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Daniel Halbheer, Ernst Fehr, Lorenz Goette, and Armin Schmutzler†

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Abstract

Are initial competitive advantages self-reinforcing, so that markets exhibit an endogenous tendency to be dominated by only a few firms? Although this question is of great economic importance, no systematic empirical study has yet addressed it. Therefore, we examine experimentally whether firms with an initial cost advantage are more likely to invest in cost reductions than firms with higher initial costs. We find that the initial competitive advantages are indeed self-reinforcing, but subjects in the role of firms overinvest relative to the Nash equilibrium. However, the pattern of overinvestment even strengthens the tendency towards self-reinforcing cost advantages relative to the theoretical prediction. Further, as predicted by the Nash equilibrium, aggregate investment is not affected by the initial efficiency distribution. Finally, investment spillovers reduce investment, and investment is higher than the joint-profit maximizing benchmark for the case without spillovers and lower for the case with spillovers.

Keywords: Cost-reducing Investment, Asymmetric Oligopoly, Increasing Dominance, Experimental Study

JEL Classification: C90, D43, L13, O31

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1 Introduction

Market dominance has many conceivable sources. In some cases, it results from exogenous sources such as state intervention, technology or demand shocks. Quite often, however, the dominance of a small number of firms or even a single market leader appears to be the endogenous outcome of market interaction. For instance, in food retailing, a small number of firms have established themselves as leaders, with *Wal-Mart* playing the most important role, not only in the U.S., but also in other countries such as Britain. Academic publishing has seen increasing concentration worldwide, with *Elsevier* leading the pack (Edlin and Rubinfeld, 2005). The 'new economy' also provides well-known examples of endogenous market dominance. For instance, *Microsoft* has acquired the lead in the markets for operating systems and office software, whereas *Google* dominates the market for search engines (Ferguson, 2005).

Obviously, an explanation of why market dominance came about in each of these examples requires detailed consideration of the particular case, each of which is characterized by idiosyncratic elements.[1] Nevertheless, the examples lead to a common question: Are there any "natural" forces that explain why firms can so often maintain or even expand an initial lead, that is, why initial advantages of firms might be self-reinforcing, thereby leading to an extension of the initial lead? To identify such a force in the simplest possible way, it is useful to consider a setting with a fixed number of firms.[2] Suppose further that firms can invest into cost reductions which increase both the output and the mark-up that they can command in product-market equilibrium.[3] These two beneficial effects of lower costs are mutually reinforcing: The higher mark-up is worth more when output is high, and conversely, the higher output is worth more when the mark-up is high. As a result of these *demand-markup complementarities*, firms that already have a high market share typically benefit more from an increase in efficiency than firms with relatively low share, thus giving them a greater incentive to invest than their lagging competitors.

This kind of mechanism lies at the heart of most explanations of self-reinforcing dominance.[4] In spite of the fact that convincing explanations for self-reinforcing dominance can be given, it is by no means true that there is a universal tendency for markets to move in this direction. Commercial jet aircraft production, for instance, has seen several changes in market leadership since World War II (Sutton, 1998). In the PC market, *IBM* lost its initial dominance in the nineteen eighties (Stavins, 1995).

[1] For instance, in the *Wal-Mart* case, incremental investments and acquisitions of smaller firms played and important role. In academic publishing, there are mergers between big players. *Microsoft* benefited from network externalities, and *Google* introduced several successful product innovations.

[2] Aydemir and Schmutzler (in press) identify similar forces in a setting where acquisitions and entry are allowed.

[3] Similar arguments can be made for product quality improvements.

[4] Athey and Schmutzler (2001) make the point most explicitly, but the models of Flaherty (1980) and Budd et al. (1993) rely on similar forces. Similar effects are also present when a higher output involves lower costs because of learning-by doing (Cabral and Riordan, 1994) or when it enhances demand because of network effects.

