_i, q_i) = 0.1k_i^2 q_i$.

In the QC treatment, subjects saw their marginal production cost, resulting from their quality choice, before choosing prices.[24] We ran 3 sessions with the NC treatment and 3 sessions with the QC treatment, with 16 subjects per session, which corresponded to a total of 96 participants. The NC session lasted an average of 60 minutes and the average payoffs were 8.50€. The QC sessions lasted an average of 120 minutes and average payoffs were 15€.[25]

Following the Experimental Economics protocols, once participants entered the lab they received a copy of the instructions,[26] which they kept in their possession during the whole experiment. At the end of the session, subjects were paid a participation fee of 5€ plus their accumulated profits for the 15 periods in cash in a sealed envelope.[27]

[22] Subjects also played 5 trial rounds that did not count for their final payoffs.

[23] If both sellers chose qualities and prices that provided a buyer with a negative utility, that buyer was not allocated to any seller.

[24] In a comprehension quiz, subjects were asked to compute the marginal cost for a given quality and 37.5% failed this task. Thus, to avoid mistakes resulting from the miscomputation of marginal costs, we presented the marginal costs to subjects before they choose prices.

[25] Different exchange rates were used in the different treatments, anticipating QC sessions to last longer than NC sessions. With the different exchange rates, we intended to align the average payment per hour.

[26] See the translated instructions in Appendix B.

[27] Subjects cannot leave the lab "owing" any money to the experimentalists, so there must be some limited liability constraint. However, subjects leaving the lab with a show-up fee regardless of what happened could generate perverse incentives. Thus, in case of negative accumulated profits, participants would need to perform additional tasks, distributed in a paper at the end of the session, to recoup their losses. This way we would avoid subjects thinking that making losses was free and was left unpunished. In the end, this did not happen as no subject got a negative accumulated profit in any session.

4. Hypotheses

In this section, we propose a set of hypotheses regarding the behavior we expect to observe in the lab. Our hypotheses are primarily based on the qualitative results of our model, but they also consider what we know from previous experiments and, for those cases where the experimental literature has shown divergence with respect to theoretical predictions, we propose two hypotheses.

The main insight of Pires et al. (2022) and Wauthy (1996) is that whether the whole market is covered or not is determined endogenously. These works show that the market structure depends on the distribution of the consumers' tastes and the cost structure. Our discrete model considers a fixed distribution of consumers' valuation of quality but explores differences in the cost structure that lead to a different market structure in the two treatments. Our first hypothesis follows directly from our theoretical model (Proposition 1), but it takes into account that participants may need to go through a learning process to behave according to the equilibrium. Thus, we hypothesize the following:

H1 (Market coverage): *The market coverage outcome depends on the cost structure: in NC there is convergence to a duopoly with full coverage, whereas in QC there is convergence to a duopoly with partial coverage.*

According to our theoretical predictions, the average quality when quality is costless is higher than when quality is costly. The reason is that when quality is costly, choosing a higher quality implies higher marginal costs. Thus, firms choose lower quality levels when quality is costly. We expect the same qualitative result to hold in an experimental setting, hence our second hypothesis is:

H2 (Quality choices): *Average firms' qualities are lower in QC than in NC.*

Our model predicts that firms differentiate the quality of their products in both treatments, a result that is very general in the theoretical VPD literature. Moreover, it also predicts that quality differentiation is higher in the NC setting.

H3 (Quality differentiation): *There exists quality differentiation under both cost structures, but it is lower in QC than in NC.*

However, there exists a vast literature branch on coordination failure in the lab (see Cooper, DeJong, Forsythe, & Ross, 1989, and Devetag & Ortmann, 2007, for detailed surveys), which suggests that a coordination problem may arise when we take our model to the lab, as participants may fail to coordinate on who is the high-quality firm and who is the low-quality firm. This problem is more likely to be relevant in the NC setting. In this treatment, the profits of the high-quality firm are much higher than the profits of the low-quality firm (Proposition 1). This implies very strong incentives to choose a high-quality. Thus participants may end up both choosing high-quality levels, implying a low quality-differentiation in the NC setting. In the QC setting the coordination problem is alleviated because the profits difference is much lower. Considering this, it is likely that differences in the observed and unobserved characteristics of the participants lead to some sort of coordination, with some participants being naturally more inclined to choose lower qualities while others choose higher qualities. Thus, according to this behavioral prediction, we could alternatively expect a higher differentiation under the QC treatment:

H3′ (Quality differentiation): *There exists quality differentiation under both cost structures, but it is lower in NC than in QC.*

The next hypothesis concerns price decisions in the second stage of the game. Our model predicts that, for given qualities and regardless of the cost structure, the high-quality firm always sets a higher price than

Table 1
Comparison of average qualities and prices in the experiment (all rounds and final round) in both treatments to theoretical predictions.

	No costs (NC)			Quality costs (QC)		
	All rounds	15th round	Theory	All rounds	15th round	Theory
Average quality	6.261	6.396	5	4.399	4.26	(4, 4.5)
Average high quality	6.436	6.5	6.5	4.91	4.688	(5, 5.5)
Average low quality	6.086	6.292	3.5	3.888	3.833	(3, 3.5)
Average price	0.669	0.583	1.75	2.415	2.281	(2.5, 3)
Average high-quality price	0.751	0.625	2.5	2.899	2.688	(3.5, 4)
Average low-quality price	0.588	0.542	1	1.931	1.875	(1.5, 2)

the low-quality firm and that prices are higher for the costly treatment. This is due to the fact that consumers are willing to pay more for the high-quality good (under both cost assumptions) and higher quality has higher marginal costs (when quality is costly). In addition, the high-quality firm also reacts differently to changes in its own quality and the rivals' quality. For the high-quality firm, an increase in its quality leads to an increase in its price as both quality differentiation and marginal costs increase (in the QC case). On the contrary, an increase in the rival's quality leads to lower quality differentiation, and thus a lower high-quality price. For the low-quality firm, when its quality increases, the degree of differentiation decreases but its marginal costs increases (in the QC case), leading to contradictory effects on its price. However, the impact of an increase of the rival's quality on price is positive as differentiation increases. Therefore, our theoretical results lead us to hypothesize the following:

H4 (Price choices): *For given quality choices, prices are higher in QC than in NC and higher for the high-quality firm. Moreover, the high-quality prices are increasing with its own quality but decreasing with the rival's quality whereas the low-quality prices depend positively on the rival's quality.*

As explained in Section 2, when quality is costly, a higher price can be the consequence of a higher marginal production cost, and not necessarily mean softer price competition. In this case, price-cost margins are better indicators of the intensity of price competition. Our model predicts that in both treatments the high-quality firm has higher price-cost margins than the low-quality firm. Moreover, in QC the price-cost margins are typically lower for both firms, as firms do not fully pass the cost increase to the consumers. However, when the products are highly differentiated, the low-quality firm may have a higher price-cost margin in the QC treatment than in the NC. Thus, we expect the following to happen:

H5 (Price competition): *In both treatments, for given quality choices, the high-quality firm gets a higher price-cost margin than the low-quality firm. The high-quality firm has a lower price-cost margins in QC than in NC. Price-cost margins of the low-quality firm are also lower in QC, unless products are highly differentiated.*

5. Results

In this section, we present our experimental results and estimate econometric models to understand the forces driving the participants' decisions and test our hypotheses.

5.1. Summary statistics

As a first approach to the data, in Table 1 we present summary statistics of the experiment's decision variables: average quality and average price. We also distinguish between these choices for the high and the low-quality firm in the market and for all data (average over the 15 rounds) and experienced data (average only of the last round). Furthermore, we present these results along with the corresponding theoretical predictions presented in Proposition 1.

