Predatory Pricing in the Presence of Network Effects: Evidence from the Lab

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Abstract

In this paper we study predatory pricing, market tipping and collusion in laboratory markets with network effects. In repeated two-player Hotelling games we compare three experimental treatments: no network effects, weak network effects and strong network effects. The experimental results show that predatory pricing is more likely in markets with weak or strong network effects, compared to markets without network effects. In markets with strong network effects there is more market tipping than in markets without or with weak network effects. In markets with network effects, the increase in product value due to network effects is to a large extent passed on to consumers through the increased number of predatory prices, which suggests that policies aimed at preventing predatory pricing may be counterproductive. There is no difference in the tendency to collude between treatments.

JEL codes: K21; L11; L12; L41

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1 Introduction

In this paper, we study predatory pricing, market tipping, and collusion in laboratory markets with network effects. In practice, firms can set predatory prices to deter, eliminate or discipline rivals. A predatory price is a low price "(...) that is profit maximizing only because of its exclusionary or other anticompetitive effects" (Bolton et al., 2000). Firms are more likely to set predatory prices in case there is the prospect of a significant reward in the recoupment phase. Network effects, which arise when the utility of a user increases with an increase in the total number of users using the same or a compatible product or service, may serve as a safeguard to future rewards, because network effects can function as a barrier to entry and, in turn, as a source of monopoly power. We therefore study whether network effects can be conducive to predatory pricing and whether predatory pricing can amplify the winner-take-all effect in network markets.

The existence of predatory pricing is a controversial topic in the fields of law (Bolton et al., 2000) and economics (Motta, 2004). On the one hand, Chicago School antitrust scholars like McGee (1958) and Bork (1978) argue that predatory pricing is never an optimal pricing strategy, due to the impossibility of recoupment. Experimental research corroborates this claim, because predatory pricing is hardly ever observed in the laboratory (Gomez et al., 2008). Moreover, there are only a handful of court cases resulting in sanctions for predatory behavior. On the other hand, economists argue that predatory pricing can be a rational profit-maximizing strategy in the case of imperfect information (Kreps and Wilson, 1982; Milgrom and Roberts, 1982). In addition, the number of court cases with alleged predatory pricing is generally undercounted, because settlements and successful predation, where no suit is filed, are not taken into account (Bolton et al., 2000). Moreover, antitrust legislation may deter firms from engaging in predatory behavior in the first place.

Due to the rise of digital platforms, predatory pricing has once again come to the attention of lawyers and policy makers. In a monopolization case in the Northern District of California in the US, the ride-hailing app Sidecar argued that its competitor Uber offered above-market incentives to drivers and low fares to consumers. After Sidecar had exited the market, Uber raised its consumer prices and driver fees to recoup the short-term loss.[1,2] In the food delivery industry, large amounts of venture capital funded a price war - consisting of low fees for restaurants, increased driver bonuses and promotional discounts for consumers - between the major food delivery firms. The price war led to a negative revenue per consumer for Uber Eats.[3] The US markets share of Uber's competitor Doordash decreased by 38 percentage points over a three year period. In a thinly veiled nod to predatory behavior, Uber's CEO stated: "(...) we will not shy away from making short-term financial sacrifices where we see clear long-term benefits".[4] In online retail, Amazon has been accused of predatory conduct, losing money on its customer loyalty program Amazon Prime and with aggressive pricing of products such as e-books (Khan, 2017) and voice-controlled speakers.[5]

[1] SC Innovations, Inc. v. Uber Technologies, Inc. et al, Case No. 18-cv-07440-JCS (N.D. Cal. 2020).

[2] The case was dismissed after a settlement was reached. See https://news.bloomberglaw.com/antitrust/uber-appears-to-settle-last-major-antitrust-challenge-by-a-rival, accessed November 19, 2022.

[3] See https://www.sec.gov/Archives/edgar/data/1543151/000119312519103850/d647752ds1.htm, accessed February 9, 2023.

[4] See https://www.vox.com/recode/2019/5/17/18624623/ubers-eats-food-delivery-loyalty-grubhub-doordash, accessed February 9, 2023.

[5] See https://www.protocol.com/sonos-amazon-echo-predatory-pricing, accessed November 19, 2022.

The aforementioned products or services have in common that they exhibit substantial direct or indirect network effects.[6] Our aim is to study whether the presence of network effects is conducive to predatory pricing. In addition, we study under what conditions predatory pricing can be a successful strategy, i.e., whether it leads to monopolization or collusion. In the case of monopolization predatory pricing can be used to deter entry or drive a competitor out of the market. In the case of collusion, predatory pricing can be used to discipline a rival that deviates from the collusive price.

Studying laboratory markets allows us to isolate the relationship between network effects on the one hand and predatory pricing, market tipping, and collusion on the other. Participants play the role of firms in repeated two-player Hotelling games, with fixed locations and automated consumers. An inefficient incumbent and an efficient entrant decide on market entry and prices in each round. Consumers' utility increases for each additional consumer that buys from the same firm, which represents a direct network effect. Incumbents start as a monopolist in the first round. We employ a between-subjects design with three treatments: no network effects, weak network effects and strong network effects.

Our theoretical analysis reveals that the range of predatory prices for which entry is deterred is greater in the case of stronger network effects. Due to a multiplicity of equilibria, our model does not provide clear-cut predictions. We show that a subgame-perfect equilibrium exists in which market tipping results in the sense that one of the firms is a monopolist in every round. Moreover, under the assumption that colluding firms can coordinate to divide the market in half, a subgame-perfect equilibrium exists in which the two firms set the joint profit-maximizing price in every round. However,

[6]Direct network effects arise when the utility, or profit, of an agent depends on the number of other users using the same service or product. Indirect network effects arise when the utility of an agent in one group depends on the number of users in another group (Jullien et al., 2021).

if the rate of discounting is low, it is likely that there are also a plethora of possible equilibria in which both firms enter the market in every period and obtain oligopoly profits. We therefore base our hypotheses on a long-run oligopoly equilibrium, in which prices and market shares are constant from one period to the next, to show that the difference between monopoly and oligopoly profits is greater in markets with stronger network effects. In particular, we hypothesize that markets with stronger network effects exhibit more predatory prices and that market tipping is more likely in markets with stronger network effects. Under the assumption that the firms' grim trigger strategies include the threat of predatory pricing in the case of deviation, we further hypothesize that there is less collusion in markets with stronger network effects.

Our experimental findings are as follows. First, we replicate the result from the existing experimental literature that predatory pricing is rare in markets without network effects: we observe only two prices, out of 1,158, where a firm prices below its own marginal costs. Second, there are significantly more predatory prices - below marginal costs and below average costs - in markets with network effects than in markets without network effects. Most predatory prices are set by the (inefficient) incumbents defending their monopoly position. However, the incumbents are generally unable to deter entry and are therefore unable to recoup their losses. Thus, contrary to the Chicago School view, participants do engage in predatory pricing, even though many of them are unable to recoup their loss in later periods. Third, market tipping is more likely in the case of strong network effects compared to markets without network effects or with weak network effects. Fourth, there is no difference in the tendency to collude between treatments. Although incumbents signal their willingness to collude in the first period in the case of strong network effects, we find no evidence of predatory pricing being used to discipline rivals. Fifth, consumer surplus is generally greater in markets with a greater number of predatory prices. In markets with predatory pricing, the increased product value due to network effects is passed on to consumers. This finding justifies the conclusion that policies aimed at preventing predatory pricing might harm consumers.

The remainder of this paper is structured as follows. In Section 2 we provide a brief overview of the literature. Section 3 contains the theoretical framework. Second 4 includes the experimental design and hypotheses. Our experimental results are in Section 5. We conclude in Section 6.

2 Literature

2.1 Theory

Our paper builds on the theoretical literature on predatory pricing, reviewed by Motta (2004, Chapter 7). Selten's (1978) *Chain store game* provides a prediction for a finitely repeated game of complete information in which an incumbent has to decide sequentially whether to accommodate a number of potential competitors. Predation does not occur in equilibrium in that the incumbent accommodates entry in every period. Studying a deep-pocket predation model with perfect information and symmetric firms, Benoit (1984) finds that in the subgame-perfect equilibrium, the entrant will not enter because the incumbent will fight entry in every period being able to sustain a price war for a greater number of periods than the entrant.

Imperfect-information models show that predatory pricing can occur as part of an equilibrium. In Kreps and Wilson (1982), the entrant does not know whether the incumbent is weak or strong. As a result, a semi-separating equilibrium exists in which a weak incumbent builds a reputation by mimicking the behavior of strong incumbents in the beginning of the game, inducing the entrants to stay out in early periods. Milgrom and Roberts (1982) derive conditions under which a pooling equilibrium exists if the entrant does not know the costs of the incumbent. Entry is deterred in equilibrium because efficient and inefficient incumbents both set a low price, which signals to the entrant that the incumbent is efficient and that entry is therefore not profitable.

More recent literature, reviewed by Farrell and Klemperer (2007), addresses the relationship between network effects and anti-competitive behavior. Farrell and Katz (2005) show that predation can be an equilibrium strategy in the case of incompatible homogeneous products with direct network effects and two subsequent user cohorts. Firms can subsidize consumers in the first period, which increases their installed consumer base - and their profits - in the second period. Similarly, in the models of Mitchell and Skrzypacz (2006), Dubé et al. (2010), Cabral (2011) and Besanko et al. (2014), firms may price below costs in equilibrium balancing the advantage-building motive - improving their competitive position in the future by expanding their network - against the (anti-competitive) advantage-denying motive - short-run aggressive pricing to prevent the rival from obtaining a larger network and becoming a more valuable competitor in the future.

Finally, collusion in two-sided markets is harder to sustain in the case of stronger indirect network effects (Ruhmer, 2010). On the one hand, the difference between Nash and collusive profits is greater in markets with stronger network effects. On the other hand, the profits in the case of a deviation by one of the firms are also greater in the case of stronger network effects. The latter effect dominates the former.

2.2 Laboratory experiments

We opted for the experimental method to investigate predatory pricing for three reasons, laid out by Van Damme et al. (2009) and Ruffle and Normann (2011). First, the experimental setup allows us to vary the treatment conditions the researcher can hardly vary exogenously in practice and to fix parameters of interest. In particular, isolate the effect of network effects on predatory pricing, market tipping, and collusion by exogenously varying the strength of the network effects. Moreover, we fix the marginal cost parameters, which are usually unobserved outside the laboratory. Second, given that our model does not provide a clear long-run Nash equilibrium prediction in the case of an oligopoly, the experimental setup allows us to select among plausible theories. Third, the experiment allows for a direct test of the theory. In network markets in practice it is cumbersome to show that a price below marginal or average costs is anti-competitive (Bostoen, 2019). In the case of network effects, a low price is not considered anti-competitive if there is a network efficiency argument, i.e., low prices lead to more users which increases the value of the product for consumers (Bolton et al., 2000; Evans and Schmalensee, 2002). In addition, products and services are often priced below cost in a two-sided market, because the elastic side of the market is subsidized (Rochet and Tirole, 2003; Jullien et al., 2021). We restrict the experiment to a one-sided market with a fixed number of consumers, so that we can identify unambiguous anti-competitive behavior which reduces welfare and consumer surplus.

The experimental literature on predatory pricing, reviewed by Holt (1995), Gomez et al. (2008) and Van Damme et al. (2009), reveals conditions under which predatory pricing occurs in laboratory markets. Most lab experiments reveal very few instances of predatory pricing, in many case as few as 0 or 1 in the entire experiment involving several hundreds of markets. Isaac and Smith (1985) examine predatory pricing in a single-market posted-offer setting with two asymmetric sellers in which the large seller has lower costs, a larger endowment and higher capacity. Predatory pricing does not occur and most of the time entry was accommodated, thereby confirming Selten's (1978) chain-store paradox. Jung et al. (1994) tested the Kreps and Wilson (1982) signalling game in the laboratory and found that weak incumbents would repeatedly fight entry, which can be interpreted as predatory behavior. Bruttel and Glöckner (2011) show that pricing below the competitors' marginal costs occurs in only one round, after which entrants re-enter. They also observe that a monopolist is limited in its price range in the recoupment phase, because consumers with considerable buyer power refuse to buy at monopolistic prices, which fosters competition. The effectiveness of policies to prevent predatory pricing in a perfect information setting is studied by Edlin et al. (2019). Pricing below own marginal costs does not occur in their experiment, but they observe frequent above-cost predatory pricing, i.e., the efficient incumbent pricing below the costs of the inefficient entrant to deter entry.

Pricing below own costs is also rare in multi-market designs. Harrison (1988) designed a multi-market experiment with multiple high and low cost sellers choosing in which market to operate. One price below own marginal costs was observed: in this market the low cost seller was able to drive a competitor out of the market and subsequently raised the price. Capra et al. (2000) and Gomez et al. (2008) adapt Harrison's (1988) experiment and find consistent patterns of predatory pricing, between own costs and the competitor's costs, in most markets. In their alternative design the demand structure was simplified, costs were common knowledge and the entry choices were made public before prices were posted, thereby providing information to the incumbent about whether it is safe to charge a monopoly price and when entry can be prevented. In essence, the goal of their modification corresponds to our experimental design: we induce predatory pricing by increasing the certainty of long-term profits by introducing network effects as an entry barrier.

There is a small related experimental literature on network effects and market tipping. Hossain and Morgan (2009) and Hossain et al. (2011) show that two-sided platforms can only coexist if they are sufficiently horizontally differentiated. Otherwise, two-sided markets almost always tip towards a monopoly due to network effects. The focus of their experiment is on the coordinating behavior of buyers and sellers that experience positive indirect and negative direct network effects. The prices set by firms are exogenous and fixed. Our focus, on the other hand, is on the endogenous price-setting behavior of firms. Dang and Ackerman (2009) investigate lock-in due to switching costs and network effects. They show that the presence of network effects leads to high prices and lock-in the case of automated buyers. With human buyers, on the other hand, network effects can foster coordination and overcome lock-in, thereby preventing monopolization. Our experiment is also related to coordination-game experiments, such as Van Huyck et al. (1990), showing that participants often fail to coordinate on an efficient equilibrium.