These counterexamples are not necessarily evidence for a contradiction of theories of self-reinforcing dominance. Indeed, authors such as Athey and Schmutzler (2001) have pointed out that countervailing forces may well limit the power of increasing dominance. For instance, when imitation is cheap, catching up with a leader may be much less costly than expanding a lead. Then, even when demand-markup complementarities make cost reductions more attractive for leaders, the fact that any given cost reduction is easier to achieve for laggards may well mean that increasing dominance does not arise.

However, without further evidence, it is hard to substantiate the claim that counterexamples to increasing dominance are *not* a challenge to the basic economic ideas outlined above. In principle, for instance, there might be behavioral forces inducing a tendency for laggards to invest excessively relative to theoretical predictions.[5] Unfortunately, in a given market environment, it is hard to be sure about whether economic fundamentals are indeed such that self-reinforcing dominance should emerge. Moreover, markets are typically subject to many exogenous influences (that may favor or hinder increasing dominance), which makes it difficult to attribute the development of dominance to an endogenous self-reinforcing process.

To see whether economic agents respond to the incentives leading to self-reinforcing dominance, it is therefore important to control for potential exogenous shocks and, at the same time, to guarantee that the setting is such that the forces in favor of increasing dominance dominate over potential countervailing forces. Finding such a clean setting in real-world markets is difficult. Therefore, it is unsurprising that the empirical analysis of self-reinforcing dominance essentially reduces to anecdotal evidence. In laboratory experiments, however, it is possible to control for the above-mentioned confounding factors. In the following, we therefore present an experiment that tests whether demand-markup complementarities indeed lead to increasing dominance. In doing so, we provide, to our knowledge, the first empirical analysis of increasing dominance.[6]

We study a simple version of a two-stage model of R&D competition that has received considerable attention in the literature. In this model, oligopolistic firms that potentially differ in their initial marginal costs first carry out cost-reducing investments which may or may not have positive spillover effects for the competitors. Then they engage in Cournot competition.[7]

To address the issue of self-reinforcing dominance, we clearly require asymmetric treatments where subjects have different initial efficiency levels. In these asymmetric treatments, we assume that there are three types of firms, namely leaders, followers and laggards (in decreasing order of marginal costs). We compare the investment

[5]For instance, it is possible to construct a model where laggards invest more than leaders if, compared to a symmetric situation, decision makers in firms experience stronger losses from falling behind than they benefit from getting ahead.

[6]Even beyond the issue of increasing dominance, the experimental analysis of R&D investment games is rare. Isaac and Reynolds (1998) and Suetens (2005) deal with issues of appropriability, Silipo (2005) and Zizzo (2002) investigate patent races.

[7]Similar two-stage Cournot models have, for instance, been used by Brander and Spencer (1983), d'Aspremont and Jacquemin (1988), Suzumura (1992), and Leahy and Neary (1997).

levels of the three types of players in the asymmetric treatments. As the theoretical model underlying our experiment displays demand-markup complementarities, it predicts *increasing dominance*, the property whereby the more efficient firm tends to increase its lead by investing more into cost-reduction than the competitors.[8] The evidence provides overwhelming support for this conclusion. Both in the spillover and in the no-spillover treatments, leaders invest more than followers and followers invest more than laggards. This result suggests that, in a dynamic context, market dominance would emerge endogenously, as small initial asymmetries would tend to reinforce each other. Importantly, increasing dominance comes out even more strongly in the lab than theory would suggest. Subjects have a tendency to overinvest relative to the Nash equilibrium, and this tendency is more pronounced the more efficient subjects initially are, that is, the lower their marginal costs. Thus the difference between the investments of more efficient and less efficient firms in the laboratory is greater than in the Nash equilibrium.

In principle, it would be possible to analyze increasing dominance in a single asymmetric treatment, by comparing the investments of leaders, followers and laggards as described. Instead, we vary treatments in three dimensions, thereby allowing us to test the robustness of the predictions, and, more importantly, to deal with issues of independent interest.