Looking at the results in the lab for the quality stage in the NC treatment, we conclude that, on average, the high-quality good is in accordance with the theoretically predicted level (the highest possible); but the same does not apply to the low-quality good. As explained before, in this treatment the payoffs of the two firms are very asymmetric: the high-quality firm profits significantly more than the low-quality firm. As a result, in the lab, each subject attempts to sell the high-quality good and hopes the other to offer a lower-quality good. As subjects do not coordinate their decisions, frequently they end up choosing the (same) highest quality level, which is harmful to both of them. It can also be seen that, on average prices in the lab are below theoretical predictions. However, we must be cautious in the interpretation of this result, as the theoretical predictions for prices (Proposition 1) are computed for the equilibrium quality levels ($k_1^{NC} = 3.5$ and $k_2^{NC} = 6.5$), which, as we have just seen, do not coincide with the subjects' average choices ($\bar{k}_1^{NC} = 6.086$ and $\bar{k}_2^{NC} = 6.436$), mainly for the low-quality good.[28] In sum, there is some discrepancy between model predictions and subjects' decisions in the lab for the NC treatment.

By contrast, the model predicts quite well the subjects' decisions in the lab for the QC treatment. Regarding quality choices, the observed values in the lab do not differ much from the theoretical predictions. Still, on average, the quality of the low-quality good is slightly above the predictions, while the quality of the high-quality good is slightly below the predictions. Regarding price choices, the average price of the low-quality firm in the lab is according to the theoretical predictions but the price of the high-quality firm is below predictions.

Regardless of the treatment, we find that there is, on average, less quality differentiation in the lab than the model predicts.

5.2. Market configuration

According to our theoretical predictions, when quality is costless, both firms are active in the market and all consumers purchase a good (Duopoly with Full Coverage); while, when quality is costly, the equilibrium is still a duopoly, but at least one consumer does not buy the good (Duopoly with Partial Coverage).

As Fig. 1 illustrates, in the early stages of the experiment, the results differed from the theoretical predictions. However, after a few rounds, there was a convergence to the theoretical predictions.[29]

Testing whether the observed results were equal to the theoretical predictions using exact binomial tests with observations from the first round, we reject the null hypothesis. However, the frequency of duopoly with full coverage becomes higher in the last rounds of the experiment. In the last round, of the 24 markets, 22 correspond to a duopoly with full coverage (see Table 2). These results suggest

[28] As shown in Table 9 in Appendix A, the equilibrium of the price stage is different for different quality combinations.

[29] Even if we graphically represent results for all the rounds, the analysis is only done based on the experimental periods (E1–E15). Trial rounds (T1–T5) are excluded given that they are non-incentivized rounds made for subjects to get familiar with the game.

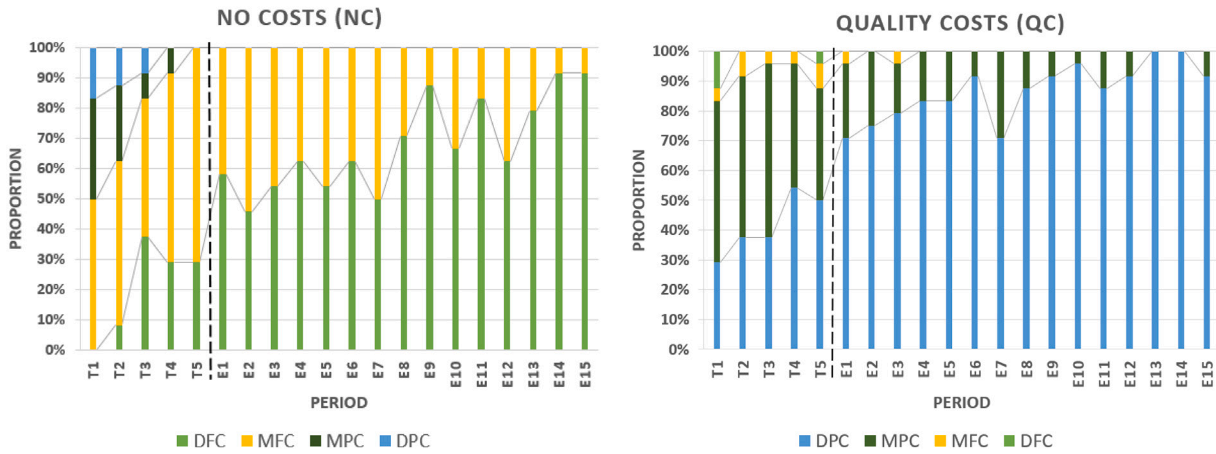

Fig. 1. Frequency of each market configuration in both treatments: Duopoly with Full Coverage (DFC), Monopoly with Full Coverage (MFC), Monopoly with Partial Coverage (MPC) and Duopoly with partial Coverage (DPC).

Table 2
Comparison of the market configuration in the experiment and in the theoretical predictions for the two cost treatments.

	No costs (NC)			Quality costs (QC)		
	1st round	15th round	Theory	1st round	15th round	Theory
DFC	14	22	24	0	0	0
DPC	0	0	0	17	22	24
MFC	10	2	0	1	0	0
MPC	0	0	0	6	2	0
NM	0	0	0	0	0	0
Observed prob. success	0.5833***	0.9167		0.7083***	0.9167	

Significance codes: $^*p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$. Exact binomial tests. Convergence is assumed when the probability of expected market configuration surpasses the 90% threshold. Null Hypothesis: $p \geq 0.9$. Alternative Hypothesis: $p < 0.9$.

that subjects need to go through a learning process to achieve the equilibrium outcome.[30]

In the QC treatment, except for 2 markets in the first and third rounds (where a monopoly with full coverage occurred), in all the other cases a partial market coverage outcome was observed, which means that at least one consumer did not buy the good. Both monopolies with partial coverage and duopolies with partial coverage were observed, but the proportion of markets with a duopoly converges rapidly to the theoretically predicted outcome. In the last round, among the 24 markets, 22 correspond to a duopoly with partial coverage.

Result 1. *The market configuration depends on the cost structure. In the NC treatment, the market configuration converges to a duopoly with full coverage whereas, in the QC treatment, the market configuration converges to a duopoly with partial coverage.*

The conclusion that different cost structures yield different market coverages strengthens the importance of making the market coverage in VPD models endogenous, and not assuming a particular configuration *a priori*, as explained by Pires et al. (2022) and Wauthy (1996).

5.3. Quality choices

Fig. 2 presents the average quality per period of both goods in the two treatments. The shaded areas represent the interval of theoretical predictions. We observe that there is a quality race in the NC treatment, with the high-quality choices converging to the maximum possible quality and the low-quality choices being only slightly lower. On the other hand, the quality choices in the QC case, converge to levels that are below the theoretically expected ones in the case of the high-quality firm, but above the expected ones in the case of the low-quality firm.[31]

In what follows, we present the results of two econometric models where the dependent variable is the quality of firm i in round t ($Quality_{i,t}$). The aim is to understand the factors that influence the quality choices in each round and test the impact of the cost structure on the quality choices. The explanatory variables are: a dummy treatment variable taking value 1 in the QC treatment (*CostlyQuality*), price in the previous round ($Price_{i,t-1}$), and price of firm j in the previous round ($Price_{j,t-1}$). In Model B we also consider the quality of firm j in the previous round ($Quality_{j,t-1}$) and a dummy variable indicating whether firm i is the high-quality firm in the market in the previous round and taking value 1 when it is ($High\text{-}quality\ firm_{t-1}$). The coefficient associated with the treatment variable (*CostlyQuality*) allows us to test H2. This coefficient is expected to be negative as costly quality implies lower equilibrium quality choices. The remaining variables were included to capture the possible impact of previous round variables on round t quality choices.

Following Xefteris et al. (2023), these regressions were estimated using Prais–Winsten panel regressions clustered at the session level. The choice of this method, which corrects the standard errors for heteroskedasticity and autocorrelation, is justified by the fact that

[30] Recall that, in the experiment, subjects were randomly rematched after each period, so it is not a matter of building reputation but of subjects understanding how the market works.

[31] These observations are based on Fig. 2, but are not a result of a statistical test. We cannot run WRS tests for the last round to statistically test such convergence processes, given that we would violate the independence assumption of this test.