We are aware of two laboratory experiments examining the relationship between pricing and network effects. Chiaravutthi (2007) finds some support for Farrell and Katz (2005)'s prediction that predatory pricing emerges in equilibrium in a setting with direct network effects and two subsequent user cohorts. The experiment shows 53 predatory pricing attempts, of which 16 successful in the sense that the efficient incumbent prevents entry by the inefficient entrant. The inefficient entrant undercutting the incumbent is attempted 10 times but never successful. We build on this experiment in three ways. First, we consider a long-run game with an extended recoupment phase, instead of a two-period market in which consumers take into account the presence of network effects in only one period. Second, we add a control treatment featuring markets without network effects and we vary the strength of the network effects between treatments. Third, we investigate the effects of potential competition (in the form of re-entry) and the effect of predatory pricing on welfare. Bayer and Chan (2007) study a finite game in which participants set prices in market with network effects and without network effects. The design of the experiment does not include costs. The results show degrading collusion over time in the treatment without network effect and lower average prices in markets with network effects than in markets without network effects.

2.3 Antitrust law

Predatory pricing in the context of the competition law is reviewed by Bolton et al. (2000), Motta (2004), Van Damme et al. (2009) and Khan (2017). Our experiment shows that pricing below marginal costs and recoupment do not always go hand in hand in network markets. This result is relevant, because it relates to the core difference between competition law in the United States and the European Union. Here we briefly discuss the similarities and differences between predatory pricing regulation in these two jurisdictions.

In the United States, predatory pricing is prohibited by section 2 of the The Sherman Antitrust Act, which states that it is unlawful to "monopolize, or attempt to monopolize, or combine or conspire with any other person or persons, to monopolize any part of the trade or commerce among the several States, or with foreign nations (...)." The main goal of the provision is to protect the competitive process, not individual competitors. As a result, driving a competitor out of the market using a low price is not deemed unlawful, because market exit by an inefficient rival can be the outcome of a valid competitive process. In order to prove anti-competitive behavior the plaintiff has to show that the dominant firm had the intent of monopolizing the market.

In *Brooke Group*, the US court established two conditions that have to be satisfied for a price to be predatory.[7] First, the short-term component of predatory pricing concerns the price itself. As a per se standard the Areeda-Turner rule states that a price below reasonably anticipated short-run marginal or average variable costs should be deemed predatory (Areeda and Turner, 1975). In practice, depending on the characteristics of the firms and market, prices below average variable costs and between average variable and average total costs can be considered anti-competitive (Bolton et al., 2000). Second, considering that a low price is good for consumers in the short-term and should therefore not be penalized, the court established that predatory pricing is unlawful only if it hurts long-run competition. A low price is only considered predatory if there is a reasonable expectation that the firm will recoup its loss in the long-run, through higher prices leading to increased profits.

The court explains in *Brooke Group* that successful predation does not necessarily lead to a reduction of the number of firms in the market. Either a competitor is driven out of the market, in which case the predatory firm is a monopolist and can recoup its loss through monopoly pricing, or the predatory price is part of a punishment strategy used to discipline the competitor, so that the competitor conforms to a tacit collusion scheme. As long as the joint profit-maximizing price in the case of collusion is high enough, so that the predator is able to recoup its loss, the burden of proof for predatory pricing is met.

In the European Union predatory pricing is prohibited by Article 102 of the Treaty on the Functioning of the European Union. The European Court of Justice established

[7] Brooke Group Ltd. v. Brown & Williamson Tobacco Corp., 509 U.S. 209 (1993).

two criteria to prove predatory pricing in *Akzo* and *Tetra Pak II*.[8] First, pricing below average variable costs is by itself sufficient to prove anti-competitive behavior. Second, pricing below average total costs, but above average variable costs, is abusive when there is proven intent to eliminate a competitor (Bostoen, 2019). The rationale behind the decisions is that the only reason for a firm to make a loss is to drive a competitor out of the market. As a result, the EU approach is more in line with section 2 of the Sherman Act than with US case law after *Brooke Group*, because the main question in the EU is whether the predatory price has lead to the intended monopoly and not whether the monopolist has correctly or incorrectly inferred whether becoming a monopolist using predatory prices is profitable.

While the burden of proof is lower in the EU than in the US, there are a limited number of predatory pricing cases in both jurisdictions. Van Damme et al. (2009) found four predatory pricing cases in the EU over the period 1968-1992. In 2008, over a ten year period and based on self-reported questionnaires, the International Competition Network (2008) reports three predatory pricing cases by the European Commission where violation were found and 12 cases by current EU member states with a violation, compared to two investigations and no cases where violations were found in the same period in the US. In the US, over the period 1973-1983, Salop and White (1996) find that plaintiffs have a success rate of 7.3% in the case of alleged predatory pricing, compared to 11% for all antitrust cases. Over the same period, at least 77.6% of cases with alledged predatory pricing were settled.

Arguably one of the most prominent antitrust cases including predatory pricing and network effects is *United States v. Microsoft Corporation*.[9] Microsoft was ac-

[8] AKZO Chemie BV v Commission of the European Communities, C-62/86 (1991); Tetra Pak International SA v Commission of the European Communities, C-333/94 P. (1996).

[9] United States v. Microsoft Corporation, 253 F.3d 34 (D.C. Cir. 2001). https://www.justice.gov/atr/complaint-us-v-microsoft-corp

cused of monopolizing the desktop computer operating system market and leveraging its monopoly power in the market for internet browsers, using a combination of exclusionary conduct and predatory pricing. Microsoft bundled a free version of its web browser Internet Explorer and operating system Microsoft Windows in an attempt to switch consumers from competing web browsers. The operating system and browser market exhibit substantial network effects, which induced the use of anti-competitive conduct due to the prospect of a durable monopoly. The Court of Appeals ruled that Microsoft had monopoly power, but was not guilty of attempted monopolization. The case was settled and behavioral remedies were adopted (Motta, 2004).

3 Theoretical framework

In our model two profit-maximizing firms, labeled $i = 1, 2$, play a Hotelling game over the interval $[0, 1]$.[10] The game is repeated for an infinite number of periods, where interaction takes place in every period $t = 1, 2, ...,$ with common discount factor $\delta < 1$.

Consider the following stage game of the infinitely repeated game. In every period, the two firms offer heterogeneous goods to consumers. The two firms decide every period t whether or not to enter the market in exchange for an entry fee $F \geq 0$. Throughout the paper, firm 1 (2) is referred to as the incumbent (entrant). Firm i is located at l_i, where $l_1 = 0$ and $l_2 = 1$, i.e., the firms are located at the extreme ends of the Hotelling line. Let c_i denote firms i's marginal costs, which are constant, with $c_1 \geq c_2 \geq 0$.

A unit mass of consumers is uniformly distributed over the interval $[0, 1]$. Every consumer buys up to one unit in every period. Let $x \in [0, 1]$ denote the location

[10]The setup of the model is similar to Lambertini and Orsini's (2013) Hotelling model with switching costs, network effects and endogenous firm locations. We assume no switching costs and we fix the firms' locations.

of a consumer. Consumers incur transportation costs $\tau|x - l_i|$ when buying from firm i, where $\tau \geq 0$ denotes the product differentiation parameter. In period t, the product offered by firm i has 'intrinsic' value r and 'extrinsic' value $\mu\tilde{n}_{i,t}$, where μ is the strength of the direct network effects and $\tilde{n}_{i,t}$ is the fraction of consumers a consumer expects to buy from firm i in period t (henceforth: market share). The resulting utility for a consumer that buys from firm i at a price $p_{i,t}$ in period t is

$$u_{i,t} = r + \mu\tilde{n}_{i,t} - \tau|x - l_i| - p_{i,t}. \tag{1}$$

At the end of every period consumers observe the market shares of both firms. Moreover, consumers are myopic in the sense that they anticipate that the market share of firm i in period t is equivalent to the market share they have observed in the preceding period (similar to the 'lagged expectations' in Farrell and Katz (2005)). Thus, in period t, consumers choose the firm i that offers the highest utility according to (1), assuming that $\tilde{n}_{i,t} = n_{i,t-1}$.

The degree to which consumers form rational expectations about the size of the market shares is an empirical question. On the one hand, when people adopt network goods they will have to form some expectation about whether others will use the product in later periods. Dang and Ackerman (2009) show that human buyers behave strategically when it comes to the adoption of network goods. On the other hand, forming rational expectations about the number of consumers that buy from firms in future periods is a profound cognitive challenge. Bounded rationality can explain empirically observed prices (Radner et al., 2014). In the switching costs and network effects literature it is therefore not anomalous to assume that consumers myopically maximize current utility without considering the future effect of their choices (Farrell and Klemperer, 2007; Boudreau, 2021). In the social-learning literature, assuming myopia is a common way to model the behavior of consumers interacting in networks (DeGroot, 1974; Chandrasekhar et al., 2020).

The way in which the assumption of consumer myopia affects our results depends on the relative importance of product differentiation and the strength of the network effects. In the absence of network effects, consumers do not care about the product that others will choose - now and in the future - and choose the differentiated product that maximizes current utility. In that case, ceteris paribus, a myopic and forward looking consumer will choose the same product. As network effects become more important, forward looking consumers are more inclined to choose the product which they expect will become popular, even though they might privately prefer another product. As a result, the existence of forward looking consumers increases the incentive of firms to gather market share early on, which drives increased price competition between firms in the early stages of the game.

Period t consists of the following consecutive stages.

1) Firms decide independently whether or not to enter. When entering, a firm incurs entry costs F. A firm that does not enter the market in period t has zero profit in that period.

2) It becomes common knowledge whether a firm has or has not entered. Firm i, when entering, sets price $p_{i,t}$ independently of the other firm.

3) Consumers decide from which firm to buy, if they buy at all.

We assume $F < \frac{\tau(c_1-c_2-3\tau+\mu)^2}{2(\mu-3\tau)^2}$ so that both firms expect positive profits if they set the equilibrium price in an oligopoly. The total payoff for firm i is the following.

$$\pi_i = \sum_{t=1}^{\infty} \delta^t \left(n_{i,t}(p_{i,t} - c_i) - F\right) I_{i,t},$$

where

$$I_{i,t} = \begin{cases} 1 & \text{if firm } i \text{ enters in period } t, \\ \\ 0 & \text{if firm } i \text{ does not enter in period } t. \end{cases}$$

The game has two Nash equilibria in which $n_{i,t-1} = n_{i,t}$ for $i = 1, 2$ in all periods: a market tipping equilibrium and a collusive equilibrium. Moreover, we define a long-run oligopoly equilibrium in which both firms enter the market and set time-invariant prices, resulting in the same market shares in subsequent periods. The proofs of the following results can be found in Appendix A.

We first examine the conditions under which a predatory price by firm i deters entry by the other firm, irrespective of firm j playing a best response.

Lemma 1. *If $\mu \geq \max\{2\tau + c_i - r, \tau - c_j\}$ and $n_{i,t} = 1$, $p_{i,t+1} = 0 \Rightarrow n_{j,t+1} = 0 \ \forall p_j \geq c_j, i = 1, 2, j = 3 - i$.*

Lemma 1 indicates that a firm can charge a predatory price preventing the competitor from obtaining positive profits in the case of entry only for sufficiently high network effects μ relative to the level of product differentiation τ, and sufficiently high marginal costs of the competitor.

Our equilibrium analysis is rooted in the concept of myopic best response, which we define as follows.

Definition 1. *Define $BR_i(p_{j,t}, n_{i,t-1}, n_{j,t-1})$ for $i \neq j$ as firm i's myopic best response, that is $p_{i,t} \in \arg\max \pi_{i,t}(p_{i,t}, p_{j,t}, c_i, n_{i,t}, n_{j,t}, F)$, to a price $p_{j,t}$ of firm j and market shares $n_{i,t-1}, n_{j,t-1}$ in period $t - 1$.*

We now examine the range of prices by firm i that deter entry by the other firm, if the entrant plays a best response.

Lemma 2. *If* $p_{j,t} = BR_j(p_{i,t}, 0, 1)$ *and* $n_{i,t} = 1 \Rightarrow n_{j,t+1} = 0 \; \forall p_i < c_j - \tau + \mu - 2\sqrt{2}\sqrt{\tau F}, i = 1, 2, j = 3 - i.$

Lemma 2 indicates that the range of prices that deter entry is greater in markets with stronger network effects.

The following proposition states the conditions under which a market tipping equilibrium exists in which only firm i enters the market. In equilibrium, firm i enters the market in every period while the other firm never enters the market. Firm i charges price $p_i = 0$ if the other firm enters the market.

Proposition 1. *(Market tipping equilibrium) If and only if* $\mu \geq \max\{2\tau + c_i - r, \tau - c_j - 2\sqrt{2}\sqrt{\tau F}\}$*, an equilibrium exists in which, in every period* t*,*

$$
\begin{aligned}
p_{i,t} &= p^M \equiv r + \mu - \tau, \\
n_{i,t} &= 1
\end{aligned}
$$

We interpret proposition 1 as follows. It is easier to sustain a monopoly the greater are the network effects. The reason is that the first condition in the proposition only holds true for sufficiently large μ.

We now turn our attention to the equilibrium in which both firms enter the market. In the long-run oligopoly equilibrium a strategy profile consists of a pair of prices and entry decisions, where, in period t, firm i's entry decision and price are a best response to those of firm j.

We assume that two conditions are satisfied in the long-run oligopoly equilibrium. First, given the entry decision by the competitor, a firm will only enter if it is able to make a positive profit in the price subgame. Second, given the entry decision by the competitor and the price chosen by the competitor, a firm that has entered has no incentive to change its price. Let $\hat{x}$ denote the location of the indifferent consumers, for which $u_{1,t} = u_{2,t}$.

Definition 2. *The price pair (p_1, p_2) constitutes a long-run oligopoly equilibrium if*

$$\begin{aligned}
&1) \quad \pi_i(p_i, p_j, c_i, n_i, n_j, F) \geq 0 \textit{ for } i = 1, 2. \\
&2) \quad p_i = BR_i(p_j, n_i, n_j), \\
&3) \quad n_i = \frac{1}{2} - \frac{p_i - p_j - \mu(n_i - n_j)}{2\tau}.
\end{aligned}$$

The long-run equilibrium provides one attainable equilibrium path. The long-run equilibrium states that, irrespective of the initial market shares, if in some period t the firms end up dividing the market $n_{i,t} = n_i$ and $n_{j,t} = n_j$, myopic firms will continue the game with constant market shares and the same prices in all periods following period t until the end of the game. The conditions under which a long-run equilibrium exists as well as closed-form solutions for prices and market shares are stated in the following proposition.

