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Catalog competition: Theory and experimental evidence

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Abstract

This paper compares the standard location-then-pricing Hotelling duopoly with a catalog competition game in which firms simultaneously decide locations and prices. We consider a three-location space and continuous pricing and fully characterize the unique symmetric equilibrium. In both games, firms employ mixed strategies, producing a mainstream product more often than a specialized one. In the catalog game, prices are always above the marginal cost of production, whereas in the sequential model, prices converge to the marginal cost when firms produce the same variety. We experimentally test our theoretical predictions in the laboratory, finding strong evidence in favor of most of them.

KEYWORDS
catalog competition, duopoly, experiments, Hotelling, mixed strategy equilibrium, risk aversion

JEL CLASSIFICATION
C72, C92, D43, D90

Abbreviations: CARA, Constant Absolute Risk Aversion; ECUs, Experimental Currency Units; OLS, Ordinary Least Squares; SEQ, sequential; SIM, simultaneous.

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1 | INTRODUCTION

Hotelling's (1929) location–price game is the cornerstone of the literature on product differentiation. In this seminal model, the product characteristics space is represented on a linear city, along which consumers' residences are uniformly distributed. Two competitors choose their locations on the line and then set prices. After locations and prices are chosen by the firms, each consumer buys a unit of the product, choosing which shop to buy from considering the distance from each seller and the price charged by each one of them. The aforementioned timing of location choices before prices fits certain cases of competition, but it is certainly not relevant for many others. It is not uncommon for firms to be informed about the characteristics of their competitors' products only after these products are introduced in the market—thus, after the competitor's price is set. Consider, for example, technology firms that present their new products in a certain exhibition, or two neighboring pastry shops in London that are specialized in avant-garde Christmas puddings. They announce product characteristics and prices at the same time. Hence, Hotelling's (1929) timing assumptions are not necessarily a good fit to some cases of competition through product and price choice.

Indeed, the idea that the simultaneous choice of product characteristics and prices might better describe certain frameworks of real-world competition has been discussed in the literature for a long time.[1] Following Monteiro and Page (2008) and Fleckinger and Lafay (2010) we use the term catalog competition to distinguish this game from the standard Hotelling model. Such a catalog game can easily be shown to admit no equilibria in pure strategies. Dasgupta and Maskin (1986) were the first to provide formal conditions that ensure that this catalog game has an equilibrium in mixed strategies (Remark 2, page 34). Moreover, Monteiro and Page (2008) proved that a large family of catalog games admits equilibria in mixed strategies and characterized a family of such games.

Despite these early results, little is known regarding the nature of equilibria of catalog competition games. This is because characterizing a mixed strategy equilibrium in a catalog game is not a straightforward task: a mixed strategy in this framework involves a probability distribution with a multidimensional support. That is, unlike the price subgames of the two-stage Hotelling game (Osborne & Pitchik, 1987) and other well-known games with mixed strategy equilibria[2] whose underlying probability distributions have unidimensional support, the equilibrium of a catalog game involves mixed strategies with two-dimensional support. This implies a severe complication that renders any general characterization intractable.

This paper sheds light on the nature of equilibria of catalog games by considering a variation with a minimal number of locations and a continuous pricing space.[3] Specifically, rather than assuming that firms locate along a continuous unit interval, we focus on a case in which firms may locate on the Western, the Central, or the Eastern districts of the linear city. Although the set of locations in our setup is finite, the set of available prices is not. Therefore, the strategy space of each firm is infinite. This, along with the fact that the game is not a constant-sum game and that firms' payoff functions exhibit discontinuities, implies that the existence of a unique symmetric equilibrium and, thereafter, the possibility of full characterization are not guaranteed by any known theorem.

In this paper, we fully characterize a symmetric equilibrium of the catalog competition game and prove that it is unique. In an extension that relaxes the assumption of risk neutrality, we also characterize the mixed equilibrium assuming a common risk attitude parameter for both firms.[4] The qualitative characteristics of the equilibrium are robust to variations in the risk attitudes. Central locations are more likely to be chosen and prices of mainstream (central) varieties are expected to be lower than specialized (peripheral) ones.

The equilibrium of the catalog competition presents some salient differences with the unique symmetric equilibrium of the standard Hotelling model. First, in the catalog game, prices are always substantially larger than the marginal cost, while the location-then-pricing model leads to prices that converge to the marginal cost when firms produce the same variety. Moreover, in the sequential location-then-price model, competition intensity depends on first-stage location choices, leading to much more extreme prices than the catalog model.

The fact that a switch in the timing assumptions of such a popular model leads to important differences in the formal results begs the question of whether these predictions are pertinent to settings of applied interest. Based on a between-subject two-treatment design, we experimentally compare simultaneous location and pricing choices to those obtained under the standard location-then-pricing game.[5] Overall, our results confirm the main theoretical findings. In particular, central locations are more often observed than extreme ones and prices are higher in the extremes than in the center in both treatments. Importantly, prices in the catalog competition treatment are systematically higher than the marginal cost, and vary much less than in the first-location-then-pricing treatment, exactly as predicted by our formal analysis. Finally risk aversion is found to have the predicted negative effect on prices, but a weaker than predicted effect on location choices.

The remainder of the article is organized as follows: We present the theoretical model in Section 2 and its formal results in Section 3. Also in Section 3, we briefly present an equilibrium of the standard first-location-then-pricing game for comparative purposes. The experimental design and results are detailed in Section 4 and in section 5, we provide some concluding observations. The Online Appendix contains technical details of the theoretical and the empirical analysis.

2 | THE MODEL

We analyze a model in which two firms simultaneously decide a product characteristic (also referred to as location, l_i) and a price (p_i). Formally, each firm $i \in \{A, B\}$ chooses a catalog $c_i = (l_i, p_i) \in \{W, C, E\} \times [0, 1]$ where $\{W, C, E\} \subset \mathbb{R}$ is our discrete linear city (see Figure 1, W stands for the Western district, C stands for the Central district and E for the Eastern district). For analytical tractability, we assume that $W = -E$, $C = 0$ and $E > 1$.

We also assume that there is a unit mass of consumers whose residences are uniformly distributed along the linear city. Formally, we consider that a consumer $j \in [0, 1]$ resides at $h(j) \in \{W, C, E\}$ and, without loss of generality, that $h(j) \leq h(j')$ for every $j < j'$. Each consumer buys exactly one unit of good from one of the two firms. Considering that the utility of a consumer $j \in [0, 1]$ with a residence at $h(j) \in \{W, C, E\}$ from a certain catalog $c = (l, p)$ is given by

$$U_j(c) = -p - |l - h(j)|$$

we assume that the consumer buys the unit of good from firm A if $U_j(c_A) > U_j(c_B)$, from firm B if $U_j(c_A) < U_j(c_B)$, and with probability $\frac{1}{2}$ from each of the two firms if $U_j(c_A) = U_j(c_B)$. We moreover define the sets of consumers who strictly prefer each of the two catalogs as

$$I_A(c_A, c_B) = \left\{ j \in [0,1] | U_j(c_A) > U_j(c_B) \right\}$$

$$I_B(c_A, c_B) = \left\{ j \in [0,1] | U_j(c_A) < U_j(c_B) \right\}.$$

Then, the profits of the two firms as functions of their catalogs are given by

$$\Pi_A(c_A, c_B) = p_A \times \left[\mu(I_A(c_A, c_B)) + \frac{1 - \mu(I_A(c_A, c_B)) - \mu(I_B(c_A, c_B))}{2} \right]$$

$$\Pi_B(c_A, c_B) = p_B \times \left[\mu(I_B(c_A, c_B)) + \frac{1 - \mu(I_A(c_A, c_B)) - \mu(I_B(c_A, c_B))}{2} \right]$$

where $\mu(S)$ is the Lebesgue measure of the set $S \subset \mathbb{R}$. Hence, like Osborne and Pitchik's (1987) model and other relevant models, we assume zero marginal costs of production.