In a first variation, we compare our asymmetric treatments with symmetric treatments where firms are initially identical. This allows us to address a fundamental issue in the analysis of R&D decisions, namely the relation between the "technological gap" (Aghion et al., 2001) and aggregate investment activity. Starting from a situation with symmetric firms, suppose one group of firms has lower marginal costs whereas another group has higher marginal costs, but the average efficiency is unaffected. Should aggregate investment in the former, "neck-to-neck" case, be higher than in the latter, leader-laggard case?[9] Theoretically, this is not obvious. On the one hand, with demand-markup complementarities, the leaders have higher investment incentives; on the other hand, the laggards have lower incentives, so that the aggregate effect is unclear. In the Cournot model underlying our analysis, the two effects exactly cancel out, so that investments are independent of the technological gap. Our experiments confirm the prediction, no matter whether we allow for spillovers or not.

A second variation concerns the appropriability of investments. We compare treatments where cost reductions have no spillovers on competitors with those where they do. This allows us to ask whether imperfect appropriability of investments indeed reduces subjects' inclination to invest, as standard theory would predict (Spence, 1984). This is another theoretical result which has proved hard to confirm

[8]In the terminology of Athey and Schmutzler (2001), this would be *weak* increasing dominance. Note that we assume away potential countervailing forces by making the marginal costs of investment independent of previous investments.

[9]The influence of the technological gap on investment incentives plays a central role in Aghion et al.'s (2001) analysis of the relation between competition and innovation. However, they consider a setting with differentiated price competition.

with field data: For instance, the disincentive effect of spillovers is not discernible in the data set employed by Levin (1988). He provides possible explanations why, contrary to the prediction of Spence's model, investment is not discouraged by the high levels of spillover in electronics-based industries. Our experiments clearly show that lower appropriability reduces investments, which supports theory.[10] The comparison of the spillover and the no-spillover treatment leads to another interesting observation. In both treatments, subjects overinvest relative to the Nash prediction. As investments have negative externalities in the no-spillover case and positive externalities in the spillover case, behavior is thus more cooperative than the Nash prediction suggests in the no-spillover case and less cooperative in the spillover case.[11] In the paper, we suggest an explanation of this phenomenon that relies on social preferences.

Our third and final treatment variation is exclusively motivated by robustness considerations. We consider both low-efficiency and high-efficiency treatments, which differ in the initial average level of marginal cost. Our results are robust with respect to this treatment variation.

A striking feature of our analysis is that the deviations from the Nash equilibrium are, albeit significant, fairly small. In fact, given the complex nature of the experiment, it is amazing how close the outcome is to the Nash equilibrium, no matter whether we are considering treatments with or without spillovers, and symmetric or asymmetric cases.

The remainder of the paper is organized as follows. Section 2 introduces the analytical framework. Section 3 formulates the testable hypotheses. Section 4 describes the experimental design. Section 5 contains the results. Section 6 concludes.

2 Analytical Framework

The analytical framework combines features of the two-stage model of d'Aspremont and Jacquemin (1988) with the dynamic analysis of Athey and Schmutzler (2001): The ex-ante heterogeneity between firms that is central to the latter paper is introduced into the static framework of d'Aspremont and Jacquemin.

Our model is deliberately designed to capture the essence of the strategic interaction in investment models. Like d'Aspremont and Jacquemin, we therefore consider only one period of investment. Even though this might seem to be at odds with our objective of understanding important aspects of dynamic investment behavior, there are several reasons why we proceeded in this fashion. First, most importantly, the basic forces towards high investments of relatively efficient firms that show up in a fully dynamic model are already present in a one-period version of the model, so that the subgame perfect equilibrium of the dynamic game also satisfies increasing dominance with respect to initial efficiency levels. Intuitively, in the static version

[10] Suetens (2005) also shows that lack of appropriability has negative effects on investment, but she only considers a symmetric Cournot duopoly setting. Isaac and Reynolds (1988) have a similar result in a stochastic invention model.