Proposition 2. *(long-run oligopoly equilibrium) If $\mu \in [c_1 + c_2 + 3\tau - 2r, 3\tau - c_1 + c_2]$, (p_1, p_2) constitute a long-run oligopoly equilibrium, with*

$$\begin{aligned}
p_i &= \frac{3\tau^2 + c_i(2\tau - \mu) + \tau(c_j - \mu)}{3\tau - \mu} \quad \textit{and} \\
n_i &= \frac{3\tau - \mu - c_i + c_j}{2(3\tau - \mu)}, \quad i = 1, 2, j = 3 - i.
\end{aligned}$$

With the prices and markets shares in the market tipping equilibrium (proposition 1) and long-run oligopoly equilibrium (proposition 2) we can compare the profits in the two equilibria. Let π_i^O denote firm i's single-period profits in the long-run oligopoly equilibrium. Let π_i^M denote firm i's single-period profits in the market tipping equilibrium.

Proposition 3. *If* $\mu < 3\tau - \sqrt{\tau(c_1 - c_2)}$*. Then,*

$$\frac{\partial}{\partial \mu}(\pi_i^M - \pi_i^O) > 0 \quad for \quad i = 1, 2.$$

We interpret proposition 3 as follows. As the strength of the network effects increases, being a monopolist is increasingly profitable, compared to an oligopoly. In the case of a monopoly, the monopolist raises the price in order to appropriate all additional consumer utility due to the presence of network effects. In the case of an oligopoly, price competition limits the ability of firms to appropriate the increase in product value due to the presence of network effects.

We now turn our attention to the collusive equilibrium. We assume that in the case of collusion firms agree to divide the market in half, so that, in the long run, the consumer in the middle is indifferent between buying from firm i and j, i.e., $n_{1,t} = n_{2,t} = n^{Col} = \frac{1}{2}$. Both firms play the game according to the following grim trigger strategy. Let p_i^{Punish} denote the price of firm i in the case of a deviation by firm j. The strategy for firm i and j is to cooperate and choose the collusive price $p^{Col} = r + \frac{1}{2}(\mu - \tau)$ in every period as long as the other firm has not deviated in the past. Once a deviation by firm j in period $t - 1$ is detected, firm i sets $p_i^{Punish} = 0$. In every subsequent period, firm i sets the price p_i^{Punish} if the other firm enters and sets the monopoly price p^M if the other firm does not enter.

Two conditions have to be satisfied for the collusive equilibrium to exist. First, the discount factors should be sufficiently high, i.e., future profits should be considered sufficiently valuable. We define the following critical discount factor:

$$\delta \geq \underline{\delta} = \frac{\left(r - c_2 + \frac{1}{2}(\mu - 3\tau)\right)^2}{(r - c_2 + \frac{1}{2}(\mu + \tau))^2 - 8\tau F}.$$

Second, the marginal costs level of both firms is above some critical marginal costs level, so that the punishment under the grim trigger strategy is enforceable. Define the critical marginal costs level as follows

$$\underline{c} = \frac{\mu(\mu + 2r) - \tau(3\mu - 4\tau) - 8\sqrt{2}\sqrt{F\tau^3}}{2(\mu + 2\tau)} \quad \text{for} \quad \mu \neq 2\tau.$$

The following proposition states the conditions under which the collusive equilibrium exists.

Proposition 4. *(Collusive equilibrium) If $\mu \neq 2\tau$, $\delta \geq \underline{\delta}$ and $c_i \geq \underline{c}$ for $i = 1, 2$. Then, a Nash equilibrium exists in which both firms play a grim trigger strategy with $p_i^{Punish} = 0$ and in every period, for $i = 1, 2$,*

$$p_i = p^{Col} = r + \tfrac{1}{2}(\mu - \tau),$$
$$n_i = n^{Col} = \tfrac{1}{2}.$$

Corollary 1. *If $\mu \notin (2(c_2 - r) + 8F - \tau, 2(c_2 - r) + 3\tau)$ and $0 < F \leq \frac{\tau}{2}$*

$$\frac{\partial}{\partial \mu}\underline{\delta} > 0.$$

And, if $0 < \tau < \frac{2}{5}(\mu + r)$

$$\frac{\partial}{\partial \mu}\underline{c} > 0.$$

According to Corollary 1, collusion becomes more difficult to sustain the greater the direct network effect μ. This result is in line with Ruhmer (2010) who shows that, in a two-sided market, collusion is less likely if the strength of the indirect network effects increases.

An additional complicating factor of collusion in markets with network effects is the issue of coordination. In the case of unstable collusive agreements market shares can shift from one period to the next while prices are held constant. As a consequence, a firm might be inclined to deviate from the collusive price if it observes that its market share and profits are decreasing over time, thereby dissolving the cartel.

4 Design and hypotheses

4.1 Experimental design

We employ a between-subject design with three treatments: no network effects (CONTROL), weak network effects (NET2) and strong network effects (NET6).[11] Each treatment consists of 32 markets with two participants. The 192 participants were recruited by public announcement from the undergraduate population of the Center for Research in Experimental Economics and Political Decision Making (CREED) of the University of Amsterdam. The online experiment is programmed in z-Tree (Fischbacher, 2007) and conducted over the internet using z-Tree Unleashed (Duch et al., 2020).

Participants earn points that are converted at a rate of 400 points for 1 euro. On average participants earned 19.05 euros (std. dev. 8.70) in sessions that lasted approximately 90–120 minutes. At the start of the experiment participants read the computerized instructions (see Appendix B) at their own pace. Participants then answer four questions on the general setup of the game, followed by four scenario-

[11] We preregistered our experiment at osf.io/pw53z and osf.io/ermnk.

questions. As soon as two participants answered all questions correctly and finished the instructions, they were matched to start the game.

The experiment is framed in an economic context, but we were careful to avoid wording that encouraged risk-taking or excessive competition. For instance, instead of 'competitor' we used 'other firm' or 'other participant' in the instructions and the experiment. We also avoided the use of the words 'network effects', but described that 'the value of the product increases by [μ] points for each consumer that has bought from the firm in the previous period'.

Participants were randomly assigned the role of incumbent or entrant, located at fixed positions $l_1 = 0$ and $l_2 = 100$ on the Hotelling line over the interval $[0, 100]$. In between are 100 consumers at locations $x = 0.5, 1.5, ..., 99.5$. Incumbents start the game as monopolist, by setting $n_{1,0} = 100$ and $n_{2,0} = 0$. The Hotelling model was employed with the following parameter values: $r = 12, \tau = 0.04, c_1 = 5, c_2 = 3, F = 50$. Consumers maximize utility according to the decision rule in equation (1).

The three treatments differ in the strength of the network effects:

- **CONTROL:** No network effects, $\mu = 0$.
- **NET2:** Weak network effects, $\mu = 0.02$.
- **NET6**: Strong network effects, $\mu = 0.06$.

The experiment consists of at least 20 periods. In every subsequent period there is a 4/5 probability of an additional period. Incumbents and entrants receive a show-up fee of 5,000 and 3,000 points, respectively, which is converted to an endowment at the beginning of the game. All losses have to be paid from the endowment and profits. In the case of bankruptcy - the sum of the endowment and total profits is negative - the participant is excluded from the experiment. The bankrupt firm will not enter the market in the remaining periods, while the other participant continues the experiment. None of the participants went bankrupt in the experiment.

The equilibrium outcomes of the game are in Table 1. In all treatments, consumer surplus is greater in the oligopoly equilibrium than in the case of a monopoly. From a consumer surplus perspective an oligopoly is preferred over a monopoly in all treatments. From a total welfare perspective a monopoly by the efficient entrant is the preferred market structure in all treatments. The intuition is that, oligopoly or monopoly, consumers always buy one unit so that the higher price they pay is a welfare-neutral transfer from them to the firm. The welfare-optimal outcome emerges if the entrant serves the entire demand realizing the maximum amount of network effects as well as the most efficient production. In contrast, a monopoly by the incumbent provides lower welfare than an oligopoly in CONTROL and NET2.

We elicit the firms' strategies using the strategy method. We do so in three steps. At the start of every period both firms receive 50 points. In the first step participants pay 50 points to enter the market or keep the 50 points and stay out. The rationale for these entry costs is twofold. First, we want to imitate a market for digital products with network effects, which are often characterized by substantial start-up costs and economies of scale (decreasing average costs). Second, the entry costs are sufficiently substantial to potentially deter entry (see proposition 1). For comparison, a participant that never enters in period 1–20 receives 1,000 points plus the endowment, which is more than 32.8% of participants earned.

Firms that enter the market set their oligopoly and monopoly price in the second and third steps, respectively, in 0.1 point increments. A calculator, which visualizes the Hotelling line and has the same function as a profit table, was available to aid the participants in their pricing decision. At the end of every period both participants observe the entry decisions, market shares and profits of both firms.

Table 1: Parameters and equilibrium outcomes

	Treatments		
	CONTROL	NET2	NET6
Network effect strength (μ)	0.00	0.02	0.06
Product differentiation (τ)	0.04	0.04	0.04
Marginal costs ($c_1; c_2$)	$5; 3$	$5; 3$	$5; 3$
Intrinsic product value (r)	12	12	12
Entry costs (F)	50	50	50
Long-run oligopoly equilibrium			
Number of consumers ($n^*_{1,t}; n^*_{2,t}$)	$42; 58$	$40; 60$	$33; 67$
Prices ($p^*_{1,t}; p^*_{2,t}$)	$8.3; 7.7$	$8.2; 7.8$	$7.7; 8.3$
Profits ($\pi^*_{1,t}; \pi^*_{2,t}$)	$88.60; 222.60$	$78.00; 238.00$	$39.10; 305.10$
Consumer surplus	303.40	404.00	611.79
Total welfare	614.60	720.00	955.99
Market tipping equilibrium			
Number of consumers	100	100	100
Price (p^M)	8.0	10.0	14.0
Profits ($\pi^M_1; \pi^M_2$)	$250; 450$	$450; 650$	$850; 1050$
Consumer surplus	200	200	200
Total welfare (firm 1; firm 2)	$450; 650$	$650; 850$	$1050; 1250$

4.2 Hypotheses

As said, proposition 1 implies that it is easier the sustain a monopoly in markets with stronger network effects. Moreover, according to proposition 3, the benefit of being a monopolist relative to being an oligopolist is greater in markets with stronger network effects. Presuming that predatory prices will lead to a sustained monopoly position, it is therefore more attractive for a firm to set predatory prices in markets with stronger network effects. As a consequence, we expect more predatory prices in markets with stronger network effects.

Hypothesis 1: There are more instances of predatory pricing in NET6 than in NET2 and in NET2 than in CONTROL.

Let $p_{i,t}^{ol}$ denote firm i's oligopoly price in period t.[12] We define four types of predatory pricing:[13]

- Type 1 predatory pricing: Firm i prices below own marginal costs ($p_{i,t}^{ol} < c_i$).
- Type 2 predatory pricing: Firm i prices below own average costs ($p_{i,t}^{ol} < c_i + F/n_{i,t}$). If a firm enters the market in period t, but serves no consumers in period t, any price is considered a Type 2 predatory price.
- Type 3 predatory pricing: Firm i prices below the marginal costs of the other firm ($p_{i,t}^{ol} < c_j$).
- Type 4 predatory pricing: Firm i prices below the average costs of the other firm ($p_{i,t}^{ol} < c_j + F/n_{j,t}$). If a firm enters the market in period t, but serves no consumers in period t, any price is considered a Type 4 predatory price.

For three reasons we also take into account average costs as a measure for predatory pricing. First, a firm that sets a price below average costs signals its willingness to incur losses to compete for the market. Below own average cost pricing reflects a real-life uncertainty about potential profits. Second, using average costs as a measure of predatory pricing is in line with legal practice, which often uses average costs, because marginal costs are difficult to estimate in practice (Areeda and Turner, 1975). Third, using average costs is in line with the experimental literature on predatory pricing (e.g., Harrison, 1988; Chiaravutthi, 2007). We also take into account pricing

[12] Recall that in every period, we collect oligopoly prices in step 3.

[13] Firms can engage in several types of predatory pricing at the same time. For example, if both firms enter, for the entrant, Type 1 predatory prices are a subset of Type 2–4 predatory prices.

below the marginal or average costs of the other firm, which corresponds to above-costs predatory pricing in Edlin et al. (2019).

We expect more market tipping in the case of stronger network effects for two reasons. First, according to proposition 3, the relative benefit of being a monopolist is greater in the case of stronger network effects. Second, consistently with Hypothesis 1, stronger network effects yielding both more (threats of) predatory pricing and, in turn, more market tipping.

Hypothesis 2: There are more instances of market tipping in NET6 than in NET2 and in NET2 than in CONTROL.

We define two types of market tipping:

- Market tipping: Exactly one firm enters the market, or both firms enter the market but at least one firm has zero market share.
- Strict market tipping: Exactly one firm enters the market.

Market tipping represents the case in which a product or service is not launched, or a product or service is developed and launched, but there is no demand for the product, because the firm is unable to accumulate a viable installed base. One can think of heavily funded failed social media ventures, such as Google+ or Color, that were shut down due to low usage.[14] Strict market tipping represent the case in which a potential competitor does not launch a product or service, because it expects not to make a profit.

[14] See www.theverge.com/2019/4/2/18290637, accessed February 10, 2023, and www.applicoinc.com/blog/lack-network-effects-killed-color-app, accessed February 10, 2023.

Corollary 1 implies that collusion is more likely in markets with weaker network effects.

Hypothesis 3: Collusion is more likely in CONTROL than in NET2 and in NET2 than in NET6.[15]

We define an oligopoly price strictly greater than the long-run oligopoly equilibrium price, $p^{ol}_{i,t} > p^{O}_{i}$, (see Table 1) as a collusive price. Two firms in a market are said to collude in period t if both firms set a collusive price in period t.

5 Results

In this section, we present the experimental results. We restrict the analysis to periods 1–20, because only for these periods we have observations for all markets. In Section 5.1 we discuss the relationship between network effects and predatory pricing. We discuss market tipping and collusion in Section 5.2 and 5.3, respectively. In Section 5.4 we examine the effect of predatory pricing on consumer surplus, producer surplus and total welfare.

The following analysis is based on the oligopoly prices, $p^{ol}_{i,t}$, set by the firms in step 3. This allows us to take into account the threat of predatory pricing, even if one of the firms does not enter and consumers are offered to buy the product at the price set by the monopolist. In Appendix A we show that the results are similar if we use only market prices observed by consumers, which we call 'realized prices'.

[15] In the preregistration we hypothesized that there was no difference in the tendency to collude between treatments. We have changed this hypothesis following additional analysis.