We consider that firms are risk-neutral, that is, that each $i \in \{A, B\}$ maximizes the expected value of $\Pi_i(c_A, c_B)$.[6] A mixed strategy profile in this setup is denoted by (σ_A, σ_B) where for each $i \in \{A, B\}$, $\sigma_i = \left(F_i^W(p), F_i^C(p), F_i^E(p)\right)$. For each $i \in \{A, B\}$ and each $l \in \{W, C, E\}$, $F_i^l(p)$ is the probability that the catalog $c_i = (l_i, p_i)$ of firm $i \in \{A, B\}$ is such that $l_i = l$ and $p_i \leq p$. A Nash equilibrium in mixed strategies is a mixed strategy profile $(\widehat{\sigma}_A, \widehat{\sigma}_B)$ such that $\widehat{\sigma}_B$ ($\widehat{\sigma}_A$) is a best response of firm B (A) to firm A (B) playing $\widehat{\sigma}_A$ ($\widehat{\sigma}_B$).

Before we advance to the characterization results, some comments regarding our assumptions are in order. The combined existence of a price cap equal to one along with the assumption $E > 1$ mitigates the intensity of competition between two firms that locate in different districts, but does not eliminate it altogether.[7] These assumptions enable crisper statements and conclusions, while still capturing the essential feature of a general catalog competition game: the presence of incentives to compete both in product characteristics and prices.[8] This is evident in the fact that local monopolies never emerge in equilibrium.

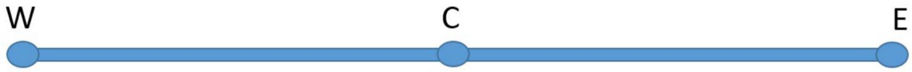

FIGURE 1 Linear city with three locations (West, Center, East)

3 | THEORETICAL RESULTS

3.1 | Simultaneous location-pricing game

The game does not admit any pure strategy equilibrium. If an equilibrium existed in which both firms charged the same positive price, then this should be a minimum differentiation equilibrium, since in all other cases firms would have incentives to approach each other and marginally undercut the price. However, if firms charge the same price in a minimum differentiation equilibrium, then each firm has an incentive to marginally undercut the other and double its profit. If firms charge different prices in equilibrium, then the low-price firm has incentives to locate at the same location as the high-price firm and take all the market, and the high-price firm has incentives to go far away from the low-price firm. Finally, it cannot be the case that both firms choose in equilibrium prices equal to zero. In such a case, one of the firms could get positive profits by moving away from the other firm and charging a positive price.

We first present a few useful definitions.

Definition 1. We say that $(\widehat{\sigma}_A, \widehat{\sigma}_B)$ is a symmetric equilibrium if (i) $\widehat{\sigma}_A = \widehat{\sigma}_B$ and (ii) $\widehat{F}_A^W(p) = \widehat{F}_A^E(p)$ for every $p \in [0, 1]$.

Symmetry in our analysis means both that the two firms employ the same strategy and that each firm uses a mixed strategy that is symmetric about the center of the linear city. This notion of symmetry is used in unidimensional spatial models with mixed equilibria (see, e.g., Aragonès & Palfrey, 2002).

Definition 2. Consider that $(\widehat{\sigma}_A, \widehat{\sigma}_B)$ is a symmetric equilibrium. Then, $q = \widehat{F}_A^W(1)$, $G(p) = \frac{\widehat{F}_A^W(p)}{\widehat{F}_A^W(1)}$ and $Z(p) = \frac{\widehat{F}_A^C(p)}{\widehat{F}_A^C(1)}$.

A mixed strategy $\sigma_i = \left(F_i^W(p), F_i^C(p), F_i^E(p)\right)$ in our setup is bidimensional. The above definition simply defines the conditional probability distributions that will help us present our results in a more intuitive manner. First, q is the probability that a firm locates at the Western (Eastern) district; $1 - 2q$ is the probability that a firm locates at the central district. Then, $G(p)$ is the probability distribution of the price of a firm conditional on it locating in the Western (Eastern) district. Finally, $Z(p)$ is the probability distribution of the price of a firm conditional on that this firm locates in the central district.

We can now state our main finding.[9]

Proposition 1. *There exists a unique symmetric equilibrium* $(\widehat{\sigma}_A, \widehat{\sigma}_B)$ *which is such that*

$$\widehat{F}_A^W(p) = \begin{cases} 0 & \text{if } p \in \left[0, \frac{1}{2}\right) \\ \frac{2}{5} - \frac{1}{5p} & \text{if } p \in \left[\frac{1}{2}, 1\right] \end{cases}$$

and

$$\widehat{F}_A^C(p) = \begin{cases} 0 & \text{if } p \in \left[0, \frac{4}{13}\right) \\ \frac{13}{15} - \frac{4}{15p} & \text{if } p \in \left[\frac{4}{13}, 1\right] \end{cases}.$$

Notice that in this unique symmetric equilibrium we have $q = \frac{1}{5}$ and, hence, it is more likely that a firm locates on the center than in the periphery. Moreover, since $\frac{1}{2} > \frac{4}{13} > 0$ and $G(p)$ stochastically dominates $Z(p)$ (see also Figure A.2 in the Appendix), we find that the prices of all product varieties are always substantially higher than marginal costs, and that "specialized" products (i.e., of varieties E and W) are, on average, more expensive than "mainstream" ones (i.e., of variety C).[10]

The simultaneity of location and price decisions is the main driving force behind the fact that prices are always substantially larger than the marginal cost. If an equilibrium mixed strategy contained in its support location-price combinations with a price equal to zero, it would yield zero expected profits to the firm that employed it. Then, this firm could deviate to a price equal to one and a uniform mixture among all locations, and would ensure a strictly positive expected profit; which contradicts the fact that the former strategy could be part of an equilibrium. As we will see in the next section where we formally solve a location-then-price version of the game, this is not true when location and price decisions are sequential. Under these more traditional timing assumptions, there are equilibria such that firms locate at the same point with a positive probability, and thus, end up charging a price equal to the marginal cost of production.