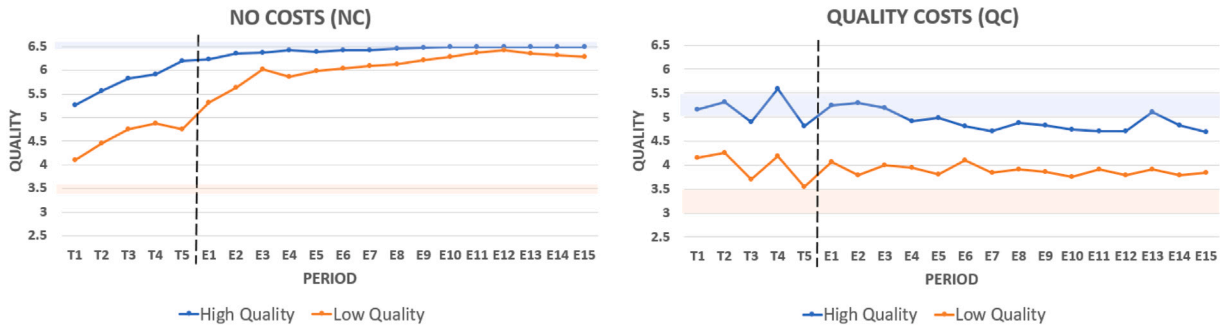

Fig. 2. Per period average qualities in the two treatments.

Table 3
Prais–Winsten panel regressions of quality choices clustered at the session level, semirobust standard errors in parentheses.

Regressors	Model A	Model B
Intercept	6.253 ***	5.679***
	(0.036)	(0.222)
Costly Quality	−1.976***	−1.754***
	(0.072)	(0.145)
$Price_{i,t-1}$	−0.007	0.020
	(0.024)	(0.032)
$Price_{j,t-1}$	0.051	−0.013
	0.035	(0.044)
$Quality_{j,t-1}$	–	0.094*
	–	(0.039)
High-quality firm	–	0.058*
	–	(0.027)
R squared	0.576	0.582
Baltagi–Li joint test	358.17***	284.42***
Breusch–Pagan	26.21***	55.80***

Significance codes: $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.
Group variable: Subject id; Time variable: Round; Total number of observations: 1344.

contemporaneous correlation is expected to exist among observations of participants belonging to the same session. To confirm the adequacy of Prais–Winsten panel regressions, we run a Baltagi–Li joint test that confirms the presence of random effects and/or serial correlation (alternative hypothesis: AR(1) errors or random effects) and a Breusch–Pagan test to identify heteroskedasticity in the panel data. The results of these tests, shown in Table 3, justify the choice of the method.

As expected, we identify a treatment effect indicating that qualities are lower in the QC treatment than in the NC treatment. Consequently, the evidence seems to support H2. We also incorporate the previous round market prices as regressors, which have a non-significant impact on quality choices in round t. In Model B, the previous round quality choice of firm j has a statistically significant positive impact on the quality choice of firm i in round t. Moreover, being a high-quality firm in the previous round increases qualities on round t, as *High-quality* $firm_{t-1}$ turns out to be positive and statistically significant.

Result 2. *When quality is costly, average quality is significantly lower than when quality is costless.*

5.4. Quality differentiation

The graphical analysis of the quality choices already suggests that differentiation is higher in the QC treatment. Fig. 2 shows that, in the NC treatment, the two quality levels converge to values close to the maximal feasible quality, implying a very low quality-differentiation. This trend is only reverted in the 13th round, with qualities starting to slightly diverge. Up to that round, subjects seemed to engage in a quality race, with both aiming to offer the high-quality good, possibly to attract more consumers and make more profits. This figure also shows that, in the QC treatment, the quality differentiation level remained relatively stable during the experiment and is larger than in the NC case, although smaller than the theoretically expected degree of differentiation.

Fig. 3 presents the quality combinations observed in the experimental markets and the corresponding frequency. Points on the bisector indicate that subjects chose the same quality level. Thus, the farther away a point is from the bisector, the more differentiated the products are. The size of the point indicates the frequency with which a given combination of qualities occurred.[32]

In the NC treatment, the modes of the quality were equal, $\tilde{k}_1^{NC} = \tilde{k}_2^{NC} = 6.5$, i.e., there was no product differentiation at the top. Indeed, subjects chose homogeneous products in 62.5% of the markets, of which 87% were of the highest possible quality (6.5). In the QC treatment, however, there is a cloud of points around intermediate qualities, $k_i \in \{3.5, 5.5\}$, and subjects chose differentiated products more often. However, there is still a significant percentage (19.7%) of cases where products were homogeneous. This graphical analysis suggests that quality differentiation is higher in the QC treatment, which goes against the theoretical prediction H3 but is in accordance with our alternative H3′, which considers the higher coordination difficulties in the NC setting.

In order to test which of the two cost structures implies more quality differentiation, we estimated two models where the dependent variable is the difference in qualities in the market to which firm i belongs in period t (*Diff. Qualities*$_t$). The regressors in these models are: a dummy treatment variable taking value 1 in the QC treatment (*CostlyQuality*), the difference in prices that firm i experienced in the previous period (*Diff. Prices*$_{t-1}$), and the interaction between the previous round differences in prices and the treatment (*Diff. Prices*$_{t-1}$***CostlyQuality*) to account for differences in the learning processes of the two treatments. The models were estimated using Prais–Winsten panel regressions clustered at the session level, we run a Baltagi–Li joint test that confirms the presence of random effects and/or serial correlation and a Breusch–Pagan test to identify heteroskedasticity in the panel data (see results in Table 4).

Table 4 shows that costly quality has a positive impact on product differentiation, indicating that firms differentiate their products more in QC than in NC. Thus, we reject H3 and do not reject H3′. We also include the previous round difference in prices as a regressor, which turns out non-statistically significant. In Model B, we add the interaction between previous round differences in prices and the QC treatment, which has a non-significant impact on product differentiation. Furthermore, the positive impact of the previous round difference in prices becomes significant. Regarding quality differentiation, the main results are:

[32] For readability reasons, the dots in the two graphs are not presented with the same scaling.

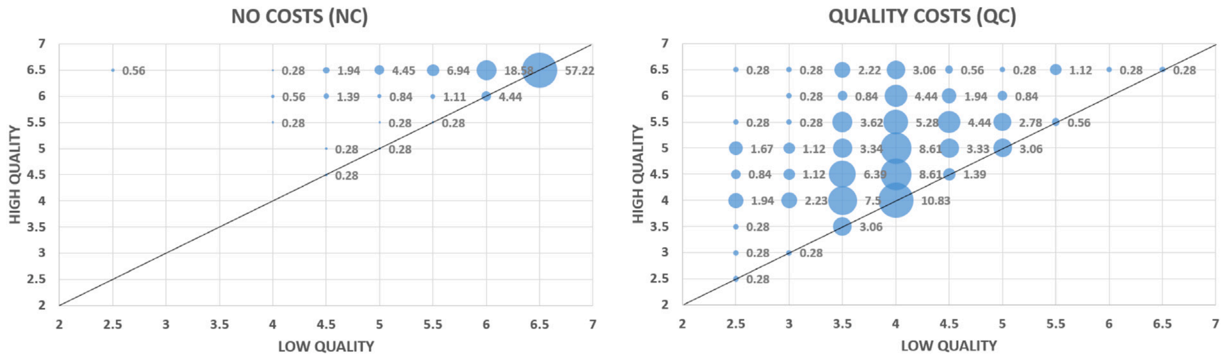

Fig. 3. Frequency of each quality combination in the experimental rounds.

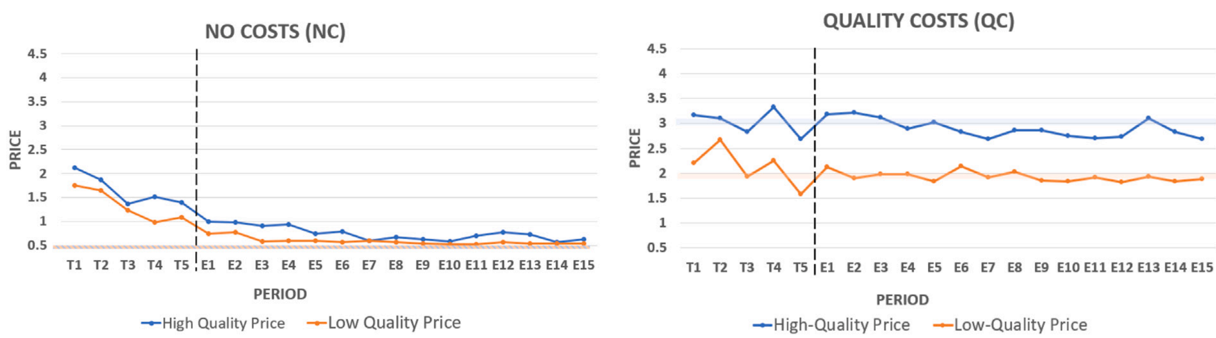

Fig. 4. Per period average individual prices in the two treatments.