5.1 Predatory pricing

Overall, we observe a positive relationship between the presence of network effects and predatory pricing. The results of the Wilcoxon rank-sum test and the Fisher exact test are presented in Table 2. The number of observed oligopoly prices that are below own marginal costs (Type 1 predatory pricing) is 2 out of 1,158 in CONTROL, 71 out of 1,191 in NET2 and 129 out of 1,149 in NET6, resulting in an average share of periods with Type 1 predatory pricing of 0.3%, 9.1% and 18.0% in CONTROL, NET2 and NET6, respectively. The differences between treatments are strongly statistically significant when comparing CONTROL to NET2 and CONTROL to NET6 (row 1, columns 3–6, in Table 2). Although NET2 and NET6 rank in line with Hypothesis 1, they do not differ significantly at a 5% level (row 1, columns 7 and 8, in Table 2). The limited occurrence of predatory pricing in markets without network effects is in line with earlier predatory pricing experiments (Gomez et al., 2008).

Incumbents are more likely to set a price below their own marginal costs than entrants: 73.8% of all Type 1 predatory prices are set by incumbents. In addition, 8.4% and 14.5% of all oligopoly prices set by incumbents in NET2 and NET6, respectively, are prices below their own marginal costs (Figure 1a). Still, incumbents do not play a monopolization equilibrium like the one displayed in Proposition 1, which exists in NET6: We do not observe prices less than or equal to 2 points by the incumbents in NET6 in the first period, which would imply that the entrant cannot obtain any consumers when entering.

Firms are more likely to set a price below their own average costs (Type 2 predatory pricing) in markets with stronger network effects. In line with Hypothesis 1, the share of periods per market with below own average cost pricing is significantly greater in NET2 than in CONTROL and in NET6 than in CONTROL and NET2 (row 2, columns 4, 6 and 8, in Table 2).

Firms are significantly more likely to price below the other firms' marginal costs (Type 3 predatory pricing) in markets with strong network effects (row 3, columns 5–8, in Table 2). In line with Hypothesis 1, the differences between treatments are strongly statistically significant when comparing CONTROL to NET6. The differences between NET2 and NET6 are significant at the 5% level. CONTROL and NET2 do not differ significantly at the 5% level.

Firms are significantly more likely to price below the other firms' average costs (Type 4 predatory pricing) in markets with network effects. In line with Hypothesis 1, the differences between treatments are statistically significant when comparing NET6 to CONTROL and NET2 (row 4, columns 6 and 8, in Table 2). Furthermore, in every period at least 28.1%/25.0%/43.8% of the entrants set a Type 4 predatory price in CONTROL/NET2/NET6.

We further explore the relationship between predatory pricing and the presence of network effects using a random-effects logit model (Table 3). The results confirm that there is a greater tendency to set a predatory price in markets with stronger network effects. In NET6, the probability of a price below own marginal costs is 17.1 and 8.7 percentage points greater than in CONTROL and NET2, respectively (rows 1 and 2, column 1, in Table 3). For the other types of predatory pricing the results are in line with Hypothesis 1 and similar to the results of the non-parametric tests: the likelihood of predatory pricing is greatest in NET6, followed by NET2 and CONTROL (Table 3).

Result 1: *In markets with network effects, participants are more likely to set a price below their own marginal costs (Type 1 predatory pricing) and below their own average*

Table 2: Market-level Summary Statistics and Non-parametric Test Results

	Share of periods per market with...	Share of markets with at least one instance...	CONTROL vs. NET2 Fisher's test p-value	CONTROL vs. NET2 rank-sum test p-value[a]	CONTROL vs. NET6 Fisher's test p-value	CONTROL vs. NET6 rank-sum test p-value[a]	NET2 vs. NET6 Fisher's test p-value	NET2 vs. NET6 rank-sum test p-value[a]
Type 1 predatory pricing ($p_i < MC_i$)			0.000***	0.000***	0.000***	0.000***	0.104	0.064
CONTROL	0.3%	6.3%						
NET2	9.1%	46.9%						
NET6	18.0%	65.6%						
Type 2 predatory pricing ($p_i < ATC_i$)			0.001**	0.001**	0.001**	0.000***	0.664	0.002**
CONTROL	12.0%	53.1%						
NET2	30.2%	90.6%						
NET6	54.1%	90.6%						
Type 3 predatory pricing ($p_i < MC_j$)			0.158	0.152	0.000***	0.000***	0.016*	0.034*
CONTROL	8.8%	37.5%						
NET2	15.8%	53.1%						
NET6	28.8%	81.3%						
Type 4 predatory pricing ($p_i < ATC_j$)			0.027*	0.229	0.027*	0.001**	0.754	0.005**
CONTROL	39.4%	78.1%						
NET2	46.6%	96.9%						
NET6	71.7%	96.9%						
Market tipping			0.202	0.960	0.005**	0.003**	0.074	0.001**
CONTROL	19.7%	65.6%						
NET2	16.1%	78.1%						
NET6	35.8%	93.8%						
Strict market tipping			0.500	0.735	0.074	0.265	0.119	0.105
CONTROL	18.9%	65.6%						
NET2	13.9%	68.8%						
NET6	20.5%	84.4%						
Collusion			0.603	0.417	0.801	0.938	0.305	0.372
CONTROL	14.8%	40.6%						
NET2	10.5%	31.3%						
NET6	10.0%	46.9%						
N			64	64	64	64	64	64

[a] Average ranks are used in the case of ties.

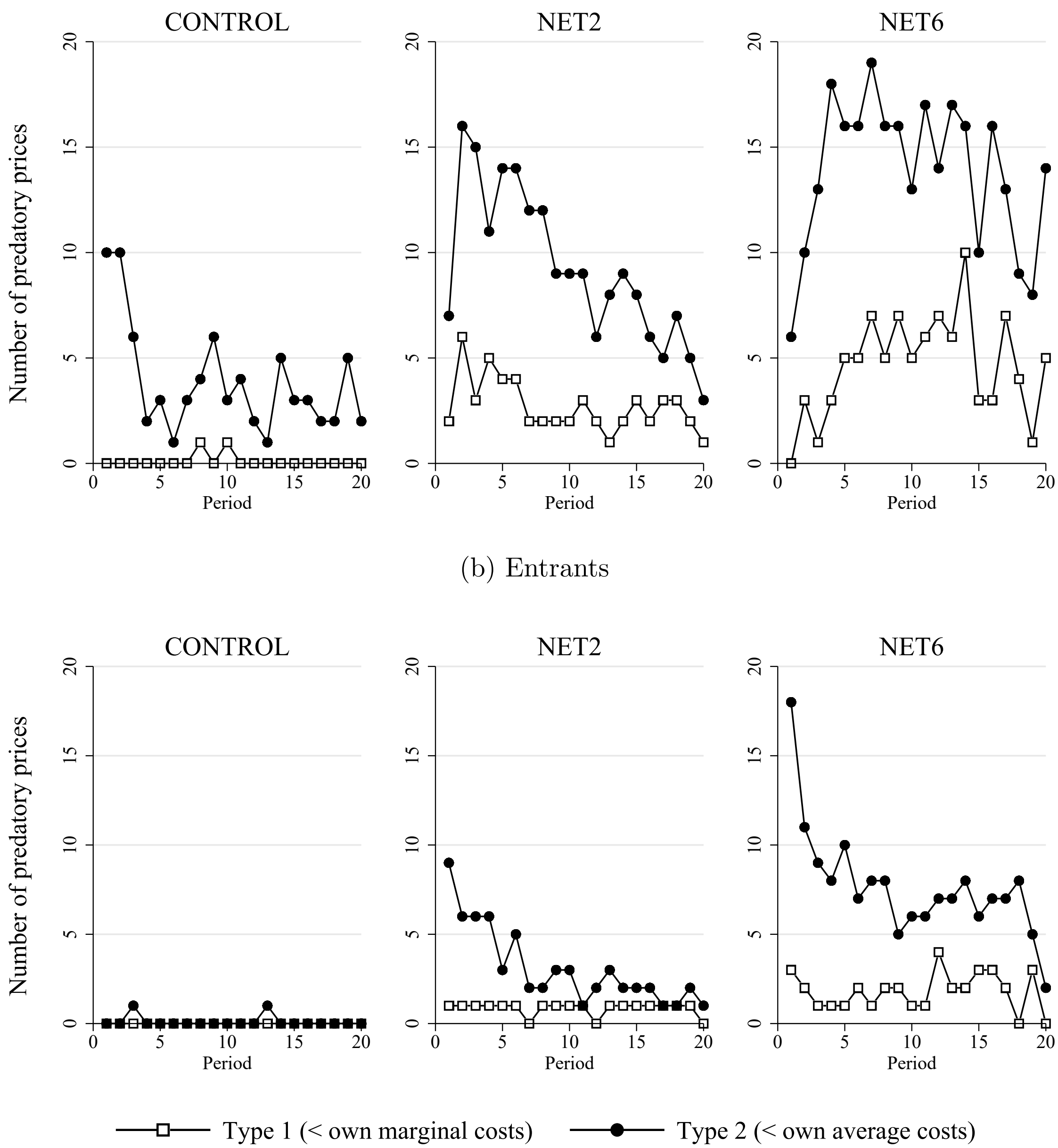
***, ** and * indicate statistical significance at the 0.1%, 1% and 5% level, respectively.

For the table with realized prices, see Table 6 in Appendix A.

Figure 1: Number of prices below own marginal costs (Type 1 predatory pricing) and below own average costs (Type 2 predatory pricing)*

(a) Incumbents

(b) Entrants



*The figures show the total number of oligopoly prices below own marginal costs and own average costs in a certain period.

Table 3: Market×period-level Random-effects logit regression for Predatory Pricing and Network Effects

Predatory price	Type 1 ($p_i < MC_i$)	Type 2 ($p_i < ATC_i$)	Type 3 ($p_i < MC_j$)	Type 4 ($p_i < ATC_j$)
NET2	0.084***	0.191***	0.079*	0.113
(ref.: CONTROL)	(3.25)	(3.42)	(1.70)	(1.37)
NET6	0.171***	0.413***	0.209***	0.321***
(ref.: CONTROL)	(4.45)	(6.75)	(3.58)	(4.06)
N	1920	1920	1920	1920

Dependent variable equals 1 if predatory price, 0 otherwise.
Average marginal effects
t statistics in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

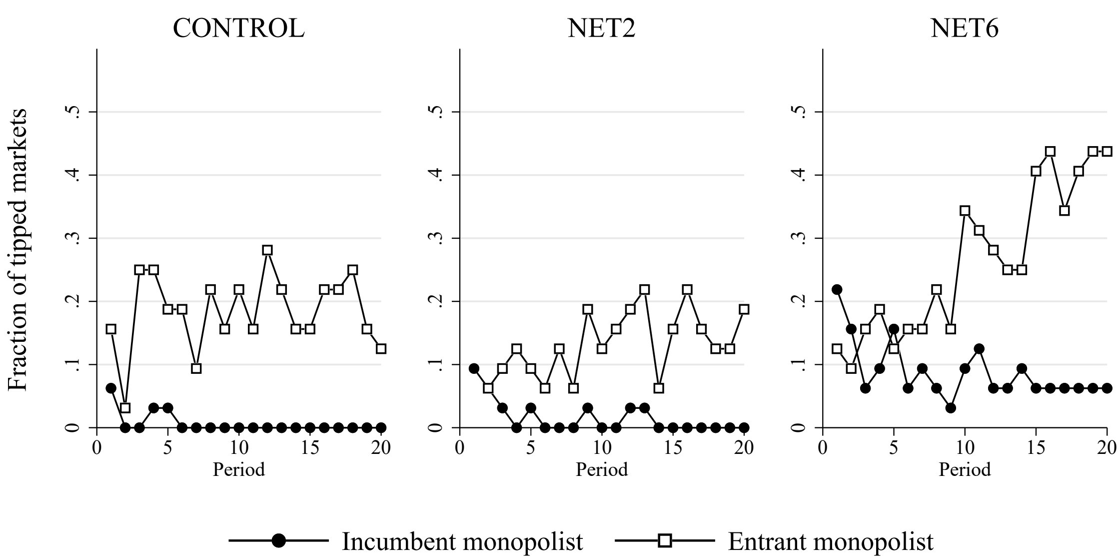
costs (Type 2 predatory pricing) than in markets without network effects. Participants are more likely to set a price below the other firms' marginal costs (Type 3 predatory pricing) and below the other firms' average costs (Type 4 predatory pricing) in markets with strong network effects, compared to markets with weak network effects or without network effects.

5.2 Market tipping

We now turn to market tipping. A tipped market - in which exactly one firm enters or one firm serves no consumers - occurs in 19.7% of periods in CONTROL, 16.1% of periods in NET2 and 35.8% of periods in NET6. In line with Hypothesis 2, there is a significant positive relationship between a market exhibiting strong network effects and the likelihood of market tipping. The results of the exact test and rank-sum tests, presented in row 5, columns 5, 6 and 8, in Table 2, suggest that there is a significantly greater number of markets with market tipping in NET6 than in CONTROL and that the share of periods with market tipping in NET6 is significantly greater than in CONTROL and NET2.

A strictly tipped market - in which at least one firm decides not to enter - occurs in 18.9% of periods in CONTROL, 13.9% of periods in NET2 and 20.5% of periods in NET6. There is no statistically meaningful relationship between the presence of network effects and strict market tipping: the null hypotheses of the exact tests and rank-sum tests presented in row 6, columns 3–8, in Table 2, cannot be rejected at conventional significance levels.

Figure 2: Fraction of tipped markets



Monopolies are more likely to exist for two or more periods in the case of strong network effects: in NET6, the probability of a tipped market in period t, conditional on a tipped market in period $t-1$, is 12.0 and 15.3 percentage points greater than in CONTROL and NET2, respectively. Furthermore, in all treatments, incumbents are rarely willing or able to deter entry. Of all (strictly) tipped markets, 83.8% (89.1%) tips towards the entrant (Figure 2). In CONTROL and NET2, all entrants sell products as early as period 2. In NET6, in all markets, the first time that both firms enter is in period 6 or earlier.

Result 2a: *In markets with strong network effects, market tipping is more likely than in markets with weak network effects or without network effects.*
Result 2b: *Strict market tipping is not significantly correlated with the presence of network effects.*

To explore the relationship between predatory pricing and market tipping we estimate a random-effects logit model (see Table 4). Surprisingly, pricing below own marginal costs is negatively related to the probability of a tipped market. One additional Type 1 predatory price significantly decreases the probability of a strictly tipped market by 11.5 and 23.9 percentage points in NET2 and NET6, respectively (rows 5 and 9, column 1, in Table 4). These results are consistent with the finding that it is mainly the incumbents who set a price below their own marginal costs, in NET2 and NET6, which unsuccessfully deters entry by the entrant.