3.2 | Sequential location-then-pricing game

To properly assess the effect of alternative timing assumptions on outcomes, we also characterize an equilibrium for the sequential location-then-pricing game. In the catalog competition game studied above, it made sense to condition pricing strategies on own location choices. In the sequential version of the game, one should study pricing strategies conditional on the realized pairs of locations that were decided in the first stage. We first classify such location pairs according to their degree of competitiveness. First, fierce competition can be triggered if firms are located at the same point. Second, if firms locate on the two opposite extremes of the line, each firm serves for sure the population located at her position and competes for the central market share. Finally, if a firm is located, say, on W and its rival in the center, C, the latter serves the population at C and E, while the former serves the population located at her position, W, without particular tensions. That is, if firms locate: a) at the same position, there is *maximum competitiveness* in the pricing game; b) at different extremes, there is *intermediate competitiveness*; c) asymmetrically—one at C and the other either at W or at E— then there is *minimum competitiveness*.[11]

Similar to Bester et al. (1996), we consider that there is no coordination device in the location selection stage, and hence we look for equilibria such that players mix symmetrically among the available locations. This allows us to produce a prediction that would be comparable to the equilibrium of the catalog competition game.

Proposition 2. *In the location-then-price version of the game, there exists a unique symmetric subgame perfect equilibrium which is such that (i) in the location stage, each firm locates to the western (eastern) district with a probability equal to* $\phi = \frac{1}{5}$ *and to the central district with probability* $1 - 2\phi = \frac{3}{5}$ *and (ii) if firms locate at the same district (maximum competitiveness), they both set prices equal to zero; if one firm locates at the western district and one at the eastern district (intermediate competitiveness), then each draws its price from* $\Psi(p) = \frac{2p-1}{p}$ *for* $p \in \left[\frac{1}{2}, 1\right]$*, and if firms locate at neighboring districts (minimum competitiveness), they both set prices equal to 1.*

This proposition shows that the probability of a firm locating at each of the three districts is identical to the corresponding probability of the unique symmetric equilibrium of the catalog competition game and that the differences between the two setups are mainly with respect to prices. Here, the prices of the two firms are identical with very high probability (that is, they are equal to the marginal cost when competitiveness is maximal, and equal to the highest possible value when competitiveness is minimal). That is, sequential timing leads to similar choices in terms of locations, but higher correlation in terms of prices.

3.3 | Risk aversion

The fact that both the equilibrium of the catalog competition game and the equilibrium of the location-then-pricing game are mixed, makes one wonder whether their predictions remain relevant when the players are not risk neutral. In Appendix 3 we solve a general model which allows for any kind of symmetric risk attitudes (i.e., the firm's utility from a profit x is given by $u(x)$, where u is some strictly increasing function of x, common for both firms). In Appendix 4, we focus on CARA utility functions and we characterize the equilibrium of each game as a function of the corresponding risk-aversion parameter.

As we show, the main features of the equilibria remain the same as in the risk neutral case developed here. The only additional predictions that we get are quite intuitive: as firms become more risk averse they locate at the center with higher probability and they charge lower prices in expectation.

Whether these predictions, and all the theoretical results of this section pertain to settings of applied interest is an empirical question, addressed in the next section.

4 | EXPERIMENT

4.1 | Design

The predictions of the theory were experimentally tested. Given the relevance of uncertainty in mixed strategy equilibria, we also measured subjects' risk-aversion with an incentivized risk elicitation task before the main experiment took place.[12] A total of 120 students (gender balanced) were recruited, following the standard procedures at LINEEX, University of Valencia (Spain). The experiment was programmed in z-Tree (Fischbacher, 2007), and subjects received their rewards at the end of the session as explained below.

Subjects were randomly allocated to a session corresponding to one of two experimental treatments, SIM (simultaneous, corresponding to catalog competition) or SEQ (sequential location-pricing competition). To represent prices on a more realistic range and to offer subjects a sufficiently fine grid, the prices in the experiment were integers from the interval [0, 1000].[13] A single 60-subject session lasting 25 periods was run under each treatment. In each session, subjects were matched within 6 independent 10-subject groups to form, in each period, random pairs of firms interacting according to the rules of the corresponding simultaneous or sequential location and pricing game. Written instructions were given to subjects, which an organizer also read aloud.[14] The subjects' understanding of the instructions was tested through a pre-play questionnaire.

Average per-subject earnings were 13 Euros from the main game, and 5 Euros from the risk-elicitation task. The total duration of a session was about 90 min. Approximately 20 min corresponded to the risk-elicitation task, including instruction provision, and 70 min to the main game, including payment.

4.2 | Hypotheses

The following hypotheses emerging from the theoretical framework can be tested with our experimental data:

On location:

H1a: In both treatments, subjects will locate more frequently to the center than in the periphery.
H1b: Location choices will not vary between SIM and SEQ.

On prices by location:

H2: Prices will be lower for central location choices than for extreme ones in SIM.
H3: Prices will be decreasing in the competitiveness of locations in SEQ.

Hypothesis *H1a* directly follows from the fact that, according to the theory regarding SIM and SEQ, the single most frequent choice is the central location for any admissible utility function (Propositions 1 and 2).

Hypothesis *H1b* is a consequence of Propositions 1 and 2, according to which the probability of locating at an extreme is the same for SIM and SEQ.

Hypothesis *H2* follows from Proposition 1 and, specifically, from the stochastic dominance of $G(p)$ over $Z(p)$, as discussed after the proposition.

Hypothesis *H3* follows from the equilibrium relationship between competitiveness and price level (see Proposition 2).

Regarding the relationship between prices and locations, note that hypotheses *H2* and *H3* differ essentially in the information subjects have on locations when setting their prices. In the former, only own location choice is known and relevant at the price-setting stage, while in the latter, subjects observe both own and rival locations when setting prices.

Following previous findings from experimental tests of mixed strategy equilibrium (Cason & Friedman, 2003; Varian, 1980), discrepancies between theoretical predictions and empirical data could be due to the absence of genuine strategy randomization. In fact, the existence of serial correlation between strategies across subsequent periods would contradict the hypothesis that subjects randomize locations and prices. Formally:

H4: Prices and locations are the result of strategy randomization (mixed-strategy play).

4.3 | Results

We first present descriptive statistics (Table 1 and Figures 2–7) of theoretical values and empirical data from the main experiment, the risk task and demographic information of the sample.

Table 1 indicates that, on average, the empirical locations are rather close to the predicted ones (centrality being 0.55 and 0.64, respectively, for SIM and SEQ, against the predicted 0.6). The observed locations are compatible with the predictions of the model under risk neutrality.[15]

Therefore, locations are consistent with *H1a*, according to which, in both treatments, the majority of location choices should be central. However, locations significantly differ across treatments ($p = 0.0374$), rejecting *H1b*. Rather than identical location choices across treatments, SEQ has produced significantly more central locations than SIM.

Empirical prices are, on average, higher than the theoretical ones in both SIM (722.42 against 591) and in SEQ (562.15 against 535). However, the difference between empirical and theoretical price values is smaller if one considers the theoretical predictions for risk averse subjects. For example, for an absolute risk aversion parameter equal to one, the theoretical predictions become 695.15 for SIM and 602.40 for SEQ. This implies that some of the divergence between the observed and the theoretical price averages on Table 1 may be due to our experimental subjects' risk aversion.