Table 4
Prais–Winsten panel regressions of product differentiation clustered at the session level, semirobust standard errors in parentheses.

Regressors	Model A	Model B
Intercept	0.304***	0.306***
	(0.030)	(0.030)
CostlyQuality	0.669***	0.649***
	(0.070)	(0.083)
Diff. Prices$_{t-1}$	0.040	0.030***
	(0.021)	(0.006)
Diff. Prices$_{t-1}$ * *CostlyQuality*	–	0.029
	–	(0.033)
R squared	0.189	0.193
Baltagi–Li joint test	57.36***	272.16***
Breusch–Pagan	111.49***	56.22***

Significance codes: *$p < 0.1$; **$p < 0.05$; ***$p < 0.01$.
Group variable: Subject id; Time variable: Round; Total number of observations: 1344.

Result 3. *There exists product differentiation under both cost structures, but it is lower when quality is costless than when quality is costly. Moreover, in both settings, differentiation is lower than theoretically predicted.*

5.5. Price choices

Fig. 4 presents the per period average individual prices in the two treatments. Low quality-differentiation in NC is associated with high-quality and low-quality prices converging to values close to 0.5. In QC, there is a much higher price differential, which is expected as the degree of quality differentiation is higher in QC and, in this scenario, there are asymmetric marginal costs, contributing to a larger price difference.

From Pires et al. (2022) and Wauthy (1996), as well as from our discrete model, we know that under VPD the price choices are affected by the cost structure (price is expected to be higher in the QC case) and by whether the firm is the high-quality firm or the low-quality firm (the high-quality firm is expected to have a higher price). Moreover we also know that the high-quality price is increasing with its own quality but decreasing with the quality of the rival and that the low-quality price is increasing on the rival's quality.

We estimate three related models where the dependent variable is the price set by firm i in round t ($Price_{i,t}$) and regressors are: a dummy variable taking value 1 when the firm was the high-quality firm in the market (*High-quality firm*) and a dummy treatment variable taking value 1 in the QC treatment (*Costly quality*). To test H4, in models A and B, we also consider the quality of firm i ($Quality_{i,t}$) and the quality of firm j ($Quality_{j,t}$) and, in model B, we add the interaction variables of these two variables with the dummy *High-quality firm.*[33] This allows us to estimate the impact of firm's quality changes and rival's quality changes on prices and, through the interaction variables, to test if the impact is the same for the high-quality and the low-quality firm. Previous experimental studies on HPD (Barreda-Tarrazona et al., 2011; Xefteris et al., 2023) showed that prices increase with product differentiation. So, to compare our results with previous experimental results on HPD, we also run model C, where we use the difference in qualities as an explanatory variable (*Diff. qualities*$_t$) while taking into account the specificities of the VPD models. In particular, we also include the dummies *High-quality firm* and *Costly quality* and, to control for the impact of quality choices on marginal costs, we include the quality of the firm in the regression. These models allow us to test H4 and compare our results with previous literature. Once again, the models were estimated using Prais–Winsten panel data regressions clustered at the session level, which are justified by the specification tests presented in Table 5.

In all the models, costly quality has a positive and significant impact on price choices. That is, prices are higher in QC than in NC. Being the high-quality firm in the market also has a positive significant effect on the models without interaction variables (A and C). While model

[33] Note that when price decisions are taken, quality decisions are already known. This alleviates concern with an endogeneity problem, although it may still exist.

Table 5
Prais–Winsten panel regressions of price choices clustered at the session level, semirobust standard errors in parentheses.

Regressors	Model A	Model B	Model C
Intercept	−3.121**	−3.173**	−3.395***
	(1.193)	(0.839)	(0.778)
Costly Quality	2.789***	2.724***	2.770***
	(0.370)	(0.308)	(0.285)
High-quality firm	0.275***	−0.118	0.114***
	(0.054)	(0.168)	(0.013)
$Quality_{i,t}$	0.571**	0.453*	0.637***
	(0.173)	(0.188)	(0.128)
$Quality_{j,t}$	0.029	0.149**	–
	(0.020)	(0.055)	–
$Quality_{i,t}$ ∗ *High-quality firm*	–	0.419**	–
	–	(0.122)	–
$Quality_{j,t}$ ∗ *High-quality firm*	–	−0.387*	–
	–	(0.159)	–
$Diff.Qualities_t$	–	–	0.188**
	–	–	(0.067)
R squared	0.745	0.778	0.777
Baltagi–Li joint test	663.50***	525.42***	537.38***
Breusch–Pagan	307.45***	196.75***	205.548***

Significance codes: $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.
Group variable: Subject id; Time variable: Round; Total number of observations: 1344.

A suggests that the price of a firm is increasing with its own quality, but is not sensitive to the quality of the rival, model B shows that, if we analyze separately the effects on the high-quality firm and the low-quality firm, prices are also sensitive to the rival's quality and that while the impact of the rival's quality is positive for the low-quality firm (0.149), it is negative for the high-quality firm (0.149–0.387). In this model, the dummy *High-quality firm* is not significant, but we observe that the positive impact of a firm's quality changes on its price is higher for the high-quality firm, which explains its higher prices. These results are all coherent with theoretical predictions and with H4. Moreover, the results in model C also show that prices are increasing with quality differentiation, which is aligned with previous experimental results on HPD. However, price choices also depend on the quality of the firm.

Result 4. *For given quality choices, prices are higher in QC than in NC and higher for the high-quality firm. In addition, prices increase with the firm's quality, increasing at a higher rate for the high-quality firm. Changes in the rival's quality have a negative impact on the high-quality price, but a positive impact on the low-quality price. Prices can also be explained by quality differentiation, with a positive relationship, but firm's quality still has a positive impact on prices.*

5.6. Intensity of price competition

In the previous section, we saw that the higher the quality differentiation, the higher the prices. This seems to confirm, for VPD, a result that has been obtained in the HPD case: more product differentiation leads to softer competition. However, as mentioned previously, with costly quality, the level of prices may not be the best measure of the intensity of competition. In this section, we test the behavior of price-cost margins in the second-stage game.

We estimate three models where the dependent variable is the price-cost margin of firm i in period t ($PC\ Margin_{i,t}$) and the independent variables are: the difference in qualities in the market firm i belongs to in that round ($Diff.\ Qualities_t$), a dummy variable indicating whether firm i is the high-quality firm in the market and taking value 1 when it is (*High-quality firm*), a treatment dummy variable taking value 1 in the costly quality case (*CostlyQuality*), the interaction between the present difference in qualities and the treatment dummy variable ($Diff.\ Qualities_t$*CostlyQuality), and the interaction between being the high-quality firm and the treatment (*High-quality firm**CostlyQuality*). The inclusion of this variable is justified by the fact that theory predicts that the effect of the treatment on the price-cost margins depends on the firm being the high or low-quality one. As in the previous estimations, we used Prais–Winsten panel regressions clustered at the session level, which are justified by the results of the Baltagi–Li joint test and the Breusch–Pagan test (see Table 6).

Table 6
Prais–Winsten panel regressions of price-cost margins clustered at the session level, semirobust standard errors in parentheses.

Regressors	Model A	Model B	Model C
Intercept	0.632***	0.594***	0.588***
	(0.041)	(0.038)	(0.038)
CostlyQuality	−0.337***	−0.236***	−0.215***
	(0.051)	(0.040)	(0.039)
$Diff.\ Qualities_t$	0.060*	0.177***	0.141***
	(0.026)	(0.018)	(0.007)
High-quality firm	0.106*	0.081**	0.182***
	(0.042)	(0.037)	(0.008)
$Diff.Qualities_t$ ∗ *CostlyQuality*	–	−0.169***	−0.126***
	–	(0.014)	(0.009)
High-quality firm ∗ *CostlyQuality*	–	–	−0.156***
	–	-	(0.027)
R squared	0.158	0.190	0.198
Baltagi–Li joint test	417.74***	342.92***	358.13***
Breusch–Pagan	315.14***	301.59***	284.35***

Significance codes: $^{*}p < 0.1$; $^{**}p < 0.05$; $^{***}p < 0.01$.
Group variable: Subject id; Time variable: Round; Total number of observations: 1344.