[11] Andreoni (1995) comes to similar conclusions for privately provided public goods.

leaders invest more because they benefit more from demand/markup-increases; in the dynamic version they also take the effects of their investments in future rounds of the investment game into account. However, these long-term considerations reinforce the short-term considerations, because any given improvement of the initial position in a future investment game is more valuable for a firm that starts out ahead of the others. Second, while a dynamic version of the game is implementable in principle, the strategic complexity of the situation is likely to lead to informational overload in an experimental context. Third, our approach of considering only one period per game allows us to put subjects into different roles in different periods, which helps us to provide treatment variation.

2.1 Setup

We consider an oligopolistic industry with a finite number of $I \geq 2$ firms producing a homogeneous product. Let $p = a - Q$ be the inverse demand function, where p and Q denote, respectively, the price and the aggregate output of this product. Firms engage in two-stage competition. In the first stage, each firm i chooses an investment in marginal cost reduction. In the second stage, firms compete à la Cournot in the product market.

We assume that firm i initially has marginal cost $c - Y_0^i$ for some exogenous reference level c of marginal costs in the industry, so that Y_0^i is interpreted as the initial (exogenous) efficiency level of firm i. In the first stage, given $\mathbf{Y}_0 \equiv (Y_0^1, ..., Y_0^I)$, each firm i takes an investment decision, y^i, and we let $\mathbf{y} \equiv (y^1, ..., y^I)$. In the second stage, firm i has marginal costs

$$c^i = c - Y_1^i, \tag{1}$$

where Y_1^i is the efficiency level at the beginning of this stage.

Firm i's efficiency level depends on its initial efficiency level, on own investment, and possibly also on each competitor's investment in marginal cost reduction. More specifically, firm i's efficiency level is

$$Y_1^i = Y_0^i + y^i + \lambda \sum_{j \neq i} y^j, \quad \text{with} \quad \lambda \in [0, 1]. \tag{2}$$

Here, the parameter λ captures spillovers: If $\lambda = 0$, there are no spillovers; if $\lambda = 1$, each firm's investments are shared completely. Obviously, for $0 < \lambda < 1$, the spillovers are imperfect.[12]

The investment cost function for a direct reduction in marginal costs is given by

$$k(y^i) = \kappa \left(y^i\right)^2, \quad \text{with} \quad \kappa > 0.$$

Thus, the function displays increasing marginal costs.[13]

[12] Letting $I = 2$, Eq. (2) includes the model of d'Aspremont and Jacquemin (1988) if the firms' initial efficiency levels are zero. In the more general framework of Athey and Schmutzler (2001), Eq. (2) provides a simple explicit specification of firm i's state dynamics.

[13] Note that this cost function depends only on investments and not on initial efficiency levels.

When firms choose their investments $\mathbf{y}$ in the first stage, they can either do so non-cooperatively or cooperatively. In both cases, we solve the game using backward induction.

2.2 The Second Stage

At the beginning of the second-stage game, $\mathbf{Y}_1 \equiv (Y_1^1, ..., Y_1^I)$ summarizes the firms' efficiency levels, which correspond to marginal costs $\mathbf{c} \equiv (c^1, ..., c^I)$. It is well known that equilibrium outputs in the linear Cournot model with heterogenous firms are given by

$$q^i(\mathbf{c}) = \frac{a - Ic^i + \sum_{j \neq i} c^j}{I+1}.$$

Substituting $c^i = c - Y_1^i$ from (1) and letting $\alpha \equiv a - c$, equilibrium output levels as a function of efficiency levels can be expressed as

$$q^i(\mathbf{Y}_1) = \frac{\alpha + IY_1^i - \sum_{j \neq i} Y_1^j}{I+1}.$$

An immediate implication is that equilibrium product market profits are given by

$$\pi^i(\mathbf{Y}_1) = \left(\frac{\alpha + IY_1^i - \sum_{j \neq i} Y_1^j}{I+1} \right)^2. \quad (3)$$