Furthermore, average prices reproduce the expected pattern, with SIM leading to significantly higher prices than SEQ ($p = 0.0065$), although median prices have not reproduced the expected ordering, because in SEQ, the median price is substantially lower than the theory predicts (550 against 800). A contrary mismatch of theoretical and empirical median prices is observed in SIM (807 against 571).[16] Therefore, SEQ is more competitive than expected, which might relate to a possible coordination failure of firms trying to achieve the competition-mitigating but asymmetric center–periphery combination. Finally, Table 1 shows that the subjects assigned to the two treatments are extracted from the same population in terms of all individual characteristics obtained—age, sex and risk attitudes.

Figure 2 presents the distribution of locations by subject, expressed as each one's share of central locations over the 25 periods of the experimental session. The similarities between SIM and SEQ are worth noting. For example, in both treatments, very few subjects (only 12 out of 120) have chosen the same type of location (central or extreme) throughout the session and only 3 have always located on an extreme. All other subjects have chosen both extreme and central locations. Further, subjects have chosen central locations more frequently (approximately 64% of the time) than extreme ones. A Wilcoxon signed-rank test comparing average locations with 0.5 in each independent matching group confirms *H1a*. That is, if extreme locations were equally likely as central locations, the average location would take the value 0.5 and the null would not be rejected. In contrast, our result is that we reject the null hypothesis in both treatments, because of more positive than negative differences from 0.5. That is, central locations are chosen significantly more often than extreme ones. In SIM, we obtain a z-value of 1.992 ($N = 6$, two-sided test $p = 0.0464$) and in SEQ, a z-value of 2.201 ($N = 6$, two-sided test $p = 0.0277$).

As already observed on Table 1, SIM has produced significantly fewer central locations than SEQ. Apart from the comparison of mean and median locations, the figure shows a higher number of subjects in SEQ who chose C in a large majority of cases, or even in all of them. In contrast, much fewer subjects always chose to locate on an extreme. This heterogeneity of choice distributions seems compatible with the randomization of strategies assumed in a mixed strategy equilibrium. However, to formally test *H4* regarding the empirical confirmation of strategy randomization, the serial independence of strategies across periods must be checked.

Figure 3 shows that, in favor of *H2*, prices are lower for central locations than for extreme ones. However, while the stochastic dominance of the price distribution for central locations over that for extreme locations is confirmed, the existence of extremely low prices and the mass of prices on the monopoly value, 1000, are both unexpected. Figure 4 further presents the dynamics of this pattern, showing that median prices have remained relatively stable over the 25 periods of the experiment, with extreme locations producing systematically high prices, near the monopoly value, whereas central locations yield much lower prices, with a median close to half the monopoly price for most of the experiment's duration.

We turn now to the graphical overview of the SEQ treatment. Note that due to the different temporal structures of SIM and SEQ, we should account for the information available to subjects when setting prices. Thus, although in SIM

TABLE 1 Descriptive statistics

	SIM				SEQ					
	Data		Theory		Data		Theory		U-test	
Variable	**Mean**	**Median**	**Mean**	**Median**	**Mean**	**Median**	**Mean**	**Median**	**z-val.**	**p-val.**
Price	722.42	807	591	571	562.15	550	535	800	2.722	0.0065
Centrality	0.55	0.83	0.6	1	0.64	1	0.6	1	−2.082	0.0374
	Mean	**S.D.**	**Min**	**Max**	**Mean**	**S.D.**	**Min**	**Max**	**z-val.**	**p-val.**
Age	23.92	4.75	18	38	22.88	3.84	18	37	1.09	0.2796
Female	0.50	0.50	0	1	0.48	0.50	0	1	0.18	0.8557
Riskavers	0.24	0.38	0.003	2.025	0.21	0.31	0.003	2.025	−0.26	0.7886

Note: Upper part: Average empirical and theoretical (under risk neutrality) prices and location centrality (extreme locations are considered to take value 0 and central locations value 1) by treatment. Unit observation is mean or median by matching group ($N = 6$). Lower part: Individual variables (age, gender and risk aversion parameter corresponding to the average choice in the risk elicitation task) ($N = 60$). Last two columns: SIM-SEQ empirical difference significance through a Mann-Whitney U-Test.

Abbreviations: SEQ, sequential; SIM, simultaneous.

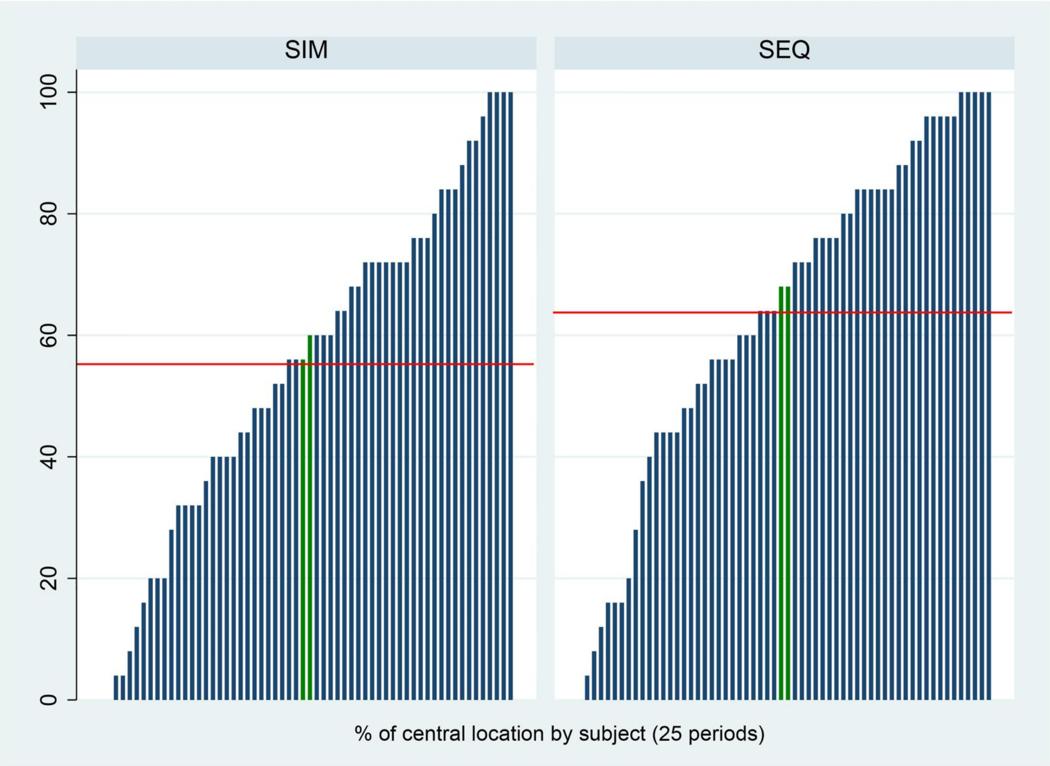

FIGURE 2 Individual location choices in simultaneous (SIM) and sequential (SEQ) (median value in green and mean in red)

we use individual location choices (central vs. extreme), in SEQ we consider location profiles (minimum, intermediate and maximum competitiveness), because in the latter a firm choosing price has already observed its rival's location.