In our initial specification (Model A), we can observe that price-cost margins in a given round depend positively on quality differentiation in that round. Furthermore, price-cost margins are lower when quality is costly and higher when a firm is the high-quality firm in the market. In Model B, we add the interaction between product differentiation and the treatment and observe that it has a positive impact on price competition (it decreases price-cost margins). Finally, in Model C, we include the interaction between being the high-quality firm in the market and the treatment. In this line, results show there is a larger decrease in the margins in the QC treatment for the high-quality firm than for the low-quality firm (the expected margins decrease by 0.371 and 0.215, for the high-quality and low-quality firm, respectively). Coefficients show the same sign and a similar impact as in the previous specifications.

It should be highlighted that although the theoretical results predict that the price-cost margin of the low-quality firm can be lower or higher in the QC treatment (depending on the level of quality differentiation), the experimental results reveal that the price-cost margin of the low-quality firm is lower in the QC scenario. This result is because a higher margin in the QC treatment only occurs when quality differentiation is high. However, in the experiment the observed differentiation is lower than theoretically predicted, thus we are in a range where the price-cost margin of the low-quality firm is lower in the QC case.

Hence, we do not reject H5 accounting for differences in price competition depending on the cost structure.

Result 5. *The high-quality firm gets a higher price-cost margin than the low-quality firm. Both the high and the low-quality firms have lower price-cost margins in QC than in NC.*

5.7. Discussion of the results

Some of our results are common to other experimental studies dealing with product differentiation. The observed quality differentiation is lower than the theoretical prediction, a result that was also observed by Amaldoss and Shin (2011) in a sequential VPD experiment and by Barreda-Tarrazona et al. (2011) under HPD. Amaldoss and Shin (2011) argue that the followers are victims of the anchor effect. That is, they tend to anchor too much of their quality decisions on the leader's choice and not differentiate as much as they should. Barreda-Tarrazona et al. (2011) consider simultaneous location choices and thus have a setup that is closer to ours in terms of the timing of the game. With simultaneous first-stage choices, we believe that the coordination problem, which is present in the first-stage choices, can partially explain why the degree of differentiation that arises in the lab is below the theoretically predicted level. In our experiment, the coordination is particularly acute in the NC setting, as with no cost both firms try to be the high-quality one, leading to very low differentiation levels.

Regarding price choices, our results also corroborate previous experimental literature on product differentiation. We observe that prices are increasing with the level of product differentiation, a result also found by Barreda-Tarrazona et al. (2011) and Xefteris et al. (2023) under HPD. However, in a VPD setting quality differentiation is not enough to explain prices as the role of the firm (being the high-quality or the low-quality) is essential and the levels of qualities are also important when costs are quality dependent. When we explore in more detail the price choices, we conclude that it is important to consider whether the firm is the high-quality or the low-quality one, as the impact of changes in the firm's quality and in the rival's quality on the firm's price is significantly different for the two firms. For instance, the rival's quality has a negative impact on the high-quality price but a positive impact on the low-quality price. Not distinguishing these two impacts leads us to the wrong conclusion that prices are not sensitive to the rival's quality (a result also mentioned by Amaldoss & Shin, 2011 but which is likely to be due to the specification error).

In addition to strengthening previous experimental results, our experiment also has interesting novelties. First, we showed the importance of considering the endogeneity of the market structure. The cost structure influenced the market structure that was observed, as with no costs there was convergence to a duopoly with full market coverage, whereas with costly quality a duopoly with partial market coverage emerged. Second, when analyzing the price choices, we showed that in VPD experiments the role of the firm (high or low-quality) is important as firms are not in a symmetric position in the second-stage game. As expected, the high-quality firm chooses higher prices and reacts differently to quality changes. Third, we showed that prices and price-cost margins may move in opposite directions, in which case price-cost margins may be a better measure of the intensity of competition.

6. Conclusions

We consider a two-stage duopoly game where firms choose simultaneously the quality of their products and, after observing these choices, decide simultaneously on prices. This quality–price mix choice is new in the experimental VPD literature, given that most contributions typically focus on only one variable. Additionally, we explore whether the market is fully covered or not, which emerges endogenously as the outcome of the game, in a market where consumers are heterogeneous regarding quality valuation. Moreover, we consider two treatments with different costs of quality improvements, to analyze the impact of the cost structure on firms' quality–price decisions, market structure, product differentiation, and intensity of competition.

We find that quality differentiation is lower in the lab than the theory predicts, which is aligned with previous experimental results by Amaldoss and Shin (2011) and Barreda-Tarrazona et al. (2011). Product differentiation is lower when quality is costless than when it is costly. The discrepancy between the theoretical prediction and the experimental results suggests that subjects require time and market experience to understand the advantages of differentiating their products. For both cost structures, prices are increasing with the level of product differentiation (as in Barreda-Tarrazona et al., 2011; Xefteris et al., 2023) and are higher for the high-quality firm. Prices increase with the firm's quality and changes in the rival's quality impact negatively on the high-quality price, but positively on the low-quality price. Both high and low-quality firms have higher price-cost margins when quality is costless. Following the theoretical predictions, firms offer quality–price combinations such that all consumers are served (full coverage) with costless quality. However, some consumers are left out of the market (partial coverage) with costly quality. This difference across treatments confirms the theoretically predicted need to endogenize the market structure. Although our results are aligned with the existing experimental evidence, to the best of our knowledge, we are the first to explore the endogeneity of the market structure and the intensity of competition (measured by price-cost margins), which are key determinants in vertically differentiated markets.

In future works, it could be interesting to consider repeated interactions, which would allow firms to build a reputation of being the high and the low-quality firm in the market and may be more realistic in many contexts. Additionally, in line with the recent HPD literature (Barreda-Tarrazona et al., 2011; Camacho-Cuena et al., 2005), considering real consumers (instead of virtual consumers) could be another interesting avenue.

Data availability

Data will be made available on request.

Acknowledgments

We would like to thank the Editor, Douglas Davis, and two anonymous referees for very helpful comments and suggestions. The authors also thank Penélope Hernández and Javier Rodero Cosano, the LINEEX team, and the participants in the 14th Annual Meeting of the Portuguese Economic Journal 2021, EARIE 2021 Conference, 15th International Conference on Game Theory and Management 2021, IAREP-SABE 2021 Conference, Young Economists Meeting 2021, I Workshop de Jóvenes Investigadores del Dep. de Análisis Económico de la U. de Valencia 2021, II Workshop of Industrial Economics Research 2021, Seminário de Teoría a Historia Económica de la U. de Málaga (October 2020), Seminário Teoría e Prática da U. de Aveiro (April 2021, May 2022) and Católica Porto Business School Seminar (April 2022). This project was funded by the Portuguese National Foundation (FCT) under project PTDC/EGE-ECO/29332/2017, UIDB/00097/2020, UIDB/00731/2020, UIDB/04058/2020, and by the Spanish Ministry of Science and Innovation under project PID2021-128228NB-I00.

Appendix A. Proof of Proposition 1

In the tables of this proof, we present, in each cell, a decision/payoff pair where the first (resp. second) coordinate corresponds to firm 1 (resp. firm 2). As the game has different characteristics when $k_1 = k_2$ (homogeneous goods), we present the outcomes corresponding to these cases in gray in the tables.

Costless Quality (NC)

Using backward induction, we start by solving the second stage of the game, where, given the qualities, firms decide prices. More precisely, for each possible quality pair (k_1, k_2), we start by determining the individual profits for all possible price combinations (p_1, p_2), i.e., we build the corresponding payoff matrices (which we omit to save space but we can send upon request). Then, for each value of p_2, we find the value(s) for p_1 that gives firm 1 the highest profit, i.e., we find the best-reply of firm 1. We repeat the analysis (but fixing p_1) to find the best-reply of firm 2. Combining the best-reply of the two firms, we obtain, for each pair (k_1, k_2), the optimal prices. Table 7 presents, for given (k_1, k_2), the Pareto-dominant Nash equilibrium prices. Replacing the pairs of prices in Table 7 in the individual profit functions, we obtain the payoff matrices of the first stage of the game, which we present in Table 8.