2.3 The First Stage

Equation (3) gives the equilibrium product market profits in the second-stage game as a function of the first-stage outcome, summarized by $\mathbf{Y}_1$. To obtain an expression for firm i's net profit in terms of cost reductions and the parameters, we substitute the efficiency levels by the corresponding expression given in (2) and subtract the costs of investing. After rearranging, firm i's net profit reads

$$\begin{aligned} &\Pi^i(\mathbf{y}; \mathbf{Y}_0, \alpha, \lambda, \kappa) \\ &= \left(\frac{\alpha + IY_0^i - \sum_{j \neq i} Y_0^j + (I + \lambda(1-I))\, y^i + (2\lambda - 1) \sum_{j \neq i} y^j}{I+1} \right)^2 - \kappa \left(y^i\right)^2. \quad (4) \end{aligned}$$

Assuming positive outputs, differentiating firm i's net profit with respect to y^j implies

$$\text{sign}\left(\frac{\partial \Pi^i}{\partial y^j} \right) = \text{sign}\left(2\lambda - 1\right),$$

which gives rise to the following observation:

Observation 1. *The game is characterized by negative (positive) externalities if the spillover parameter λ is smaller (larger) than 0.5, as a marginal increase of a rival's investment reduces (increases) firm i's net profit.*

To understand this observation, note that an increase in the investment of a competitor affects a firm through two channels. First, there is a negative effect of facing a more efficient competitor. Second, there is a positive effect of becoming more efficient by obtaining spillovers. For $\lambda < 0.5$, the negative effect dominates; for values of $\lambda > 0.5$, the positive effect does.

We now proceed to determine the subgame-perfect equilibrium investments.

2.4 The Subgame-Perfect Equilibrium

Assuming that the firms choose their investments non-cooperatively, firm i's optimal investment decision, taking the decisions of the other firms $\mathbf{y}^{-i}$ as given, solves

$$\max_{y^i \geq 0} \quad \Pi^i(y^i, \mathbf{y}^{-i}; \mathbf{Y}_0, \alpha, \lambda, \kappa).$$

In the subsequent analysis, we proceed under the assumption that second-order and stability conditions hold.[14] Reflecting the quadratic objective function, firm i's best-response function is linear and shown in the Appendix to be of the form

$$R^i(\mathbf{y}^{-i}) = \phi^i - \frac{\Pi^i_{ij}}{\Pi^i_{ii}} \sum_{j \neq i} y^j, \quad \text{with} \quad \phi^i > 0,$$

where subscripts denote partial derivatives. Note that firm i's output depends only on the sum of the opponents' outputs.[15] This property of the Cournot game allows us to present the game to the subjects in matrix form.

In the Appendix, we provide a closed-form solution for the equilibrium investment levels. Substituting these quantities in the corresponding expression above produces firm i's equilibrium output level, the product market profit, and the net profit attained in equilibrium.

2.5 Implications

In this section, we shall derive three testable implications of the theory. The first result addresses increasing dominance and shows that more efficient firms invest more in equilibrium that their competitors. The proposition thus provides the core of an argument for self-reinforcing concentration.[16]

[14]A formal statement of these conditions is provided in the Appendix.

[15]Moreover, using the second order condition,

$$\text{sign}\left(\frac{\partial R^i(\mathbf{y}^{-i})}{\partial y^j}\right) = \text{sign}\left(\Pi^i_{ij}\right) = \text{sign}\left(2\lambda - 1\right),$$

so that reaction curves are downward sloping if $\lambda < 0.5$ (i.e., investments are strategic substitutes) and upward sloping if $\lambda > 0.5$ (i.e., investments are strategic complements). If $\lambda = 0.5$, the firms' investment choices are independent of rivals' actions. The proof of the last equality is provided in the Appendix.

[16]Increasing dominance can also be derived from more general results in Athey and Schmutzler (2001); the remaining results we provide are novel for the asymmetric case.

Proposition 1 (Dominance). *For all* $i \neq j$, $Y_0^i > Y_0^j$ *implies* $y^{i^*} > y^{j^*}$.