Figure 5 provides a clear picture of the evidence obtained in favor of *H3*. When pooled by degree of competitiveness, price distributions follow the predicted pattern: Maximum competitiveness leads to prices dominated by those under intermediate competitiveness, which are dominated by prices under minimum competitiveness. However, as in the case of SIM, the mass of prices on the monopoly value under intermediate competitiveness is unexpected. Therefore, we can conclude that some attempts by the subjects to coordinate and tacitly collude have been successful in both treatments.

As explained, competitiveness is maximum when both firms locate at the same position, and minimum when one is at the center and the other at one extreme. Intermediate competitiveness corresponds to the case in which both firms

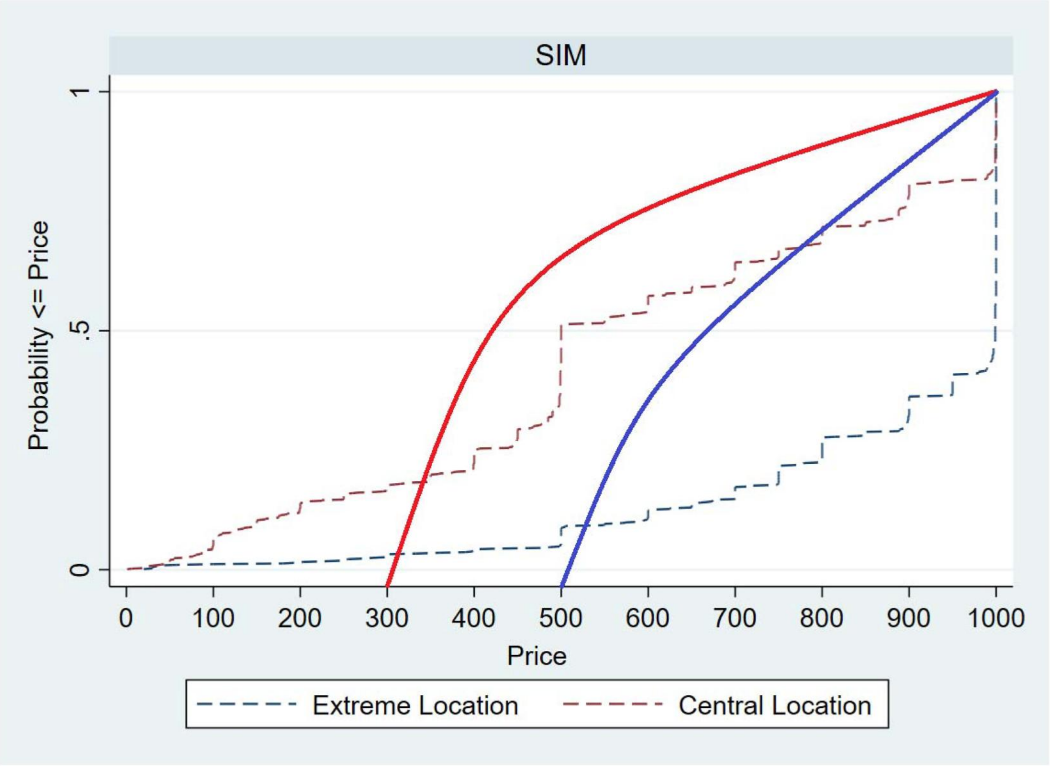

FIGURE 3 Predicted (thick solid lines) and empirical (dashed lines) price distributions (CDFs) by location in simultaneous (SIM)

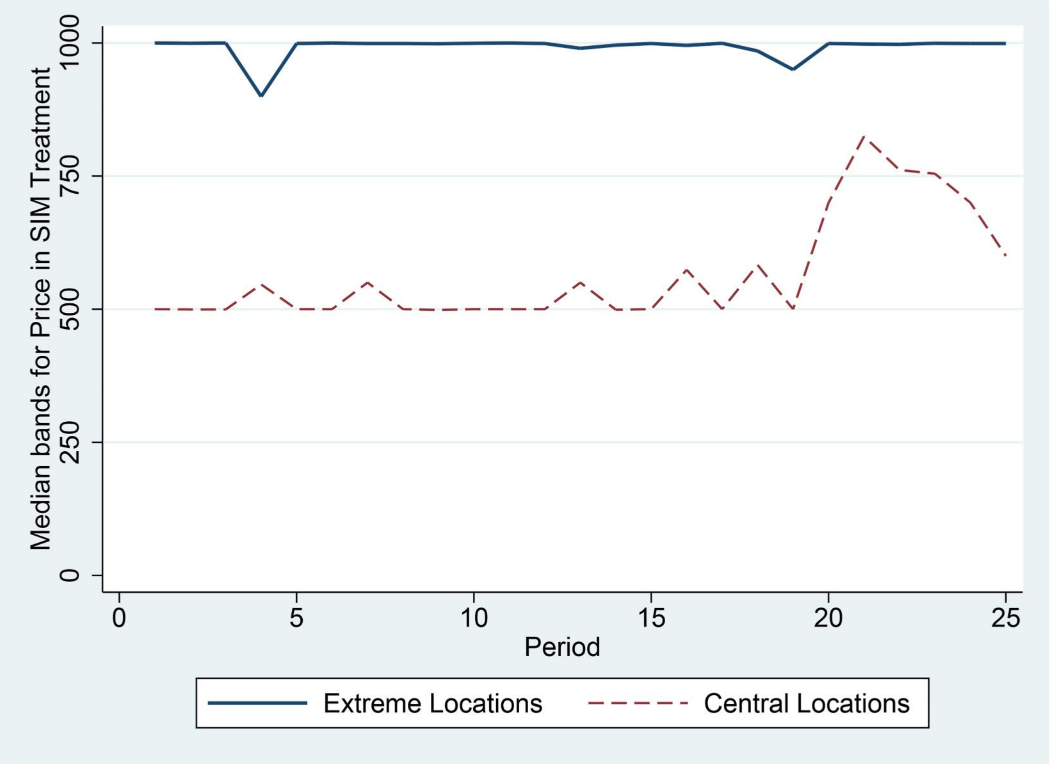

FIGURE 4 Evolution of (median) price by location in simultaneous (SIM)