To find the Nash equilibrium of the quality stage, we proceed as before: we find the best-reply of each firm and then combine the

Table 7
Pareto-dominant Nash equilibrium prices for given qualities (k_1, k_2), when quality is costless (NC).

k_2										
		2.5	3	3.5	4	4.5	5	5.5	6	6.5
	2.5	(0.5, 0.5)	(0.5, 0.5)	(0.5, 1)	(0.5, 1.5)	(0.5, 1.5)	(0.5, 2)	(0.5, 2.5)	(0.5, 2.5)	(0.5, 2.5)
	3		(0.5, 0.5)	(0.5, 0.5)	(0.5, 1)	(0.5, 1.5)	(0.5, 1.5)	(0.5, 2)	(0.5, 2.5)	(0.5, 2.5)
	3.5			(0.5, 0.5)	(0.5, 0.5)	(0.5, 1)	(0.5, 1.5)	(1, 2)	(0.5, 2)	(1, 2.5)
	4				(0.5, 0.5)	(0.5, 0.5)	(0.5, 1)	(0.5, 1.5)	(1, 2)	(0.5, 2)
k_1	4.5					(0.5, 0.5)	(0.5, 0.5)	(0.5, 1)	(0.5, 1.5)	(1, 2)
	5						(0.5, 0.5)	(0.5, 0.5)	(0.5, 1)	(0.5, 1.5)
	5.5							(0.5, 0.5)	(0.5, 0.5)	(0.5, 1)
	6								(0.5, 0.5)	(0.5, 0.5)
	6.5									(0.5, 0.5)

Table 8
First-stage payoff matrices when firms charge the Pareto-dominant Nash equilibrium prices in the second stage and quality is costless (NC).

k_2										
		2.5	3	3.5	4	4.5	5	5.5	6	6.5
	2.5	(2.5, 2.5)	(0, 5)	(1.25, 7.5)	(2, 9)	(1.25, 11.25)	(1.75, 13)	(2, 15)	(1.5, 17.5)	(1.25, 18.75)
	3		(2.5, 2.5)	(0, 5)	(1.25, 7.5)	(2, 9)	(1.25, 11.25)	(1.75, 13)	(2, 15)	(1.5, 17.5)
	3.5			(2.5, 2.5)	(0, 5)	(1.25, 7.5)	(2, 9)	(2.5, 15)	(1.75, 13)	**(2.5, 18.75)**
	4				(2.5, 2.5)	(0, 5)	(1.25, 7.5)	(2, 9)	(2.5, 15)	(1.75, 13)
k_1	4.5					(2.5, 2.5)	(0, 5)	(1.25, 7.5)	(2, 9)	(2.5, 15)
	5						(2.5, 2.5)	(0, 5)	(1.25, 7.5)	(2, 9)
	5.5							(2.5, 2.5)	(0, 5)	(1.25, 7.5)
	6								(2.5, 2.5)	(0, 5)
	6.5									(2.5, 2.5)

Table 9
Pareto-dominant Nash equilibrium prices for given qualities (k_1, k_2), when quality is costly (QC).

k_2										
		2.5	3	3.5	4	4.5	5	5.5	6	6.5
	2.5	(1, 1)	(1, 1.5)	(1, 1.5)	(1, 2)	(1, 3)	(1.5, 3.5)	(1.5, 4)	(1.5, 4.5)	(1.5, 4.5)
	3		(1, 1)	(1, 1.5)	(1, 2)	(1, 2.5)	(1.5, 3.5)	(1.5, 4)	(1.5, 4.5)	(1.5, 4.5)
	3.5			(1.5, 1.5)	(1.5, 2)	(1.5, 2.5)	(1.5, 3)	(2, 4)	(2, 4.5)	(2, 4.5)
	4				(2, 2)	(2, 2.5)	(2, 3)	(2, 3.5)	(2.5, 4.5)	(2, 4.5)
k_1	4.5					(2.5, 2.5)	(2.5, 3)	(2.5, 3.5)	(2.5, 4)	(2.5, 4.5)
	5						(2.5, 2.5)	(3, 3.5)	(3, 4)	(3, 4.5)
	5.5							(3.5, 3.5)	(3.5, 4)	(3.5, 4.5)
	6								(4, 4)	(4, 4.5)
	6.5									(4.5, 4.5)

best-reply of the two firms to find the Nash equilibrium of the stage game. Once more, we apply a Pareto-dominant refinement to reduce the number of equilibria. By doing do, we obtain one equilibrium, $(k_1^{NC}, k_2^{NC}) = (3.5, 6.5)$, presented in bold in Table 8. From Table 7, it follows that the corresponding prices are $(p_1^{NC}, p_2^{NC}) = (1, 2.5)$. In this scenario, price-cost margins coincide with prices (as there are no production costs), $\mu_i^{NC} = p_i^{NC}$. To find the number of consumers firm i supplies in equilibrium, q_i^{NC}, we determine, for each consumer θ_j, for $j \in \mathcal{J}$, whether he/she gets a positive utility with any of the firms and, in case of both firms providing him/her a positive utility, compare the utilities. Then, q_i^{NC} corresponds to the number of consumers served by firm i. Finally, $\pi_i^{NC} = \mu_i^{NC} q_i^{NC} = p_i^{NC} q_i^{NC}$.

Costly Quality (QC)

To find the equilibrium of the game in this scenario, we proceed as before and obtain Tables 9 and 11. In the NC case, for given qualities, the (Nash) equilibrium price-cost margins coincide with the equilibrium prices. As this is no longer the case in the QC case, we present, in Table 10, the price-cost margins for this case if, for given qualities, firms set the Nash equilibrium prices presented in Table 9.

In this case, we obtain two equilibria, $(k_1^{QC}, k_2^{QC}) = (3, 5)$ and $(k_1^{QC}, k_2^{QC}) = (3.5, 5.5)$, presented in bold in Table 11. From Table 9, it follows that the corresponding prices are $(p_1^{QC}, p_2^{QC}) = (1.5, 3.5)$ and $(p_1^{QC}, p_2^{QC}) = (2, 4)$, respectively. In this case, the price-cost margins are $\mu_i^{QC} = p_i^{QC} - 0.1\left(k_i^{QC}\right)^2$. To obtain the number of consumers supplied by each firm in equilibrium, q_i^{QC}, we proceed as in the NC case. Finally, $\pi_i^{QC} = \mu_i^{QC} q_i^{NC}$.

Appendix B. Instructions

In this Appendix, we provide the instructions for the QC [NC] treatment that were distributed to subjects at the beginning of the experiment.

The Experiment

During this experiment, you will be a **SELLER** in a market with **2** sellers and **10** consumers. **All** participants in the room are **SELLERS**. **Consumers** are virtual.

As a seller, you will produce a good for which you will have to choose the quality and the price. In each period, you will be randomly paired with another person in this room.