Proof. See the Appendix. □

To understand the intuition, it is important to note two key properties of firm i's net profit function given in (4), namely

$$\frac{\partial^2 \Pi^i(\cdot)}{\partial Y_0^i \partial y^i} > 0 \quad \text{and} \quad \frac{\partial^2 \Pi^i(\cdot)}{\partial Y_0^j \partial y^i} < 0. \tag{5}$$

The first property is very intuitive once one takes the underlying oligopoly model into account: Other things equal, firms with high initial efficiency level Y_0^i have high demand (mark-up). The profit gain from increasing mark-up (demand) by investing into marginal cost reduction is therefore higher. This property suggests that, *leaving strategic effects aside*, firms with high initial efficiency levels should invest more than firms with low initial efficiency levels. Similar reasoning can be used to explain the second property intuitively: This property implies that firms invest more when competitors have low initial efficiency levels. Together, both properties identify the source of increasing dominance: The high demand of a leader coming from its high initial efficiency level and the competitor's low initial efficiency level both increase the marginal incentive to invest.[17]

The next result is an immediate consequence of the quadratic net profit function.

Proposition 2 (Technological Gap). *(i) Given* $\mathbf{Y}_0$, *aggregate investment* $y^* \equiv \sum_i y^{i^*}$ *is determined by the sum of the initial efficiency levels,* $\sum_i Y_0^i$, *independently of their distribution. (ii) For an asymmetric initial efficiency profile* $\mathbf{Y}_0$ *and a symmetric profile* $\mathbf{Y}_0^S$ *with the same sum of initial efficiency levels, the most efficient type in* Y_0 *invests more than each firm in the symmetric profile and the least efficient type invests less.*

Proof. See the Appendix. □

The result implies that in the specific setting of the linear Cournot model with quadratic investment costs, increasing asymmetry of firms has no effects on their aggregate investments. Higher incentives to invest for more efficient firms are exactly offset by lower incentives for less efficient firms. In other words, neck-to-neck competition and leader-laggard structures lead to the same aggregate investment.

The third result shows that decreasing appropriability reduces investments.

Proposition 3 (Appropriability). *Suppose that the following condition holds:*

$$\frac{\partial^2 \Pi^i(\cdot)}{\partial \lambda \partial y^i} < 0. \tag{6}$$

Then, for any pair λ', λ'' *such that* $\lambda' < 0.5 < \lambda''$ *and every* i, $y^{i^*}(\lambda') > y^{i^*}(\lambda'')$.

[17] Propositions 1 and 2 in Athey and Schmutzler (2001) make this intuition more precise by showing that the properties given in (5) imply increasing dominance both in the case of strategic substitutes and in the case of strategic complements.

Proof. See the Appendix. □

Intuitively, an increase in λ has two countervailing effects on marginal investment incentives. First, higher spillovers mean that investments have a stronger positive effect on the competitor's efficiency, which makes investment less attractive. Second, however, for given cost reductions of the competitors, larger values of the spillover parameter reduce firm i's marginal cost and thus increase its efficiency level. The resulting increase in demand (mark-up) then leads to a higher investment of firm i. Condition (6) ensures that the first of the two effects dominates, so that a higher value of the spillover parameter reduces firm i's marginal incentive to invest.[18]

2.6 The Cooperative Benchmark

As a benchmark for the non-cooperative game, we now consider the model where firms choose outputs non-cooperatively, but choose investments so as to maximize their joint profit. The main reason for doing so is that, in our experimental setting, we shall reduce the game to a one-period investment model, with payoffs for each investment profile corresponding to those implied if players choose the Nash equilibrium in the corresponding output game. The cooperative benchmark is then simply the joint-profit maximizing outcome in this static game.[19]

Assuming that the firms pick their investments cooperatively, the problem is to

$$\max_{\mathbf{y}\in\mathbb{R}^I} \quad \Pi(\mathbf{y};\mathbf{Y}_0,\alpha,\lambda,\kappa) = \sum_{i=1}^{I} \Pi^i(\mathbf{y};\mathbf{Y}_0,\alpha,\lambda,\kappa)$$
$$\text{s.t.} \quad y^i \geq 0, \quad i = 1,...,I.$$

Assuming that the Hessian of the joint-profit function is negative definite, a unique solution exists. We refrain from characterizing the solution analytically and evaluate it numerically for our experimental study.[20]

The final result allows us to compare firm i's non-cooperative investment decision to firm i's optimal investment choice under a cooperative agreement.