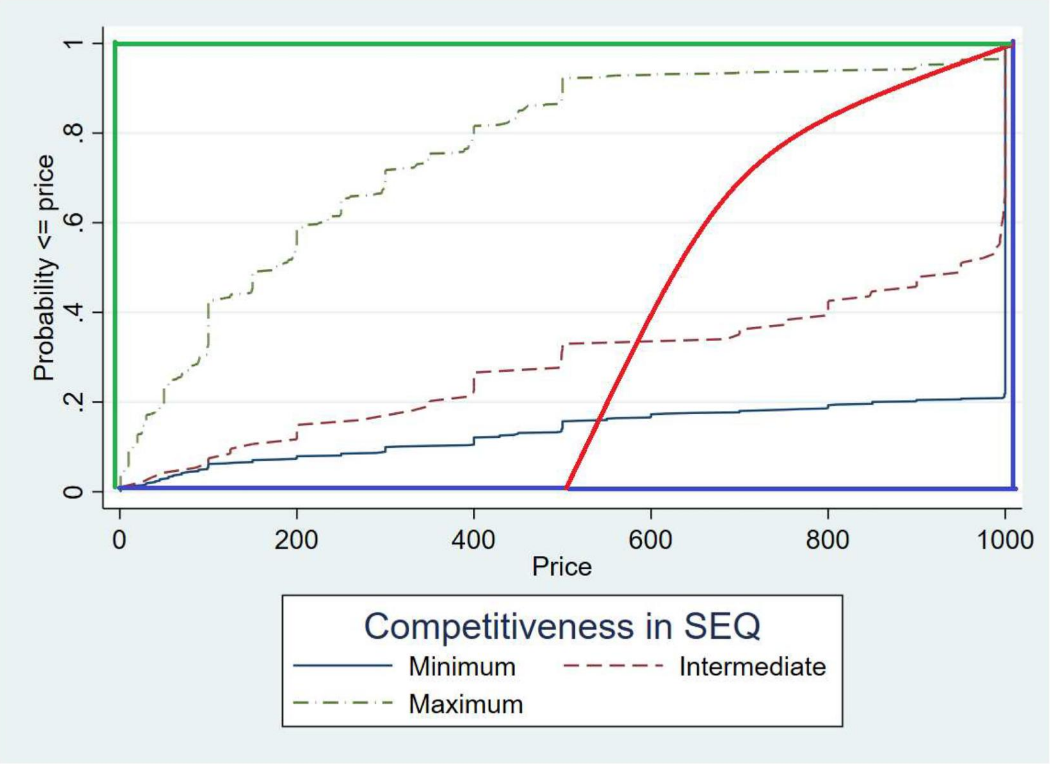

FIGURE 5 Predicted (thick solid lines) and empirical price distributions by competitiveness in sequential (SEQ)

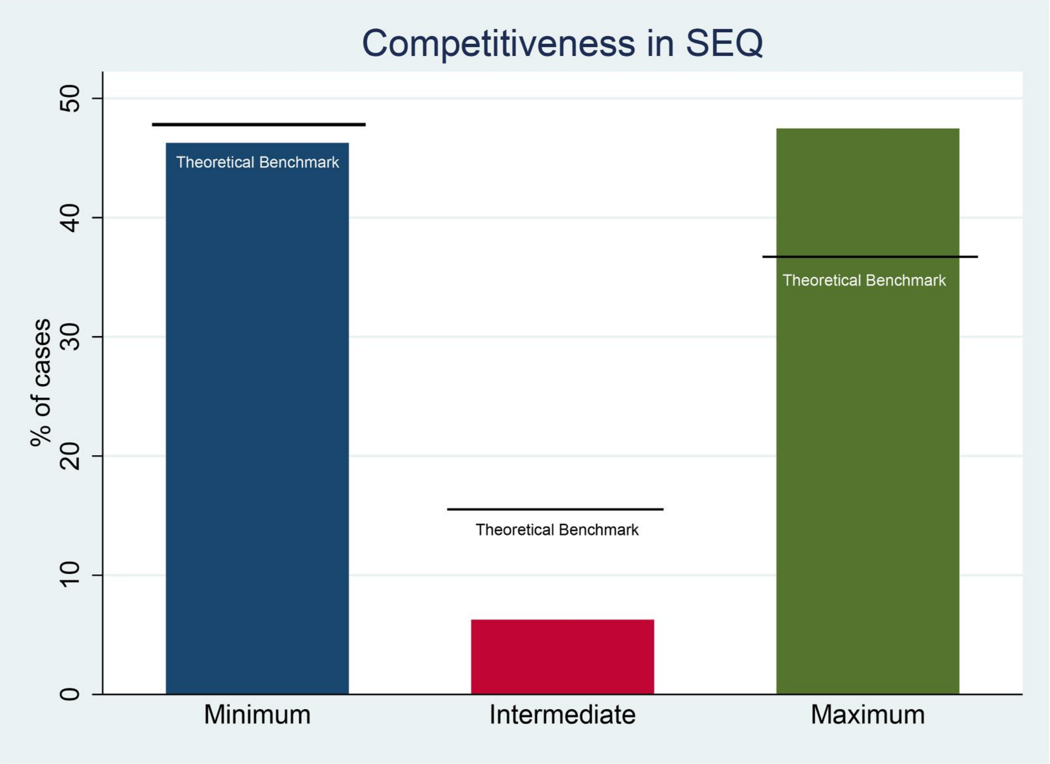

FIGURE 6 Aggregate competitiveness in sequential (SEQ)

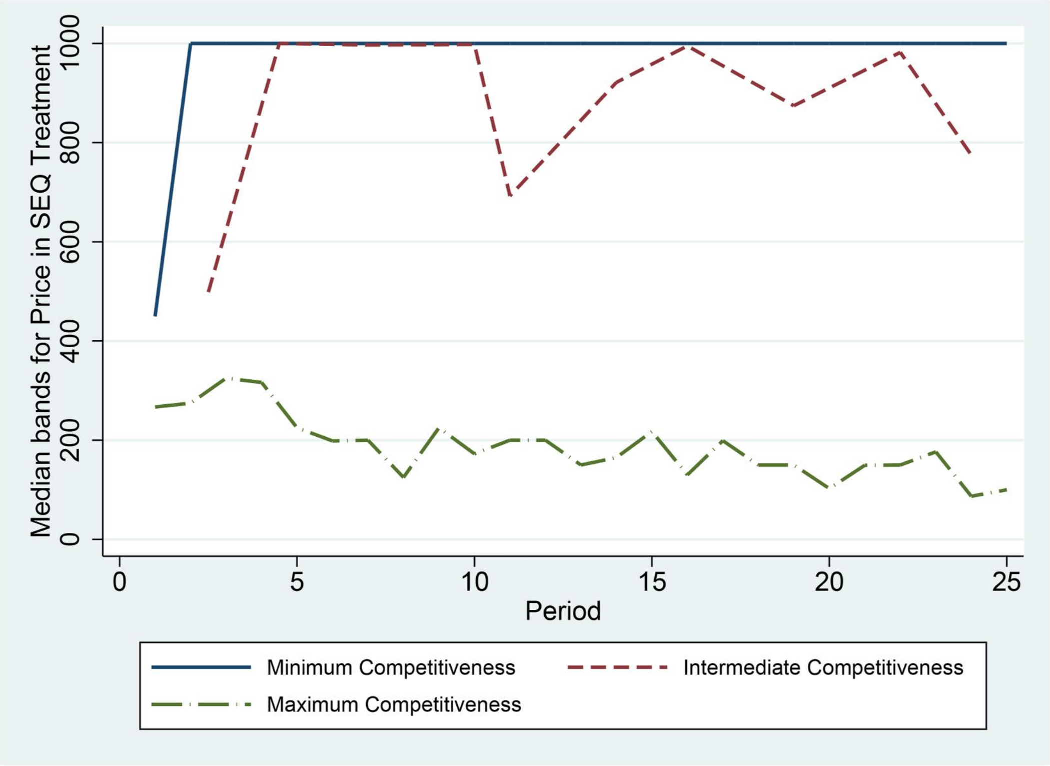

FIGURE 7 Evolution of prices by competitiveness in sequential (SEQ)

symmetrically locate on the extremes of the segment. Figure 6 shows the observed degrees of competitiveness alongside the theoretically predicted ones.