Consumers differ in how much they value quality. The utility function of a consumer is:

$U = \theta_i k - p$

where:

- k is the quality of the product the consumer buys,

Table 10
Pareto-dominant Nash equilibrium price-cost margins for given qualities (k_1, k_2), when quality is costly (QC).

	k_2									
		2.5	3	3.5	4	4.5	5	5.5	6	6.5
	2.5	(0.375, 0.375)	(0.375, 0.875)	(0.375, 0.875)	(0.375, 1.375)	(0.375, 2.375)	(0.875, 2.875)	(0.875, 3.375)	(0.875, 3.875)	(0.875, 3.875)
	3		(0.1, 0.1)	(0.1, 0.6)	0.1, 1.1)	(0.1, 1.6)	(0.6, 2.6)	(0.6, 3.1)	(0.6, 3.6)	(0.6, 3.6)
	3.5			(0.275, 0.275)	(0.275, 0.775)	(0.275, 1.275)	(0.275, 1.775)	(0.775, 2.775)	(0.775, 3.275)	(0.775, 3.275)
	4				(0.4, 0.4)	(0.4, 0.9)	(0.4, 1.4)	(0.4, 1.9)	(0.4, 2.9)	(0.4, 2.9)
k_1	4.5					(0.475, 0.475)	(0.475, 0.975)	(0.475, 1.475)	(0.475, 1.975)	(0.475, 2.475)
	5						(0, 0)	(0.5, 1)	(0.5, 1.5)	(0.5, 2)
	5.5							(0.475, 0.475)	(0.475, 0.975)	(0.475, 1.475)
	6								(0.4, 0.4)	(0.4, 0.9)
	6.5									(0.275, 0.275)

Table 11
First-stage payoff matrices when firms charge the Pareto-dominant Nash equilibrium prices in the second stage and quality is costly (QC).

	k_2									
		2.5	3	3.5	4	4.5	5	5.5	6	6.5
	2.5	(1.5, 1.5)	(2.0625, 1.5)	(0.1875, 2.0625)	(0.75, 2.4)	(2.0625, 2.4375)	(2.1875, 4.5)	(2.625, 3.9)	(2.625, 3.6)	(1.75, 1.375)
	3		(0.45, 0.45)	(0.65, 0.6875)	(0.65, 1)	(0.65, 1.1875)	**(2.7, 2.5)**	(2.7, 2.4375)	(2.7, 2.25)	(1.8, 1.1)
	3.5			(1.1, 1.1)	(1.5125, 1)	(1.5125, 1.1875)	(1.5125, 1.25)	**(3.4875, 2.4375)**	(3.4875, 2.25)	(2.325, 1.1)
	4				(1.4, 1.4)	(1.8, 1.1875)	(1.8, 1.25)	(1.8, 1.1875)	(3.15, 2.25)	(1.8, 0.6875)
k_1	4.5					(1.6625, 1.6625)	(2.1375, 1.25)	(2.1375, 1.1875)	(2.1375, 1)	(2.1375, 0.6875)
	5						(0, 0)	(2.25, 1.1875)	(2.25, 1)	(2.25, 0.6875)
	5.5							(1.425, 1.425)	(1.6625, 1)	(1.6625, 0.6875)
	6								(1.2, 1.2)	(1.4, 0.6875)
	6.5									(0.825, 0.825)

- p is the price of the product the consumer buys,
- θ_i is a measure of how much a consumer values the quality of the product he/she is buying.

The measure of how much consumers value quality, θ_i, is uniformly distributed between 0.3 and 1.2. That means that consumers will have the following utility functions:

Consumer	Utility function
Consumer 1	$U = \mathbf{0.3}k - p$
Consumer 2	$U = \mathbf{0.4}k - p$
Consumer 3	$U = \mathbf{0.5}k - p$
Consumer 4	$U = \mathbf{0.6}k - p$
Consumer 5	$U = \mathbf{0.7}k - p$
Consumer 6	$U = \mathbf{0.8}k - p$
Consumer 7	$U = \mathbf{0.9}k - p$
Consumer 8	$U = \mathbf{1.0}k - p$
Consumer 9	$U = \mathbf{1.1}k - p$
Consumer 10	$U = \mathbf{1.2}k - p$

How do consumers buy?

- Each consumer will buy from the seller that provides him/her a **greater utility**.
- If both sellers provide a **negative utility** to a given consumer, that consumer will not buy and will have a utility of $U = 0$.
- If both sellers provide the **same utility** to a given consumer, that consumer will buy from each seller with a probability of 50%.

As a seller, you will have to **choose the quality and the price of your product.** In each period, your payoff (in points) is given by the following profit function:

$$\pi = pq - 0.1k^2q$$

$[NC : \pi = pq]$

where:

- p is the price of your product,
- q is the number of consumers you sell to (from a maximum of 10),
- k is the quality of your product. [*Not present in NC*]

Therefore, your revenues depend on the price you set, p, and the number of consumers you sell to, q. Your **costs** depend on the quality of your product, k, and the number of consumers you sell to, q. [*NC: Therefore, your earnings depend on the price you set, p, and the number of consumers you sell to, q.*]

In each period, you will make the decisions in two stages:

Stage 1 - Quality choice

Both sellers in the market simultaneously choose the quality of their product. The quality must be between 2.5 and 6.5. You will have to choose an option from the following possibilities:

2.5 3 3.5 4 4.5 5 5.5 6 6.5

Stage 2 - Price choice

Both sellers observe the two chosen qualities and simultaneously decide the price of their product. The price must be between 0.5 and 4.5. You will have to choose an option from the following possibilities:

0.5 1 1.5 2 2.5 3 3.5 4 4.5

After these decisions are made, each consumer will automatically buy from the seller that produces the product that provides him/her a greater utility. If both sellers provide a negative utility to a given consumer, that consumer does not buy to any of the sellers.

If both sellers choose the **same quality level,** consumers will buy from the seller that sets a lower price. If both sellers choose the same quality level and set equal prices, sellers will divide the market into equal parts.

At the end of each period, you will observe:

- the qualities and prices of the two sellers,
- the number of consumers that each seller sells to,
- your earnings in that period,
- your earnings up until that period.

Payment

You will participate in **15 periods** as the one described.

In each period, you will be randomly paired with an anonymous participant from this room and you will have to make the decisions of quality and price choice. At the end of the 15 periods, you will receive a **(fixed) amount for your participation in this experiment of 5€,** increased by your **accumulated earnings** during this experiment.

Your points will be converted into Euros according to the following ratio:

1 point = 0,50€

[*NC: 1 point =0,07€*]

If at the end of the 15 periods you have negative accumulated earnings, you will have to perform some tasks to recoup your losses. These tasks will be distributed on paper at the end of the session. [*Not present in NC*]

Quiz and Trial Rounds [*NC: Trial Rounds*]

Before the experiment begins, you will have a quiz to ensure that you understand how the market works. [*Not present in NC*]

Afterward, you will have 5 trial rounds to get familiar with the market. These periods will **not** count for your final payoff. [*NC: Before the experiment begins, you will have 5 trial rounds to get familiar with the market. These periods will **not** count for your final payoff.*]

Illustrative Example

Let us see an example of how consumers choose which seller to buy from.

During the experiment, in each period, each seller will have to choose a quality between 2.5 and 6.5 and a price between 0.5 and 4.5.

For this example, we are going to consider that in each period, each seller has to choose a quality between 30 and 35 and a price between 15 and 25.

Suppose that Seller 1 chooses quality of 30 and Seller 2 chooses quality of 35.

Seller	Quality
Seller 1	30
Seller 2	35

In this case, as Seller 2 offers a product of higher quality, it has a greater ability to attract consumers (because consumers prefer products of greater quality).

However, the number of consumers that each seller sells to also depends on the price they will fix.

Suppose that Seller 1 chooses a price of 16 and Seller 2 chooses a price of 21.

Seller	Quality	Price
Seller 1	30	16
Seller 2	35	21

In this case, as Seller 1 fixed a lower price, it has a greater possibility of attracting consumers (because consumers prefer paying a lower price for the product).

Let us now see how many consumers does each seller sell to:

Starting with **Consumer 1** ($U = 0.3k - p$):

- If Consumer 1 buys from **Seller 1**, it will obtain a utility of:

$U = 0.3 \times (30) - (16) = -7$

- If Consumer 1 buys from **Seller 2**, it will obtain a utility of:

$U = 0.3 \times (35) - (21) = -10.5$

Therefore, Consumer 1 does **not buy** from any seller (as he/she will obtain a negative utility).

Repeating this exercise for **Consumer 4** ($U = 0.6k - p$):

- If Consumer 4 buys from **Seller 1**, it will obtain a utility of:

$U = 0.6 \times (30) - (16) = 2$

- If Consumer 4 buys from **Seller 2**, it will obtain a utility of:

$U = 0.6 \times (35) - (21) = 0$

Therefore, Consumer 4 **buys from Seller 1** (as it is the one that sells him/her the product that provides him/her a greater utility.