Proposition 4 (Deviation from JPM). *Let y^{i^*} and $y^{i^{**}}$ denote firm i's equilibrium investment levels under non-cooperation and cooperation, respectively, and suppose that $\Pi(\cdot)$ is concave. For $\lambda < 0.5$, we have $y^{i^*}(\lambda) > y^{i^{**}}(\lambda)$; for $\lambda > 0.5$, we have $y^{i^*}(\lambda) < y^{i^{**}}(\lambda)$.*

Proof. See the Appendix. □

[18] Straightforward calculations show that condition (6) is automatically satisfied in symmetric games and met in asymmetric games if and only if firms are not "too asymmetric". In the experimental specification, the parameters are chosen to meet the requirement.

[19] Also, for the symmetric case, the cooperative benchmark is often regarded as an appropriate description of R&D-cartels, where firms are allowed to cooperate in R&D, but must compete on the product market (see, e.g., d'Aspremont and Jacquemin, 1988).

[20] Given a set of parameters, it is easy to check whether the Hessian is negative definite.

The intuition reflects the nature of the externality from investment. For illustration, consider the case where $\lambda < 0.5$, where investing exerts a negative externality on rival firms. Therefore, players invest more than socially optimal for the group of players and the equilibrium investment lies above the joint-profit maximizing level.

3 Hypotheses

We now summarize the testable hypotheses that the theory provides. The following Hypotheses 1 through 4 are implications of Nash behavior. If they are confirmed in the laboratory setting, findings are consistent with the view that the rational choice model of Section 2 captures important aspects of subjects' behavior.

The first hypothesis corresponds to Proposition 1.

Hypothesis 1 (Dominance). *In asymmetric games, firms with a higher initial efficiency level invest more than firms with a lower initial efficiency level.*

Next, we turn to the two comparative-statics predictions. Proposition 2 yields the following hypothesis.

Hypothesis 2 (Technological Gap). *Changes in the distribution of initial efficiency levels have no impact on aggregate investments, but compared to the symmetric case, a mean-preserving spread of the initial efficiency levels leads to higher investments of the leader and lower investments of the laggard.*

Thus, in the specific setting discussed here, it does not matter for the aggregate outcome whether competition is neck-to-neck or if firms with high marginal costs face competitors with low marginal costs.

Proposition 3, which reflects the notion that decreasing appropriability reduces investments, leads to the following hypothesis.

Hypothesis 3 (Appropriability). *As spillovers increase, players invest less.*

Our final derived hypothesis concerns the players' deviation from the joint-profit maximization benchmark.

Hypothesis 4 (Deviation from JPM). *Relative to joint-profit maximization, players overinvest (underinvest) in the presence of negative (positive) externalities.*

Hence, we expect players to deviate in precisely the way that one would expect from rational players in settings with positive and negative externalities, respectively.

4 Experimental Design

4.1 Overview

The experiment was designed to investigate Hypotheses 1 through 4. To test Hypothesis 1, we clearly require asymmetric treatments, where firms differ in their initial

Table 1: Summary of treatments.

Across Subjects Treatments						
No-Spillover (*NS*)				Spillover (*S*)		
Within Subjects Treatments:				Within Subjects Treatments:		
	LE	*HE*			*LE*	*HE*
SYM	*SYM-LE*	*SYM-HE*		*SYM*	*SYM-LE*	*SYM-HE*
ASYM	*ASYM-LE*	*ASYM-HE*		*ASYM*	*ASYM-LE*	*ASYM-HE*

efficiency levels. To test Hypothesis 2, we compare such asymmetric treatments with symmetric treatments where all firms have identical initial efficiency levels, but the average efficiency is the same. To test Hypotheses 3 and 4, we compare treatments with and without spillovers. Finally, to investigate the robustness of our results, we introduce a third dimension of treatment variation apart from symmetry (*SYM*) vs. asymmetry (*ASYM*) and spillovers (*S*) vs. no-spillovers (*NS*): We compare a setting where firms have high initial efficiency levels (*HE*) with settings with low initial efficiency levels (*LE*). This treatment variation is attractive, because it seems conceivable that the absolute levels of initial cost differences might have an effect on the occurrence of increasing dominance.