We observe a relatively good correspondence between the theoretical predictions and observed frequencies of competitiveness, with maximum (intermediate) competitiveness occurring slightly more (less) often than expected. This can be the result of some coordination failure by subjects trying to minimize competitiveness through the asymmetric center–periphery profile, ending up both on the center. Figure 7 presents the evolution of (median) price for the three levels of competitiveness. Median prices consistently reflect the theoretically expected ordering. Furthermore, subjects seem to often achieve coordination on the monopoly price, even for intermediate levels of competitiveness.

We complement the descriptive graphical presentation of the data with econometric models explaining location and pricing behavior separately for each treatment. Considering Cason and Friedman's (2003) argument, we check for serial and cross-sectional correlation in experimental decisions. To this aim, we use lagged strategies in both pricing and location models. Also, to account for the possible effects of risk attitudes on locations and prices, the average choice in the risk elicitation task is also used as an explanatory variable. Given the nature of our data, the more suitable model is a Prais–Winsten correlated panels corrected standard errors model. However, a standard OLS regression with robust standard errors offers virtually identical results (see Appendix 6.).

Tables 2 and 3 report the estimation results for the location and pricing models, respectively. A Baltagi–Li joint test confirms the presence of random effects and serial correlation (LM(Var(u) = 0, rho = 0) = 190.16, $Pr > \chi^2(2) = 0.0000$ for SIM, and LM(Var(u) = 0, rho = 0) = 460.28, $Pr > \chi^2(2) = 0.0000$ for SEQ). Further, a modified Wald test identifies groupwise heteroskedasticity in our data (MW = 26,551.26, $Pr > \chi^2(60) = 0.0000$ for SIM and MW = 3583.64, $Pr > \chi^2(60) = 0.0000$ for SEQ). These results, together with the fact that contemporaneous correlation exists among observations belonging to participants in the same matching group, justify the choice of Prais–Winsten panel regressions that correct the standard errors for heteroskedasticity and contemporaneous correlation. We also include a lag of the dependent variable as a regressor to capture any serial correlation.

Table 2 presents the estimates of the location models, including lags for own and rival location strategies and the player's risk aversion. In SIM, lagged location centrality is significantly correlated with present location centrality; this contradicts *H4*, which predicts that subjects would randomize their strategies. In SEQ, lagged own-location centrality is still significantly related to current centrality, which also contradicts *H4*. Finally, risk aversion has a strong effect in favor of central locations in SIM, but has no effect in SEQ.

TABLE 2 Prais-Winsten panel regression for location, correlated panels corrected standard errors (PCSEs)

Regression on location centrality Independent vars:	SIM				SEQ			
	Coef.	Std. Err.	z	$p > z$	Coef.	Std. Err.	z	$p > z$
Risk-aversion	0.12	0.029	4.06	0.000	−0.037	0.042	−0.88	0.381
Lagged own location centrality	0.40	0.024	16.59	0.000	0.40	0.025	15.88	0.000
Lagged partner location centrality	−0.012	0.024	−0.50	0.616	−0.07	0.024	−2.91	0.004
Constant	0.298	0.023	12.97	0.000	0.43	0.028	15.53	0.000
Obs.				1440				1440
R^2				0.18				0.16
Wald χ^2				335.07				263.68
Prob > χ^2				0.0000				0.0000

Note: Group variable: subjectid; Time variable: period; Number of groups = 60 per treatment; Panels: heteroskedastic (balanced); Obs. per group: 24; Estimated covariances = 60 per treatment.

Abbreviations: SEQ, sequential; SIM, simultaneous.

TABLE 3 Prais-Winsten panel regression for price, correlated panels corrected standard errors (PCSEs)

Regression on price Independent vars:	SIM				SEQ			
	Coef.	Std. Err.	z	$p > z$	Coef.	Std. Err.	z	$p > z$
Risk-aversion	−41.16	13.00	−3.16	0.002	−82.67	24.34	−3.40	0.001
Lagged own price	0.59	0.022	26.65	0.000	0.22	0.023	9.63	0.000
Lagged partner price	0.12	0.021	5.87	0.000	−0.08	0.023	−3.26	0.001
Competitiveness					−317.86	6.95	−45.73	0.000
Constant	222.75	22.67	9.83	0.000	823.42	15.07	54.64	0.000
Obs.				1440				1440
R^2				0.40				0.61
Wald χ^2				819.79				2254.46
Prob > χ^2				0.0000				0.0000

Note: Group variable: subjectid; Time variable: period; Number of groups = 60 per treatment; Panels: heteroskedastic (balanced); Obs. per group: 24; Estimated covariances = 60 per treatment. For the Competitiveness variable: 0 = "Minimum Competitiveness", 1 = "Intermediate Competitiveness", 2 = "Maximum Competitiveness".

Abbreviations: SEQ, sequential; SIM, simultaneous.

Table 3 presents the estimation results for the pricing equations. Lagged own and rival prices are highly significant in both treatments. Thus, hypothesis *H4* on price-strategy randomization is rejected due to the strong serial correlation of pricing decisions. In accordance with *H3*, in SEQ, competitiveness has a strong negative effect on prices. Risk aversion has a strong negative effect on prices both in SIM and in SEQ.

We summarize the findings of our empirical analysis.

> *Result 1a:* In both SIM and SEQ, central locations are significantly more frequently chosen than peripheral ones. Thus, *H1a* is confirmed.

This is confirmed in Table 1 and by a Wilcoxon signed-rank test (SIM: $p = 0.0464$; SEQ: $p = 0.0277$).

> *Result 1b:* Location choices are more central in SEQ than in SIM. Thus, *H1b* is rejected.

This is confirmed by a Mann-Whitney U-test ($p = 0.0374$) in Table 1.

Result 2: Prices are lower for central location choices than for extreme ones in SIM. Thus, *H2* is supported.

This is due to the stochastic dominance of prices associated to central locations over prices in extreme locations (Figure 3) and can be observed in the graph presenting the median prices during the 25 periods (Figure 4).

Result 3: Prices are decreasing in the competitiveness of locations in SEQ. Thus, *H3* is confirmed.

This is supported by the econometric results (Table 3) and the cumulative distributions in Figure 5.

Result 4: Both location and pricing strategies are serially correlated in both SIM and SEQ. Thus, *H4*, is rejected.

This follows the results of our regression analysis (Tables 2 and 3). Irrespective of this last result, the mix of competitiveness profiles in SEQ satisfactorily reproduces the theoretically predicted mix of profiles at a population level (Figure 6).