Repeating this exercise for **Consumer 8** ($U = 1.0k - p$):

- If Consumer 8 buys from **Seller 1**, it will obtain a utility of:

$U = 1.0 \times (30) - (16) = 14$

- If Consumer 8 buys from **Seller 2**, it will obtain a utility of:

$U = 1.0 \times (35) - (21) = 14$

Therefore, Consumer 8 **buys from Seller 1 or Seller 2** with a probability of 50%.

We could repeat this exercise for each of the 10 consumers and we would obtain the results of the following table:

Consumers	Utility of buying from Seller 1	Utility of buying from Seller 2	Who will he/she buy from?
1	−7	−10.5	Nobody
2	−4	-7	Nobody
3	−1	−3.5	Nobody
4	**2**	0	**1**
5	**5**	3.5	**1**
6	**8**	7	**1**
7	**11**	10.5	**1**
8	**14**	**14**	**1 or 2**
9	17	**17.5**	**2**
10	20	**21**	**2**

Concluding, Seller 1 will sell to 4 or 5 consumers and Seller 2 will sell to 2 or 3 consumers. There are 3 consumers that do not buy from any seller.

References

Alventosa, A., Pinho, J., Jorge, S. F., & Catalão-Lopes, M. (2023). Vertical product differentiation in the lab: Impact of consumers' preferences. *Applied Economics Letters*, Forthcoming.

Amaldoss, W., & Shin, W. (2011). Competing for low-end markets. *Marketing Science*, *30*(5), 776–788.

Aoki, R., & Prusa, T. J. (1996). Product development and the timing of information disclosure under us and japanese patent systems. *Journal of the Japanese and International Economies*, *10*(3), 233–249.

Barreda-Tarrazona, I., García-Gallego, A., Georgantzís, N., Andaluz-Funcia, J., & Gil-Sanz, A. (2011). An experiment on spatial competition with endogenous pricing. *International Journal of Industrial Organization*, *29*(1), 74–83.

Benassi, C., Chirco, A., & Colombo, C. (2006). Vertical differentiation and the distribution of income. *Bulletin of Economic Research*, *58*(4), 345–367.

Brown-Kruse, J. B., Cronshaw, M. B., & Schenk, D. J. (1993). Theory and experiments on spatial competition. *Economic Inquiry*, *31*(1), 139–165.

Brown-Kruse, J. B., & Schenk, D. J. (2000). Location, cooperation and communication: An experimental examination. *International Journal of Industrial Organization*, *18*(1), 59–80.

Burgmeier, K. (2012). Multiplayer coordination and competition in a vertically differentiated market. *The Journal of Behavioral Finance & Economics*, *2*(1), 97–121.

Camacho-Cuena, E., García-Gallego, A., Georgantzís, N., & Sabater-Grande, G. (2005). Buyer-seller interaction in experimental spatial markets. *Regional Science and Urban Economics*, *35*(1), 89–108.

Chen, D. L., Schonger, M., & Wickens, C. (2016). oTree - an open-source platform for laboratory, online, and field experiments. *Journal of Behavioral and Experimental Finance*, *9*, 88–97.

Choi, C. J., & Shin, H. S. (1992). A comment on a model of vertical product differentiation. *The Journal of Industrial Economics*, *40*(2), 229–231.

Collins, R., & Sherstyuk, K. (2000). Spatial competition with three firms: An experimental study. *Economic Inquiry*, *38*, 73–94.

Cooper, R., DeJong, D. V., Forsythe, R., & Ross, T. W. (1989). Communication in the battle of the sexes game: Some experimental results. *Rand Journal of Economics*, 568–587.

Crampes, C., & Hollander, A. (1995). Duopoly and quality standards. *European Economic Review*, *39*(1), 71–82.

Devetag, G., & Ortmann, A. (2007). When and why? a critical survey on coordination failure in the laboratory. *Experimental Economics*, *10*, 331–344.

Gabszewicz, J. J., & Thisse, J.-F. (1979). Price competition, quality and income disparities. *Journal of Economic Theory*, *20*(3), 340–359.

García-Gallego, A., & Georgantzís, N. (2009). Market effects of changes in consumers' social responsibility. *Journal of Economics & Management Strategy*, *18*(1), 235–262.

Holt, C., & Sherman, R. (1990). Advertising and product quality in posted offer experiments. *Economic Inquiry*, *28*(1), 39–56.

Hotelling, H. (1929). Stability in competition. *The Economic Journal*, *39*(153), 41–57.

Huck, S., Müller, W., & Vriend, N. (2002). The east end, the west end, and king's cross: On clustering in the four-player hotelling game. *Economic Inquiry*, *40*(2), 231–240.

Jorge, S. F., Pires, C. P., Catalão-Lopes, M., Carrilho-Nunes, I., & Alventosa, A. (2022). *Vertical product differentiation: Organizing and interpreting the existing results* (1st ed.). UA Editora.

Lambertini, L. (1996). Choosing roles in a duopoly for endogenously differentiated products. *Australian Economic Papers*, *35*, 205–224.

Lambertini, L. (1999). Endogenous timing and the choice of quality in a vertically differentiated duopoly. *Research in Economics*, *53*(1), 101–109.

Lambertini, L., & Tampieri, A. (2012). Low-quality leadership in a vertically differentiated duopoly with cournot competition. *Economic Letters*, *115*, 396–398.

Liao, P. C. (2008). A note on market coverage in vertical differentiation models with fixed costs. *Bulletin of Economic Research*, *60*(1), 27–44.

Luini, L., & Mangani, A. (2000). *Vertical Product Differentiation and Adverse Selection: An experimental note*. University of Siena, Department of Economics, Working Paper 305.

Lynch, M., Miller, R. M., Plott, C. R., & Porter, R. (1984). *Product Quality, Informational Efficiency, and Regulations in Experimental Markets*. Working Papers from the California Institute of Technology, Division of the Humanities and Social Sciences 518.

Mangani, A. (2002). *Does product differentiation relax price competition? An experimental answer*. University of Siena, Department of Economics, Working Paper 350.

Motta, M. (1993). Endogenous quality choice: price vs. quantity competition. *The Journal of Industrial Economics*, 113–131.

Mussa, M., & Rosen, S. (1978). Monopoly and product quality. *Journal of Economic Theory*, *18*(2), 301–317.

Niem, L. D. (2019). A note on the low-quality advantage in vertical product differentiation. *Managerial and Decision Economics*, *40*(2), 176–179.

Orzen, H., & Sefton, M. (2008). An experiment on spatial price competition. *International Journal of Industrial Organization*, *26*(3), 716–729.

Pires, C., Jorge, S., Catalão-Lopes, M., Pinho, J., Garcês, P. M., & Alventosa, A. (2022). *Endogenous market coverage with quality dependent unit production costs*. SSRN Working Paper id4232594.

Rode, J., Hogarth, R. M., & Le Menestrel, M. (2008). Ethical differentiation and market behavior: an experimental approach. *Journal of Economic Behavior & Organization*, *66*(2), 265–280.

Schmidt, R. C. (2006). On the robustness of the high-quality advantage under vertical differentiation. *Journal of Industry, Competition and Trade*, *6*(3–4), 183–193.

Schubert, S. (2017). The low-quality advantage in vertical product differentiation. *Managerial and Decision Economics*, *38*(7), 923–928.

Selten, R., & Apesteguia, J. (2005). Experimentally observed imitation and cooperation in price competition on the circle. *Games and Economic Behavior*, *51*(1), 171–192.

Shaked, A., & Sutton, J. (1982). Relaxing price competition through product differentiation. *Review of Economic Studies*, *49*(1), 3–13.

Tirole, Jean (1988). *The theory of industrial organization*. Cambridge, MA: MIT Press.

Vasileiou, E., & Georgantzís, N. (2015). An experiment on energy-saving competition with socially responsible consumers: Opening the black box. *Journal of Behavioral and Experimental Economics*, *58*, 1–10.

Wauthy, X. (1996). Quality choice in models of vertical differentiation. *The Journal of Industrial Economics*, *34*, 5–353.

Xefteris, D., Barreda-Tarrazona, I., García-Gallego, A., & Georgantzís, N. (2023). Catalog competition: Theory and experimental evidence. *Economic Inquiry*, *61*(1), 122–137.