A price below the other firms' marginal cost increases the probability of market tipping in the case of weak network effects and decreases the probability of market tipping in the case of strong network effects. One additional Type 3 predatory price in NET2 increases the probability of a (strictly) tipped market by 13.8 (8.2) percentage points (row 7, columns 3 and 7, in Table 4). This is in accordance with the finding that entrants often price below the marginal costs of the incumbents, which sometimes successfully leads to a monopoly in the following period and corresponds to Edlin et al. (2019). In NET6, an additional Type 3 predatory price decreases the probability of a (strictly) tipped market by 25.8 (18.8) percentage points (row 11, columns 3 and 7, in Table 4).

Table 4: Market×period-level Random-effects logit regression estimates for Market Tipping and Predatory Pricing

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Strict market tipping (t)				Market tipping (t)			
Predatory price in market M (t)								
CONTROL								
Type 1 ($p_i < MC_i$)	N/A				N/A			
Type 2 ($p_i < ATC_i$)		-0.200***				-0.135***		
		(-9.29)				(-3.85)		
Type 3 ($p_i < MC_j$)			0.184***				0.234***	
			(2.79)				(3.47)	
Type 4 ($p_i < ATC_j$)				0.474***				0.493***
				(15.00)				(15.62)
NET2								
Type 1 ($p_i < MC_i$)	-0.115***				-0.025			
	(-4.09)				(-0.53)			
Type 2 ($p_i < ATC_i$)		-0.162***				-0.090***		
		(-7.46)				(-3.16)		
Type 3 ($p_i < MC_j$)			0.082*				0.138***	
			(1.91)				(2.94)	
Type 4 ($p_i < ATC_j$)				N/A				N/A
NET6								
Type 1 ($p_i < MC_i$)	-0.239***				-0.288***			
	(-11.52)				(-7.72)			
Type 2 ($p_i < ATC_i$)		-0.414***				-0.131***		
		(-14.01)				(-3.45)		
Type 3 ($p_i < MC_j$)			-0.188***				-0.258***	
			(-6.75)				(-7.11)	
Type 4 ($p_i < ATC_j$)				N/A				N/A
N	640	640	640	640	640	640	640	640

Dependent variable equals 1 if market tipped, 0 otherwise.
CONTROL (NET2/NET6): Type 1 (Type 4) predicts Pr[market tipping] = 0 perfectly.
Average marginal effects
t statistics in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$
For the table with realized prices, see Table 7 in Appendix A.

5.3 Collusion

There is no significant relationship between the presence of network effects and collusion: the null hypotheses of the exact tests and rank-sum tests presented in row 7, columns 3–8, in Table 2, cannot be rejected at conventional significance levels. The prices set by incumbents in markets with network effects might indicate a willingness to collude in the beginning of the game: off all oligopoly prices set by incumbents in the first period, 6.6% in CONTROL, 37.5% in NET2 and 77.4% in NET6 are above the long-run oligopoly equilibrium price. The average oligopoly price of incumbents in the first period, conditional on entry, is 7.6 and 10.0 points in NET2 and NET6, respectively (Figure 4). However, their counterparts are unlikely to reciprocate, because in the first period only 15.6% and 9.3% of entrants sets a collusive price in NET2 and NET6, respectively.

We do observe differences in time trends in terms of collusion across treatments. The number of markets with collusion - both firms pricing above the long-run oligopoly equilibrium price - increases over time in CONTROL and NET2 (Figure 3). In NET6, there is a smaller number of collusive markets in periods 14–20 than in CONTROL and NET2, indicating a reduced incentive to collude or increased breakdown of collusion in the case of strong network effects. Moreover, collusion is less stable in the case of strong network effects: the probability of a collusive market in subsequent periods is 80.0% in CONTROL, 78.7% in NET2 and 56.5% in NET6.

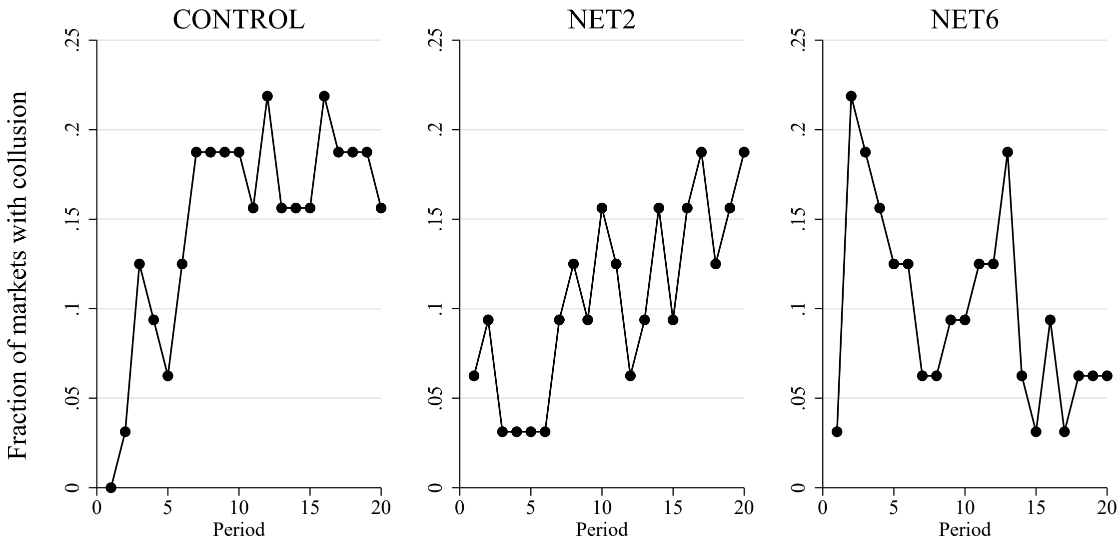
Result 3: *There is no statistically significant relationship between the presence of network effects and the share of markets with collusion.*

5.4 Welfare

To examine the relationship between network effects, predatory pricing and surplus we estimate the following linear-regression model:

$$Surplus = \alpha + \beta' X + \epsilon, \tag{2}$$

Figure 3: Fraction of markets with collusion

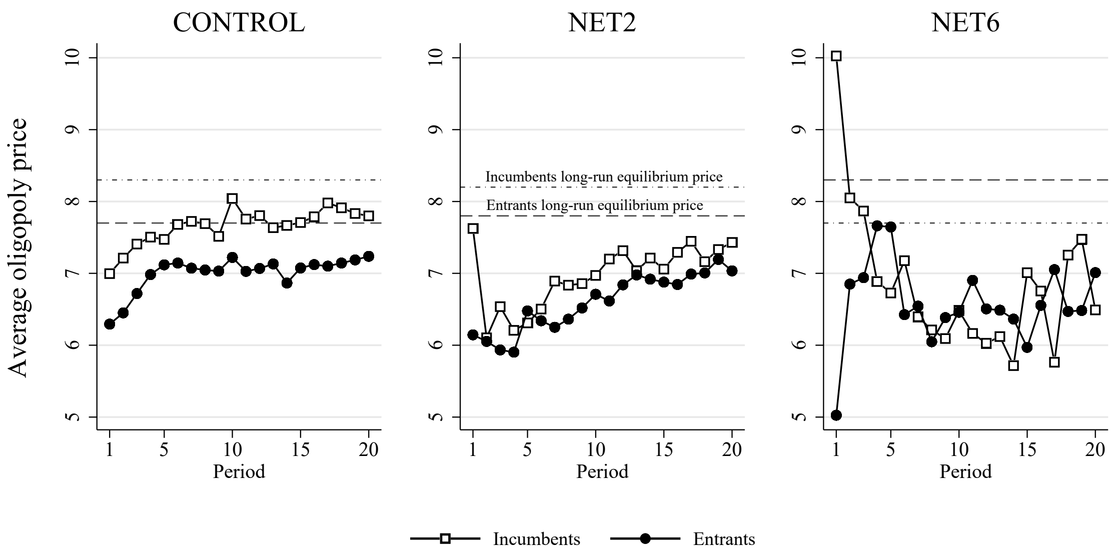


where $Surplus$ is either consumer surplus, producer surplus or total welfare averaged over rounds 1–20; X includes a dummy for predatory pricing and treatment dummies; ϵ is the error term. The estimates of equation (2) are presented in Table 5.

By and large, consumer surplus is greater in markets with network effects. The increase in the extrinsic value of the product is reflected in higher total welfare and consumers surplus in NET2 and NET6, compared to CONTROL (rows 1 and 2, columns 1 and 11, in Table 5).

There is no significant relationship between the presence of network effects and producer surplus, which suggest that the extrinsic value of the product is passed on to consumers (rows 1 and 2, column 6, in Table 5). The results presented in row 2, columns 7–10, in Table 5, show that producer surplus is significantly greater in NET6 than in CONTROL if we include predatory pricing dummies. This finding indicates that firms that do not set predatory prices in NET6 capture part of the increase in

Figure 4: Average oligopoly price

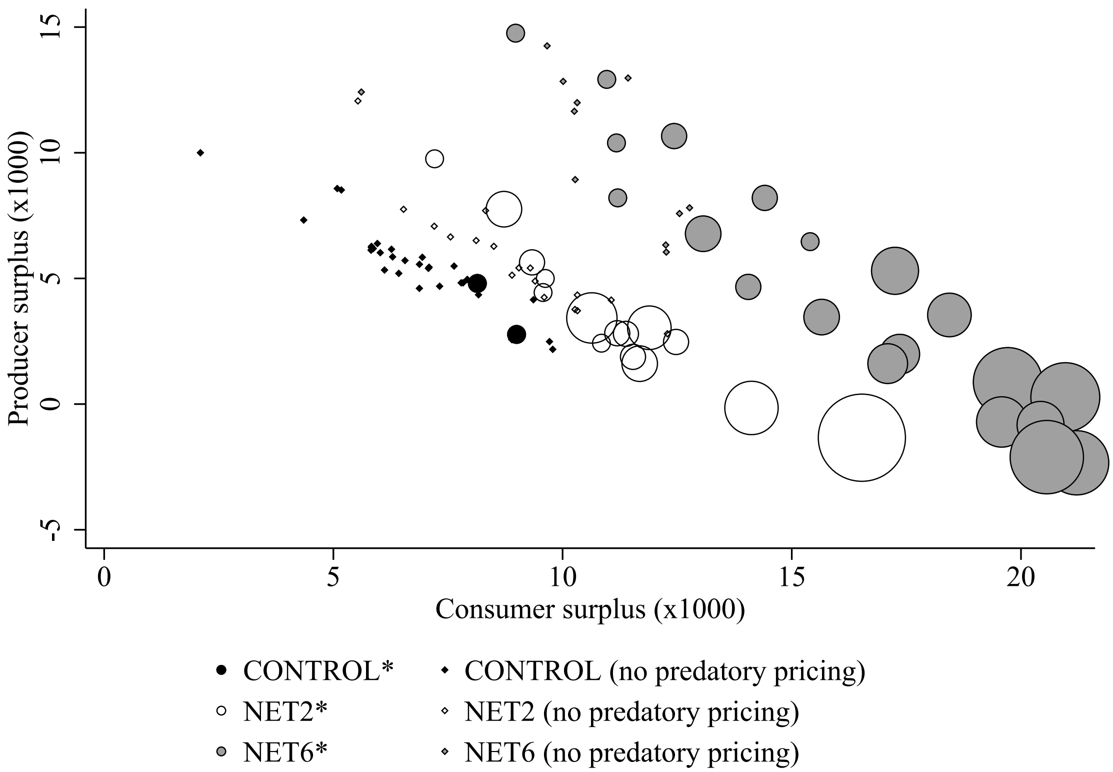


product value due to network effects, but that the general increase in profits in the case of strong network effects is offset by the greater number of predatory prices.

Predatory pricing is positively related to consumer surplus and negatively related to producer surplus (Figure 5). An additional Type 1 predatory price - below own marginal costs - increases total per period consumer surplus by 26.8 points and decreases total per period producer surplus by 29.3 points (row 3, columns 2 and 7, in Table 5). For the other types of predatory pricing the size of the effect is smaller, but one has to take into account that these types of predatory pricing are more common (see Section 5.1). There is no economically significant relationship between predatory pricing and total welfare.

Based on these result we conclude that predatory pricing leads to a wealth transfer from firms to consumers. The gain from a predatory price for consumers is equivalent to the foregone profits for firms.

Figure 5: Surplus and the number of realized Type 1 predatory prices per market



*Size of marker indicates the number of periods with predatory pricing

Result 4: *Predatory pricing is positively related to consumer surplus and negatively related to producer surplus. There is no economically significant relationship between predatory pricing and total welfare.*

Table 5: Estimation Results for Predatory Pricing and Welfare

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
	Consumer surplus					Producer surplus					Total welfare				
NET2	154.5***	96.8***	66.0***	120.2***	130.2***	-39.7	23.5	51.1	-4.0	-21.8	114.8***	120.4***	117.2***	116.2***	108.4***
(ref. CONTROL)	(4.22)	(3.87)	(3.04)	(4.85)	(4.29)	(-0.90)	(0.71)	(1.56)	(-0.12)	(-0.52)	(7.06)	(7.29)	(6.87)	(7.06)	(7.00)
NET6	371.6***	265.4***	186.8***	283.0***	278.0***	50.1	166.5***	239.9***	142.3***	119.2**	421.7***	431.9***	426.6***	425.3***	397.2***
(ref. CONTROL)	(10.16)	(10.08)	(7.58)	(10.91)	(8.38)	(1.14)	(4.79)	(6.47)	(4.00)	(2.62)	(25.94)	(24.84)	(22.06)	(24.71)	(23.45)
Predatory price															
Type 1		26.76***					-29.33***					-2.570			
($p_i < MC_i$)		(10.80)					(-8.96)					(-1.57)			
Type 2			16.85***					-17.30***					-0.445		
($p_i < ATC_i$)			(13.99)					(-9.54)					(-0.47)		
Type 3				18.31***					-19.04***					-0.729	
($p_i < MC_j$)				(10.69)					(-8.09)					(-0.64)	
Type 4					10.67***					-7.871***					2.796***
($p_i < ATC_j$)					(6.73)					(-3.62)					(3.45)
Constant	344.0***	342.3***	302.3***	311.9***	260.0***	273.2***	275.1***	315.9***	306.6***	335.2***	617.2***	617.4***	618.3***	618.5***	595.2***
	(13.30)	(19.82)	(20.15)	(17.70)	(10.54)	(8.80)	(12.06)	(14.00)	(12.66)	(9.90)	(53.69)	(54.13)	(52.50)	(52.85)	(47.22)
N	96	96	96	96	96	96	96	96	96	96	96	96	96	96	96

t statistics in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

For the table with realized prices, see Table 8 in Appendix A.