5 | CONCLUSIONS

In this paper, we present a simultaneous discrete location-pricing game of catalog competition. For comparison, we also obtain the equilibrium corresponding to the sequential location-then-pricing version of the game. Given the absence of pure strategy equilibria, we characterize the mixed strategy equilibrium. Our analysis considers a simplified discrete location space with only two types of locations, center and periphery. We experimentally test the predictions of the model regarding the role of simultaneity on location and pricing. Overall, aggregate data seem to support theoretical predictions more than individual data do.

From a theoretical point of view, a fundamental difference between the sequential and the simultaneous version of the model is that, in catalog competition, firms never choose very low prices even when they produce the same variety, unlike in the two-stage game in which firms end up setting their prices equal to their marginal cost when their goods are not differentiated. In both settings, central locations should be equally likely and more likely than peripheral ones.

An experimental test confirms most of these theoretical predictions, except the one concerning the similarity of location choices between the sequential and the simultaneous versions of the game. Sequential location-then-pricing leads to more central locations than simultaneous location and pricing. Further, in both settings, the theoretical predictions regarding the impact of location choices on pricing are confirmed. That is, central locations in the simultaneous game and higher location competitiveness in the sequential setting lead to lower prices.

Despite the similarity observed between the theoretical and empirical shares of strategies at a population level, subjects do not genuinely randomize their strategies in either location or price, rejecting the hypothesis of mixed strategy play. Instead, we find possible signs of coordination failure to minimize competitiveness in the simultaneous location-pricing setting and some coordination on monopoly pricing in both settings.

Experimental subjects exhibited a moderate degree of risk aversion. Using the risk attitudes elicited, we found evidence in favor of the predictions of our model for the catalog competition game. Risk-averse subjects are more likely to locate on the center and set lower prices, with the risk-aversion effects on location being significant when location and prices are chosen simultaneously.

Several generalizations and extensions remain open. On the theoretical front, a natural next step would be to allow firms to determine the timing of their actions endogenously, catalog versus first-location-then-pricing. Furthermore, subsequent studies should explore a richer location space, general consumer distributions and preferences. For instance, allowing consumers to enjoy product variety in the spirit of Sajeesh and Raju (2010), could provide a robustness check of our conclusions in alternative settings. From an experimenter's point of view, one could think of other more appealing interface designs, including continuous and multidimensional product spaces, to bring the Hotelling (1929) model closer to its many real-world applications.

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ENDNOTES

[1] It is first encountered in Lerner and Singer's (1937) critique of Hotelling's (1929) work. They specifically argue that when the competition is between player A and player B, player B should *take both A's location and his price as fixed in choosing her own location and price*. Dasgupta and Maskin (1986) and Economides (1984, 1987) discussed some properties of this more intuitive simultaneous model of product differentiation. Slade (1990) explores a subset of pricing models that are based on the notion of an infinitely repeated game with discounting and which predict nontrivial pricing dynamics, with particular attention to price wars, cartel breakdowns, and other pricing phenomena.

[2] The all-pay auctions (Baye et al., 1996), Downsian competition with a favored candidate (Aragonès & Palfrey, 2002) or other games that admit equilibria only in mixed strategies.

[3] Discretization of continuous games to identify a mixed equilibrium is not uncommon in the spatial competition literature. See, for example, Aragonès and Palfrey (2002) and Hummel (2010).

[4] Although this is an obvious limitation, it implies an advancement compared to risk-neutrality imposed in Arad and Rubinstein (2012), Collins and Sherstyuk (2000) and Aragonès and Palfrey (2004). Notably, Collins and Sherstyuk (2000) experimentally study a three-firm location model in the unit interval with fixed prices and attribute the divergence between the theoretical predictions (Shaked, 1982) (a random draw from a uniform distribution with support $\left[\frac{1}{4}, \frac{3}{4}\right]$) and experimental evidence (bimodal distribution of location choices) to the fact that agents are risk-averse. They computationally obtain some approximate equilibria for a case of risk-averse agents and show that these approximate equilibrium predictions fit the data better than the Nash equilibrium of the risk-neutral scenario.

[5] Models of spatial differentiation have been tested by several experimental studies. For example, Brown-Kruse and Schenk (2000), Collins and Sherstyuk (2000), Huck et al. (2002), and Kephart and Friedman (2015), study experimental spatial markets with two, three, and four firms, respectively. In all these papers, the only decision variable is location. Therefore, like in Brown-Kruse et al. (1993), price is an exogenously given parameter. In contrast, Camacho-Cuena et al. (2005) extend the basic framework considering endogenous consumer locations as well. Further, Orzen and Sefton (2008) study price dispersion as predicted by mixed strategy equilibria, considering exogenous firm locations. Finally, Barreda-Tarrazona et al. (2011) experimentally study the standard location-then-pricing framework.

[6] In Appendix 3, we present a generalization, relaxing the risk neutrality assumption.

[7] Economides (1984, 1987) considers that consumers have a very low valuation of the good—only the consumers located very near a "shop" will buy the good—and, hence, pure strategy equilibria in the catalog game exist such that each firm is a local monopolist. In our case, this can never occur as price competition is intense at a non-degenerate degree.

[8] If one assumed $E < 1$ or reservation prices applied to the total cost undertaken by the consumers instead, then price competition would be even more intense. However, we stress that the equilibrium derived is robust to considering values of $E < 1$, as long as they are not very small (we elaborate on this after the proof of Proposition 1).

[9] All proofs can be found in the Appendix 3.

[10] Since $\frac{1}{2} > \frac{4}{13}$, it also follows that there is an $\epsilon > 0$ such that the described equilibrium exists as long as $E \geq 1 - \epsilon$. When $E \in \left(\frac{1}{2}, 1\right)$ and firms end up at adjacent locations, a firm can win the consumers at its competitor's location by choosing a price p smaller than $1 - E$, conditional on the other firm setting a price larger than $E + p$. If the competitor employs this mixed strategy and $1 - E$ is small enough, then such an undercutting behavior is not profitable, and our equilibrium survives.

[11] For an analysis of factors that affect the intensity of price competition beyond product similarity, refer to Cabral and Villas-Boas (2005).

[12] An extension of the model under a CARA utility function is presented in Appendix 4. The subjects' risk preferences were elicited using the lottery panel test introduced by Sabater-Grande and Georgantzís (2002). As discussed in Sabater-Grande and Georgantzís (2002), Georgantzís and Navarro-Martínez (2010), and especially, García-Gallego et al. (2012), a subject's average choice across panels can be used as a measure of risk aversion. A detailed description of the test can be found in Appendix 2.

[13] The solution of the model for this price interval is provided in Appendix 5.

[14] An English translation of the instructions (originally in Spanish) is provided in Appendix 1.

[15] In fact, our subjects' choices in the risk elicitation task correspond to a low degree of risk aversion. On average, the estimated absolute risk aversion parameter is 0.23. Its distribution is positively skewed, with a strong concentration around the mode at 0.1, as shown in Figure A.1.

[16] In fact, this difference becomes even larger when risk aversion is assumed. For a risk averse population with absolute risk aversion parameter equal to 1, the theoretical median prices become 700 for SIM and 920 for SEQ. Thus, median deviations from theoretical values cannot be attributed to the subjects' risk aversion.

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