6 Conclusion

In this paper, we have experimentally analyzed predatory pricing, market tipping, and collusion in markets exhibiting network effects. Our main contributions to the literature are the following. Our experimental design is inspired by a rich experimental literature studying predatory pricing in markets without network effects (Isaac and Smith, 1985; Harrison, 1988; Capra et al., 2000; Gomez et al., 2008; Jung et al., 1994; Bruttel and Glöckner, 2011; Edlin et al., 2019) and with network effects (Chiaravutthi, 2007). We study a repeated two-player Hotelling game where an inefficient incumbent and an efficient entrant decide whether or not to enter the market. We extend the literature by exogenously varying the existence and the strength of network effects, which allows us to identify the effects of network effects on predatory pricing, market tipping, and collusion.

We observe the following. First, predatory pricing, in the sense of below-own-marginal-cost pricing, is rare in markets without network effects, which perfectly resonates with earlier observations the existing experimental literature. Second, prices below the own marginal costs and prices below the own average costs are significantly more frequent in markets with network effects than in markets without network effects. Third, markets with strong network effects exhibit more market tipping in the case of strong network effects than markets without network effects or markets with weak network effects. Fourth, collusive pricing is equally unlikely to occur across treatments. Collusion is less stable in the case of strong network effects than in the case of no network effects or weak network effects. Fifth, for the firms, predatory pricing is not an effective strategy because they tend to be unable to recoup the losses that they incur, in line with the predictions by Chicago School antitrust scholars (McGee, 1958; Bork, 1978). Consumers benefit from predatory pricing while no economically meaningful relationship between predatory pricing and total welfare exists.

Our results speak to the way predatory pricing is evaluated in the realm of antitrust law. As discussed in our literature review, the burden of proof for predatory pricing is arguably higher in the US than in the EU. The primary difference between the US and EU legal practices is that in the US, a low price is only considered predatory if there is a reasonable expectation that the firm will recoup its loss in the long-run. Our findings suggest that the recoupment requirement is relevant because consumers generally benefit from predatory pricing and predatory pricing is an indicator that the market is highly competitive. As Milgrom (1991) puts it: "[E]xpectational competition is not always a social bad: when two or more strong competitors battle to gain market share, demonstrating their commitment to their industry by cutting prices and introducing new products, the public benefits from vigorous competition."

Further research should reveal how robust our conclusions are, which are based on a single set of parameters. Our welfare results are driven by fact that for the firms, predatory pricing is an ineffective strategy in that it does not suffice to drive competitors out of the market. Future experiments may identify settings where predatory pricing is more attractive for the firms, for instance in the case of even stronger network effects or if consumers face switching costs so that it is easier and more attractive for firms to lock them in.

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Appendix A

Here, we provide the proofs of the lemma and propositions.

- Let $\tilde{u}_{i,t}$ denote the payoff of consumer x buying from firm i, assuming that $n_{i,t} = n_{i,t-1}$.
- Let p^M denote the market coverage equilibrium price in the case of a monopoly.
- Let p_i^O denote firm i's long-run equilibrium price in the case of an oligopoly.
- Let $\Delta p_{ij,t} \equiv p_{i,t} - p_{j,t}$ denote the price difference between firms in period t.
- Let $\Delta n_{ij,t} \equiv n_{i,t} - n_{j,t}$ denote the difference in the size of the market shares between firms in period t.

Location of the marginal and indifferent consumer
The market form is an oligopoly in period t when both firms pay the entry fee, F, in the first stage. Let $\hat{x}$ denote the location of the indifferent consumer in period t. The location of the indifferent consumer is determined by solving $\tilde{u}_{1,t} = \tilde{u}_{2,t}$.

$$\hat{x} = \frac{1}{2} - \frac{\Delta p_{12,t} - \mu \Delta n_{12,t-1}}{2\tau}. \tag{3}$$

The market form is a monopoly in period t when firm i pays the entry fee F, while firm j does not pay the entry fee in the first stage. Let $\overline{x}_i$ denote the location of the marginal consumer of firm i in period t. The marginal consumer is indifferent between visiting firm i and not visiting firm i in the absence of competition. The location of the marginal consumer is determined by solving $\tilde{u}_{i,t} = 0$.

$$\overline{x}_i = \left| l_i - \frac{r - p_{i,t} + \mu n_{i,t-1}}{\tau} \right| \quad \text{for} \quad i \neq j.$$

Monopoly price and monopoly profits
Assume $i \neq j$, $n_{i,t-1} = 1$ and $\overline{x}_i > 0$. If firm j does not enter the market, the profit of firm i is the following.

$$\pi_{i,t}(p_{i,t}, n_{i,t}, c_i, F) = (p_{i,t} - c_i)|\overline{x}_i - l_i| - F.$$

The one-shot Nash equilibrium monopoly price is the following.

$$p_i^* = \frac{1}{2}(c_i + r + \mu).$$

The market coverage monopoly price is found by solving $\tilde{u}_{i,t} = 0$ for the marginal consumer, located at $\overline{x}_i = 1 - l_i$.

$$p^M = r + \mu - \tau.$$

The market coverage monopoly price is also the profit maximizing price when

$$p^M \geq p_i^* \implies \mu \geq 2\tau + c_i - r. \tag{4}$$

Given that equation (4) holds, profit in the case of a monopoly is the following.

$$\pi_i^M = (r + \mu - \tau - c_i) - F. \tag{5}$$

Proof of Lemma 1

Assume $i \neq j$, $n_{i,t-1} = 1$ and equation (4) holds. Assume firm i sets $p_{i,t} = 0$ in the case of entry by firm j. As a result, $n_{j,t} = 0$ if, for the consumer located at $x = 1 - l_i$,

$$\tilde{u}_{i,t} \geq \tilde{u}_{j,t} \implies \mu \geq \tau - p_j.$$

Substitute $p_j = c_j$ to find the result stated in the lemma.

Proof of Lemma 2

Assume $n_{1,t-1} = 1$. Firm 2 is deterred from entering the market in period t if $\pi_{2,t} \leq 0$ at a price $p_{1,t} = 0$. The reaction function of the entrant is $p_{2,t} = \frac{1}{2}(p_{1,t} + c_2 + \tau - \mu)$. The location of the indifferent consumer in the case of entry is the following.

$$\hat{x} = \frac{3\tau - p_{1,t} + c_2 + \mu}{4\tau}$$

Firm 2 stays out if the following condition holds.

$$\hat{x} > 1 \implies p_{1,t} < c_2 - \tau + \mu \tag{6}$$

The profit of firm 2 in the case of entry is the following.

$$\begin{aligned}\pi_{2,t} &= (p_{2,t} - c_2)(1 - \hat{x}) - F \\ &= \frac{(c_2 - p_{1,t} - \tau + \mu)^2}{8\tau} - F\end{aligned}$$

Assume $i \neq j$. The maximum price that deters entry, $\overline{p}_i$, follows from the symmetry of the two firms, $\pi_{2,t} = 0$ and equation (6).

$$\overline{p}_i = c_j - \tau + \mu - 2\sqrt{2}\sqrt{\tau F}. \tag{7}$$

Proof of Proposition 1

Assume $i \neq j$, $n_{i,t-1} = 1$, $n_{j,t-1} = 0$, $p_{j,t} = BR_j(p_{i,t}, 0, 1)$ and equation (4) holds. Substitute $p_1 = 0$ in equation (7). This price will deter entry if

$$\pi_{2,t} \leq 0 \implies \mu \geq \tau - c_2 - 2\sqrt{2}\sqrt{\tau F}.$$

The result follows from the symmetry of the two firms.

Proof of Proposition 2

We now turn our attention to oligopolistic markets.

Location of the indifferent consumer, prices and profits

In the case of an oligopoly and if and only if the indifferent consumer buys a product in equilibrium, the profit of firm i is the following.

$$\pi_{i,t}(p_{i,t}, p_{j,t}, n_{i,t}, n_{j,t}, c_i, F) = (p_{i,t} - c_i)|\hat{x} - l_i| - F \quad \text{for} \quad i = 1, 2. \tag{8}$$

We maximize the profit function, defined in (8), with respect to p_{it}, which gives us the following reaction functions.

$$\begin{aligned} \max_{p_{i,t}} \pi_i(p_{i,t}, p_{j,t}, n_{i,t}, n_{j,t}, c_i, F) \implies p_{1,t} &= \frac{1}{2}(p_{2,t} + c_1 + \tau + \mu\Delta n_{12,t-1}), \\ p_{2,t} &= \frac{1}{2}(p_{1,t} + c_2 + \tau - \mu\Delta n_{12,t-1}). \end{aligned}$$

In the long-run equilibrium, $\Delta n_{12,t-1} = 2\hat{x} - 1$ for $t \to \infty$. The location of the indifferent consumer is the following.

$$\hat{x} = \frac{1}{2} - \frac{\Delta p_{12,t} - \mu(2\hat{x} - 1)}{2\tau} \tag{9}$$

The equilibrium prices are as follows.

$$\begin{aligned} p^*_{1,t} &= \tau + \frac{2c_1 + c_2 + \mu(2\hat{x} - 1)}{3} \\ p^*_{2,t} &= \tau + \frac{2c_2 + c_1 - \mu(2\hat{x} - 1)}{3} \end{aligned} \tag{10}$$

We substitute (10) into (9) and solve for the location of the indifferent consumer in the long-run equilibrium, $\hat{x}$. In the long-run equilibrium, the location of the indifferent consumer is given by

$$\hat{x} = \frac{3\tau - \mu - c_1 + c_2}{2(3\tau - \mu)} \quad \text{for} \quad 0 < \hat{x} < 1, \quad 3\tau \neq \mu.$$

The location of the indifferent consumer gives us the admissible marginal cost difference for the existence of an oligopoly.

$$\begin{aligned} \hat{x} \geq 0 &\implies \mu \leq 3\tau - c_1 + c_2 \\ \hat{x} \leq 1 &\implies c_1 - c_2 \geq \mu - 3\tau \end{aligned}$$

Notice that the second equation always holds as $c_1 - c_2 \geq 0$ implies that $3\tau \geq \mu$. The long-run equilibrium prices are the following.

$$p_i^O = \frac{3\tau^2 + c_i(2\tau - \mu) + \tau(c_j - \mu)}{3\tau - \mu}, \quad \text{for} \quad i \neq j, \quad 3\tau \neq \mu.$$

Profits in the long-run equilibrium are given by

$$\pi_1^O = \frac{\tau(c_1 - c_2 - 3\tau + \mu)^2}{2(\mu - 3\tau)^2} - F, \quad \pi_2^O = \frac{\tau(c_1 - c_2 + 3\tau - \mu)^2}{2(\mu - 3\tau)^2} - F, \quad \text{for} \quad 3\tau \neq \mu. \tag{11}$$

Maximum entry fee
In order to ensure entry by both firms, the maximum entry fee is equal to the profit of firm 1, which has the highest marginal costs. This gives

$$\pi_1^O < 0 \implies F < \frac{\tau(c_1 - c_2 - 3\tau + \mu)^2}{2(\mu - 3\tau)^2}.$$

Market coverage
If the indifferent consumer, located at $\hat{x}$, buys a product from one of the firms in equilibrium, we know that all consumers will buy a product in equilibrium. Therefore, in the long-run equilibrium, the market is covered if and only if

$$\tilde{u}_i^{\hat{x}} \geq 0 \implies \mu \geq c_1 + c_2 + 3\tau - 2r.$$

Proof of Proposition 3

Combining the profit of firm i as a monopolist, equation (5), and in the long-run equilibrium, equation (11), we find that

$$\frac{\partial}{\partial\mu}(\pi_1^M - \pi_1^O) = \frac{(\mu-3\tau)(\tau(c_1-c_2)+(\mu-3\tau)^2)+\tau(c_1-c_2)^2}{(\mu-3\tau)^3},$$
$$\frac{\partial}{\partial\mu}(\pi_2^M - \pi_2^O) = \frac{(\mu-3\tau)(\tau(c_2-c_1)+(\mu-3\tau)^2)+\tau(c_1-c_2)^2}{(\mu-3\tau)^3}.$$

Apply symmetry to find that $\frac{\partial}{\partial\mu}(\pi_i^M - \pi_i^O) > 0$, for $i = 1, 2$, if $\mu < 3\tau$ and $(\mu - 3\tau)^2 > \tau(c_1 - c_2)$.

Proof of Proposition 4

We now turn our attention to the collusive equilibrium.

- Let p^{Col} denote the collusive equilibrium price.
- Let π_i^{Col} denote one-shot profits when firms i, j set p^{Col}.
- Let p_i^{Dev} denote the one-shot profit-maximizing price for a firm that deviates from p^{Col}.
- Let π_i^{Dev} denote the profits that the deviating firm i will obtain in period t by setting a price p_i^{Dev}.
- Let π_i^{Punish} denote the profits of firm i, after it has deviated and when it is is being punished by firm j.
- Let $\hat{x}_t^i$ denote the location of the indifferent consumer in period t in the case of a deviation by firm i.

We assume that the two firms agree to divide the market in half and set a price, so that the consumer located in the middle is indifferent between visiting firm i and firm j. Firms play according to a grim trigger strategy with $p_i^{Punish} = 0$.

The price in the case of collusion is the following.

$$p^{Col} = r + \tfrac{1}{2}(\mu - \tau).$$

Profit in the case that both firm set the collusive equilibrium price is the following.

$$\begin{aligned}\pi_i^{Col} &= (p^{Col} - c_i)\tfrac{1}{2} \\ &= \frac{r - c_i + \frac{1}{2}(\mu - \tau)}{2} - F, \quad \text{for} \quad i = 1, 2.\end{aligned}$$

Given that firm j sets the collusive price p^{Col}, the profit-maximizing price for firm i in period t is the following.

$$p_i^{Dev} = \frac{r + c_i + \frac{1}{2}(\mu + \tau)}{2}.$$

The location of the indifferent consumer in the case that firm $i = 1, 2$ deviates in period t is the following.

$$\hat{x}_t^1 = \frac{1}{8} + \frac{2(r - c_1) + \mu}{8\tau}, \quad \hat{x}_t^2 = \frac{7}{8} - \frac{2(r - c_2) + \mu}{8\tau}.$$

In the case that firm $i = 1, 2$ deviates in period t, profits for firm i are

$$\begin{aligned} \pi_i^{Dev} &= (p_i^{Dev} - c_i)|l_i - \hat{x}_t^i| - F \\ &= \frac{(2(r - c_i) + \mu + \tau)^2}{32\tau} - F. \end{aligned}$$

Collusion is sustainable if the discounted collusive profits are be sufficiently high. This is the case if the case of the following critical discount factor.

$$\delta \geq \underline{\delta} = \frac{\pi_i^{Dev} - \pi_i^{Col}}{\pi_i^{Dev} - \pi_i^{Punish}} = \frac{\left(r - c_i + \frac{1}{2}(\mu - 3\tau)\right)^2}{(r - c_i + \frac{1}{2}(\mu + \tau))^2 - 8\tau F} \quad \text{for} \quad i = 1, 2.$$

Notice that $\frac{\partial}{\partial \mu}\underline{\delta} > 0$ if $\mu \notin (2(c_i - r) + 8F - \tau, 2(c_i - r) + 3\tau)$ and $0 < F \leq \frac{\tau}{2}$. If the strength of the network effects increases a firm will obtain half of the additional extrinsic value in the case of collusion. In the case of a monopoly, the firm can extract all of the additional extrinsic value. A monopoly therefore becomes relatively more attractive and the incentive to deviate greater if the strength of network effects increases.

We now turn to the critical marginal costs level. The marginal costs of firm j should be sufficiently high, so that firm j cannot profitably enter the market in the punishment phase if firm i sets $p_i^{Punish} = 0$. In the case of a deviation by firm 1, the anticipated difference in market shares in period $t + 1$ is

$$\Delta\tilde{n}_{12,t+1} = 2\hat{x}_t^1 - 1 = \frac{2r - 2c_1 - 3\tau + \mu}{4\tau}.$$

In the case of a deviation by firm 2, the anticipated market share difference in period $t + 1$ is

$$\Delta\tilde{n}_{12,t+1} = 2\hat{x}_t^2 - 1 = \frac{2c_2 - 2r + 3\tau - \mu}{4\tau}.$$

Firm j punishes a deviation by firm i in period $t+1$ by setting a price of $p_j^{Punish} = 0$. The best response of firm i is the following.

$$p_{i,t+1} = \frac{c_i(4\tau - 2\mu) + \mu(2r - 3\tau) + \mu^2 + 4\tau^2}{8\tau} \quad \text{for} \quad i = 1, 2.$$

In the case of a deviation by firm 1 and given that firm 2 sets a price $p_2^{Punish} = 0$, the location of the indifferent consumer in period $t+1$ is the following.

$$\hat{x}^1_{t+1} = \frac{\mu(2r - 3\tau) - c_1(4\tau + 2\mu) + \mu^2 + 12\tau^2}{32\tau^2}.$$

In the case of a deviation by firm 2 and given that firm 1 sets a price $p_1^{Punish} = 0$, the location of the indifferent consumer in period $t+1$ is the following.

$$\hat{x}^2_{t+1} = \frac{c_2(4\tau + 2\mu) - \mu(2r - 3\tau) - \mu^2 + 12\tau^2}{16\tau^2}.$$

Firm $i = 1, 2$ is deterred from entering if and only if

$$\begin{aligned} &\pi_i^{Punish} \leq 0 \\ &\underline{c} \equiv c \geq \frac{\mu(\mu + 2r) - \tau(3\mu - 4\tau) - 8\sqrt{2}\sqrt{F\tau^3}}{2(\mu + 2\tau)} \quad \text{for} \quad \mu \neq 2\tau. \end{aligned}$$

Notice that $\frac{\partial}{\partial\mu}\underline{c} > 0$ if $\mu > \frac{5}{2}\tau - r$ and $\tau > 0$.

Table 6: Market-level Summary Statistics and Non-parametric Test Results (realized prices)

	Share of periods per market with...	Share of markets with at least one instance...	H_0: incidence in CONTROL ≥ NET2 Fisher's test p-value	rank-sum test p-value[a]	H_0: incidence in CONTROL ≥ NET6 Fisher's test p-value	rank-sum test p-value[a]	H_0: incidence in NET2 ≥ NET6 Fisher's test p-value	rank-sum test p-value[a]
Type 1 predatory pricing ($p_i < MC_i$)			0.000***	0.000***	0.000***	0.000***	0.104	0.063
CONTROL	0.3%	6.3%						
NET2	8.8%	46.9%						
NET6	18.0%	65.6%						
Type 2 predatory pricing ($p_i < ATC_i$)			0.001**	0.001**	0.001**	0.000***	0.664	0.002**
CONTROL	11.9%	53.1%						
NET2	29.5%	90.6%						
NET6	53.4%	90.6%						
Type 3 predatory pricing ($p_i < MC_j$)			0.104	0.104	0.000***	0.000***	0.032*	0.043*
CONTROL	6.4%	34.4%						
NET2	12.7%	53.1%						
NET6	27.2%	78.1%						
Type 4 predatory pricing ($p_i < ATC_j$)			0.027*	0.229	0.027*	0.001**	0.754	0.005**
CONTROL	39.4%	78.1%						
NET2	46.6%	96.9%						
NET6	71.7%	96.9%						
N			64	64	64	64	64	64

[a] Average ranks are used in the case of ties.

***, ** and * indicate statistical significance at the 0.1%, 1% and 5% level, respectively.

Table 7: Market×period-level Random-effects logit regression estimates for Market Tipping and Predatory Pricing (realized prices)

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Strict market tipping (t)				Market tipping (t)			
Realized predatory price in market M $(t-1)$								
CONTROL								
Type 1 ($p_i < MC_i$)	N/A				N/A			
Type 2 ($p_i < ATC_i$)		0.137**				0.162***		
		(2.43)				(2.82)		
Type 3 ($p_i < MC_j$)			0.277***				0.299***	
			(3.46)				(3.71)	
Type 4 ($p_i < ATC_j$)				0.381***				0.387***
				(11.48)				(11.58)
NET2								
Type 1 ($p_i < MC_i$)	-0.079**				-0.061			
	(-2.07)				(-1.35)			
Type 2 ($p_i < ATC_i$)		0.008				0.019		
		(0.27)				(0.56)		
Type 3 ($p_i < MC_j$)			0.084*				0.105**	
			(1.71)				(2.03)	
Type 4 ($p_i < ATC_j$)				0.220***				0.242***
				(7.82)				(8.21)
NET6								
Type 1 ($p_i < MC_i$)	-0.148***				-0.227***			
	(-4.43)				(-5.38)			
Type 2 ($p_i < ATC_i$)		-0.116***				-0.103***		
		(-3.48)				(-2.65)		
Type 3 ($p_i < MC_j$)			-0.170***				-0.199***	
			(-5.60)				(-5.06)	
Type 4 ($p_i < ATC_j$)				0.165***				0.312***
				(5.40)				(8.83)
N	606	608	608	608	606	608	608	608

Dependent variable equals 1 if market tipped, 0 otherwise.
Average marginal effects
t statistics in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 8: Estimation Results for Predatory Pricing and Welfare (realized prices)

	(1) CS	(2) CS	(3) CS	(4) CS	(5) CS	(6) PS	(7) PS	(8) PS	(9) PS	(10) PS	(11) TW	(12) TW	(13) TW	(14) TW	(15) TW
NET2	154.5***	99.35***	64.43***	116.9***	130.2***	-39.72	20.88	52.69	1.096	-21.76	114.8***	120.2***	117.1***	118.0***	108.4***
	(4.22)	(3.99)	(3.00)	(5.48)	(4.29)	(-0.90)	(0.64)	(1.62)	(0.04)	(-0.52)	(7.06)	(7.30)	(6.86)	(7.24)	(7.00)
NET6	371.6***	265.8***	181.6***	262.1***	278.0***	50.10	166.3***	245.0***	168.8***	119.2**	421.7***	432.1***	426.6***	431.0***	397.2***
	(10.16)	(10.12)	(7.41)	(11.58)	(8.38)	(1.14)	(4.80)	(6.60)	(5.30)	(2.62)	(25.94)	(24.88)	(21.91)	(24.95)	(23.45)
Type 1		27.70***					-30.42***					-2.717			
		(10.84)					(-9.02)					(-1.61)			
Type 2			17.47***					-17.92***					-0.447		
			(14.24)					(-9.63)					(-0.46)		
Type 3				21.90***					-23.75***					-1.842	
				(13.63)					(-10.51)					(-1.50)	
Type 4					10.67***					-7.871***					2.796***
					(6.73)					(-3.62)					(3.45)
Constant	344.0***	335.7***	301.4***	315.9***	260.0***	273.2***	282.3***	316.9***	303.7***	335.2***	617.2***	618.0***	618.3***	619.6***	595.2***
	(13.30)	(19.46)	(20.31)	(20.91)	(10.54)	(8.80)	(12.40)	(14.10)	(14.30)	(9.90)	(53.69)	(54.16)	(52.46)	(53.75)	(47.22)
N	96	96	96	96	96	96	96	96	96	96	96	96	96	96	96

t statistics in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Appendix B

These are the instructions and practice questions for participants in treatment NET6. Participants in CONTROL received the same instructions and practice questions, minus the information on the number of consumers buying from the firm in the previous period.

Welcome!

This is an economics experiment. If you pay close attention to these instructions, you can earn a significant sum of money, which will be transferred to your bank account within 7 days.

Online experiment
This is an online experiment. The software we use has been adapted for online laboratory experiments. This means that we expect you to behave as if this is an offline experiment in the laboratory: pay attention to the information on the screen, make sure that you are not interrupted during the experiment and do not communicate with other people, offline or online.

In this online experiment, all the rules for economic experiments at the *CREED Laboratory* apply and the experiment has been approved by the *Economics and Business Ethics Committee* (EBEC) of the University of Amsterdam.

The experiment

In this experiment you will act as a firm. There are 100 consumers that want to buy a product. Another participant plays the role of another firm that wants to sell products to the same consumers.

Timing
The experiment consists of at least 20 rounds. From round 20 onwards, a new round starts with 80% probability. In other words, from round 20 onwards, the experiment stops with 20% probability.

Participants
Before the start of the experiment, you will be matched to another participant. You will continue to play with the same participant throughout the experiment. Participants will remain anonymous; you will not know with whom you are matched. Moreover, participants will only communicate with each other through the experimental software.

We, as experimenters, also do not know your identity. Information that might lead to your identity - such as correspondence or your bank account number - will be deleted after the money has been transferred to your bank account.

Earnings
In every round of the experiment, you can earn or lose points. At the end of every round, these points are added to or subtracted from your 'Total payoff'. At the end of the experiment, the 'Total payoff' will be exchanged for Euros.

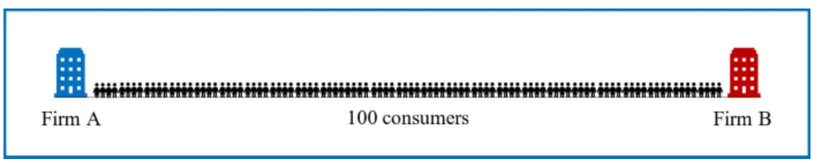
The exchange rate: **400 points = €1**

Two firms
The market consists of two firms. You play the role of firm A or B, while the other participant is the other firm. Firm A is located on the east end of a street, while firm B is located at the west end of the same street (see image below).

Endowment
Firm A starts with an endowment of 5,000 points and firm B starts with 3,000 points. The endowment is added to your 'Total payoff' at the beginning of the game.

Bankruptcy
You are bankrupt if, at the end of some round, your 'Total payoff' is below 0 points. You will be excluded from the experiment after this round and will not receive any money in your bank account.

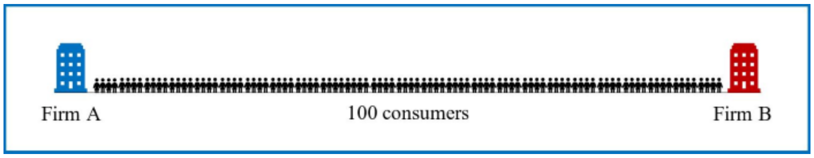
Total payoff = endowment + sum of profits over all rounds.



Entry fee
At the start of each round, both firms receive 50 points. In every round both firms decide whether to enter the market. If a firm enters the market, it pays an entry fee of 50 points. If a firm does not enter the market, it does not sell products and its profit in that round will be 50 points.

Unit cost
If a firms wants to sell a product it has to be produced. The unit cost to produce one unit is 5 points for firm A and 3 points for firm B. Imagine you are firm A and sell your product to 30 consumers; in that case your total costs in this round is 5 * 30 = 150 points.

100 Consumers
There are 100 consumer that all have an address on the same street, located between firm A and firm B (see image below).
The 100 consumers decide every round whether to buy a product and from which firm to buy that product. Consumers do not have to buy a product; if a consumer does not obtain positive utility from buying, he or she will not buy from either of the firms in that round.



The choice made by a consumer is automated. A consumers buys a product from the firm which provides her with the highest utility. A consumer does not buy a product when she receives negative utility from both firms.

The utility a consumer derives from a product is calculated as follows:
Consumer utility = value of the product - travel costs - price

We will now examine these three aspects in more detail.

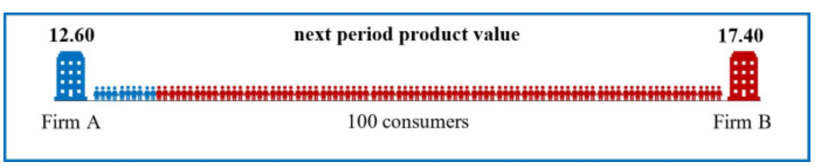
The utility a consumers derives from a product is calculated as follows:
Consumer utility = value of the product - travel costs - price

The value of the product is 12 points
The value of the product is the same for your product and the product offered by the other participant.

The value of a firm's product increases by 0.06 points for each consumer that has bought from the firm in the previous round.
Consumers attribute more value to a product when other consumers bought from the same firm in the previous round.

Example 1:
If you do not enter the market in a certain round, you will have 0 consumers in that round and your product will therefore be worth 12 points in the next round.

Example 2 (see image below):
10 consumers buy a product from firm A and 90 consumers buy a product from firm B.
The value of firm A's product in the next round is 12 + 10 * 0.06 = 12.60 points.
The value of firm B's product in the next round is 12 + 90 * 0.06 = 17.40 points.

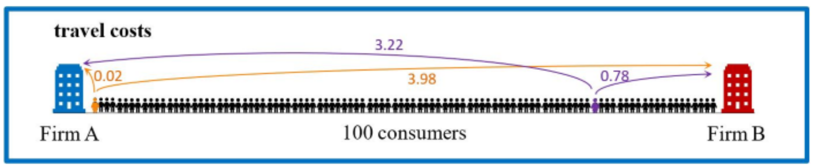


The utility a consumers derives from a product is calculated as follows:
Consumer utility = value of the product - travel costs - price

Travel costs: Consumers pay 0.02 points to travel, plus 0.04 points for every consumer they pass on the way to a firm.

Example 1 (see image below):
The consumer in orange is called Alice.
There are no consumers to the left of Alice, which means that her travel costs equal 0.02 points if she buys from firm A.
There are 99 consumers to her right, which means that her travel costs equal 99 * 0.04 + 0.02 = 3.98 points when buying from firm B.

Example 2 (see image below):
The consumer in purple is called Bob.
Bob has to pass 80 people to buy from firm A, which will cost him 80 * 0.04 + 0.02 = 3.22 points.
Bob passes 19 consumers on his way to firm B, which will therefore cost him 19 * 0.04 + 0.02 = 0.78 points.



The utility a consumers derives from a product is calculated as follows:
Consumer utility = value of the product - travel costs - price

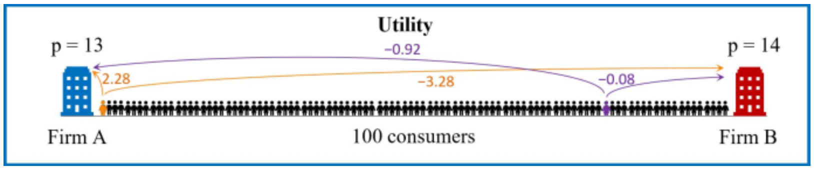
The price of the product.
Consumers buy from the company that provides them with the highest utility, taking into account the prices the companies set, the travel costs and the number of customers in the previous round.

Suppose that firm A sets a price of 13 and firm B sets a price of 14. Moreover, in the previous round, 55 consumers have bought a product from firm A and 45 consumers have bought a product from firm B.

Example 1:
Alice's utility from buying from firm A is 12 + 3.3 - 0.02 - 13 = 2.28
Alice's utility from buying from firm B is 12 + 2.7 - 3.98 - 14 = -3.28
Alice will therefore buy from firm A.

Example 2:
Bob's utility from buying from firm A is 12 + 3.3 - 3.22 - 13 = -0.92
Bob's utility from buying from firm B is 12 + 2.7 - 0.78 - 14 = -0.08
Bob will therefore not buy a product in this round.

Now that we know how consumers decide, it is time to look at your decisions.

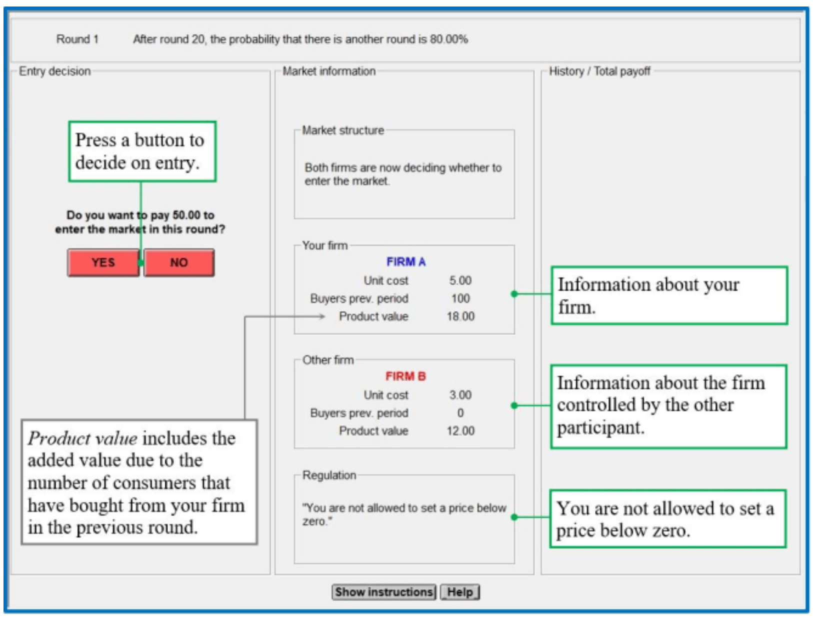


Your decisions

Every round consists of 3 steps. Each step is accompanied by a decision screen, which is displayed in the image below.

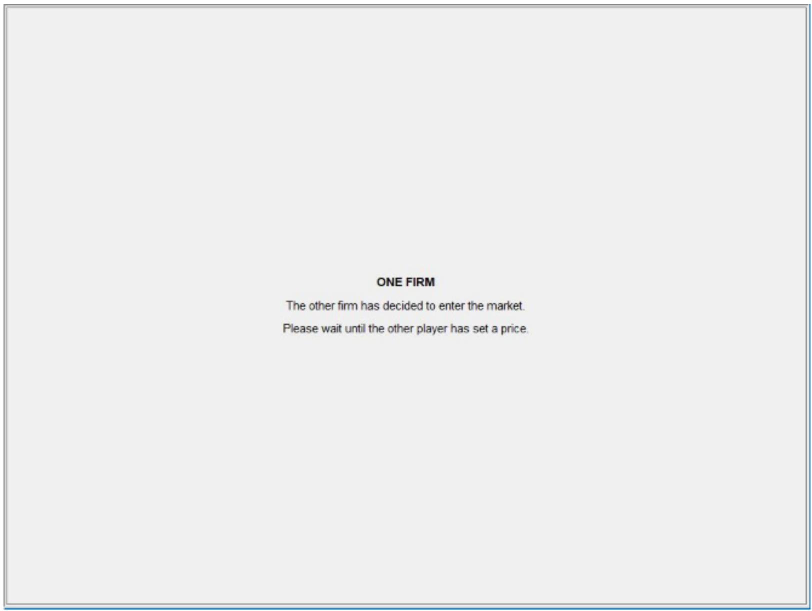
Step 1: Entry decision

In step 1, you will decide whether you want to pay 50 points to enter the market in this round. Independently of your decision, the other firm decides whether or not to pay 50 points to enter the market



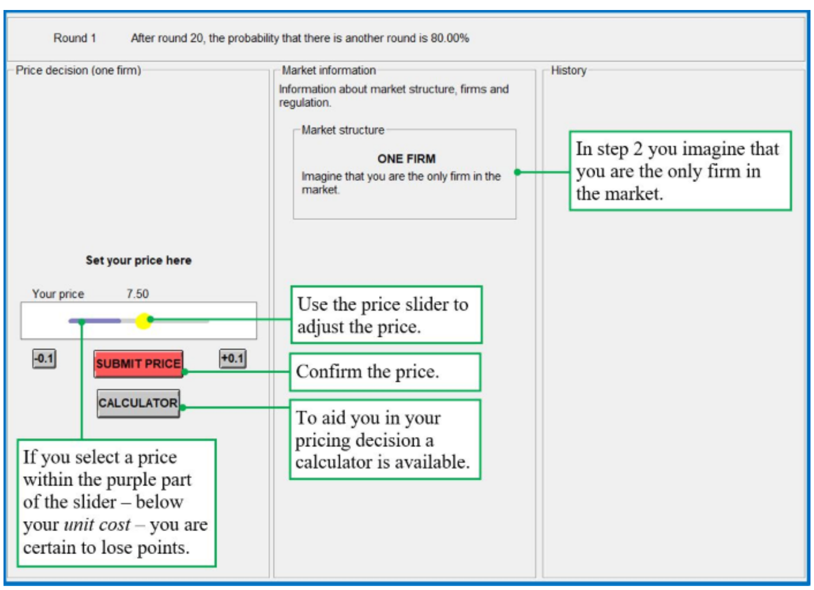
What happens if you decide not to enter the market?

If only one of the participants decides to enter the market, the screens shown to participants differ. A participant that has not entered the market keeps the 50 points received at the start of the round and waits until the other participant has completed step 2 and 3.



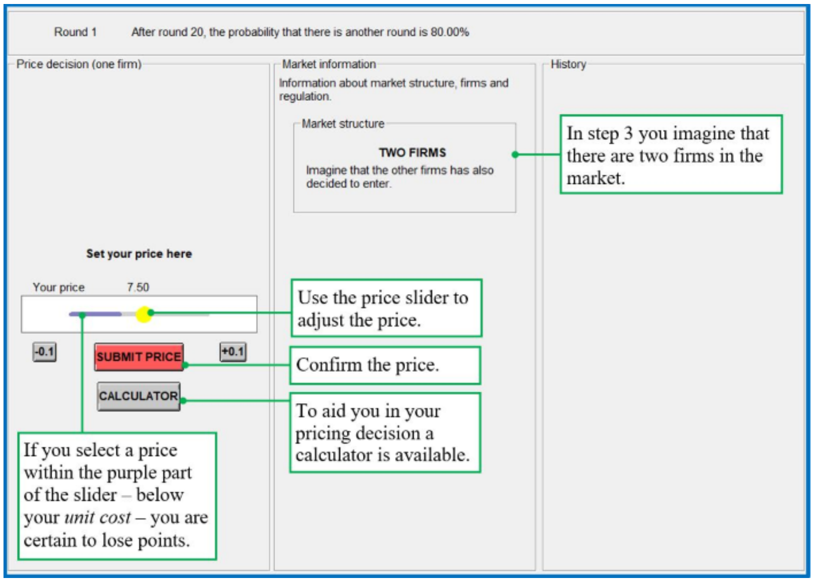
Your decisions
Every round consists of 3 steps. Each step is accompanied by a decision screen.

Step 2: Price in the case of entry by your firm only
The price you set in step 2 determines your profit if the other firm does not enter the market.

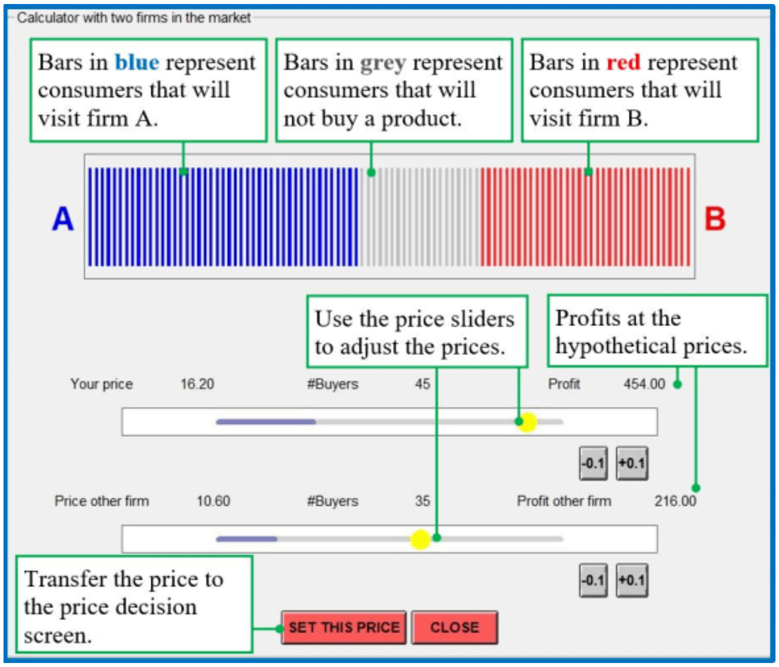


Your decisions
Every round consists of 3 steps. Each step is accompanied by a decision screen.

Step 3: Price in the case of entry by both firms
The price you set in step 3 determines your profit if the other firm has also decided to enter the market.



The calculator
The street, with the two firms and the 100 consumers, is graphically displayed. The calculator automatically takes into account the number of consumers that have visited both firms in the previous round and the travel costs of consumers.



What happens if the experiment crashes?
The experimental software might experience a crash, either for one or all participants. The procedure after a crash is as follows:

* First crash: We will try to restart the experiment. This will take a couple of minutes. If the restart is successful you continue in the same round the crash occurred. If the restart is not successful we will pay you the amount you have earned up until the moment of the crash.

* Second crash: We will not restart the experiment. We will pay you the amount you have earned up until the moment of the second crash.

Practice questions
Now that you know everything about the game it is time to start with 8 practice questions. These questions will familiarize you with the interface and test your understanding of the instructions.

What is the minimum number of rounds you will play?
◯ 10
◯ 20
◯ 30
◯ 40

After period 20, what is the probability that there is another round?
◯ 60%
◯ 70%

◯ 80%
◯ 90%

During the game, you will...

◯ ...be matched to another participant after round 5, 10, 15 and 20.
◯ ...always be matched to the same participant.
◯ ...be matched to another participant with 5% probability every round.
◯ ...not be matched to another participant.

In the first step you have to decide whether or not to enter the market. If you decide not to enter the market you will...

◯ ...lose all consumers that have bought from your firm in the previous round.
◯ ...retain only the consumers that decide not to visit the other firm.
◯ ...be able to transfer your consumers to the following round.

The following four questions represent different scenario's. Use the calculator to find the answers.

In this scenario you are **FIRM A** and all 100 consumers have chosen to buy from your firm in the previous round.

Assume that the other firm has also decided to enter the market.
You set a price of 16.00, while the other participant sets a price of 11.00.
How many consumers decide NOT to buy a product in this round?
(Hint: Press the CALCULATOR-button)

Number of consumers not buying a product:

...

In this scenario you are **FIRM B** and 45 consumers have chosen to buy from your firm in the previous round, The other 55 consumers have visited the other firm.

Assume that the other firm has also decided to enter the market.
You set a price of 2.00, while the other firm sets a price of 3.00.

1) How many consumers decide to buy from your firm?

...

2) What is your profit in this round?

...

(Hint: Press the CALCULATOR-button)

In this scenario you are **FIRM A** and all 100 consumers have chosen to buy from your firm in the previous round.

Assume that the other firm has also decided to enter the market.
The other firm sets a price of 6.00 in this round.

1) What is the price that MAXIMIZES your profit?

...

2) How many consumers visit your firm at this price?

...

(Hint: Press the CALCULATOR-button)

In this scenario you are **FIRM B** and all 100 consumers have chosen your firm in the previous round.

Assume that the other firm has decided NOT to enter the market.

1) What is the MAXIMUM price for which all 100 consumers visit your firm?

...

2) What is your profit in this case?

...

(Hint: Press the CALCULATOR-button)