Table 1 summarizes our treatments, highlighting the three dimensions of treatment variation. As we shall detail in Section 4.2, we varied the spillover dimension across subjects and the two other dimensions within subjects. More specifically, we chose the parameter values as follows. In all treatments, groups of six players were formed, possible investment choices were restricted to the interval $[0, 12]$, and the net-demand parameter ($\alpha = 120$) and the cost parameter ($\kappa = 3$) were unaltered. We chose $\lambda = 0$ in the no-spillover treatments and $\lambda = 0.6$ in the spillover treatments.[21] These choices guarantee that we have negative externalities (and strategic substitutes) in the no-spillover case, and positive externalities (and strategic complements) in the spillover case. Finally, we chose the initial efficiency levels as shown in Table 2. The levels are the same in the spillover and no-spillover case. For the symmetric treatments, we chose $Y_0 = (5, ..., 5)$ and $Y_0 = (11, ..., 11)$. In the corresponding asymmetric treatments, $Y_0 = (9, 9, 6.5, 6.5, 1, 1)$ and $Y_0 = (18, 18, 13, 13, 2, 2)$, respectively. In particular, there are three types of players, "leaders" (highest efficiency), "followers" (medium efficiency) and "laggards" (lowest efficiency).

[21] The parameter value $\lambda = 0.6$ was chosen to make the calculations for the subjects relatively simple.

Table 2: Distributions of initial efficiency levels.

Within Subjects Treatments		
	LE	*HE*
SYM	$Y_0 = (5.5, ..., 5.5)$	$Y_0 = (11, ..., 11)$
ASYM	$Y_0 = (9, 9, 6.5, 6.5, 1, 1)$	$Y_0 = (18, 18, 13, 13, 2, 2)$

4.2 Details

To implement our treatment variations, we chose to vary the spillover dimension across subjects, whereas the other two dimensions where varied within subjects only. Specifically, in both the spillover and the no-spillover treatment, two sessions were run, each consisting of 16 replications of the stage-game in five six-player groups. In both treatments, we confronted subjects with eight different roles, with each role repeated twice. Subjects played the symmetric high-efficiency and low-efficiency treatments, and they took the role of the leaders, laggards and followers in the asymmetric high-efficiency and low-efficiency treatments, respectively.

In the two-stage model of Section 2 firms first choose their investment levels and then they compete in the product market. In order to isolate the impact of the incentives arising from the investment stage in the cleanest possible way we confronted subjects at the investment stage with payoff tables that were based on the Cournot equilibrium that results from every efficiency combination at the investment stage. Thus, subjects did not choose the output quantities at the second stage of the game; they merely determined their investment levels at the first stage, knowing the consequences of each combination of their own efficiency level and the efficiency level of the other members of the group. This simplification is crucial because otherwise it would have been impossible to isolate the impact of the investment incentives on self-reinforcing market dominance. If, for example, subjects deviate (for whatever reason) from the Cournot equilibrium this deviation may dilute or remove the incentives for leaders to invest more than laggards. Thus, if subjects had played the second stage of the game we would have lost control over investment incentives and, as a consequence, we would have been unable to isolate the impact of investment incentives on behavior.

Irrespective of the treatment, each replication of the static game is described as follows. At the beginning of each replication, the experimenter informs subjects about the initial efficiency level of the firm they are representing, and the initial efficiency levels of the other firms in their group. Then, they can choose investment levels which improve their initial efficiency level. Each subject knows that its product market profit depends both on the own efficiency level and the average efficiency level of the other players in the group. Since the subjects choose their investment

Table 3: Part of the product market profit table.

$Y_1^i \rightarrow$ $\bar{Y}_1^{-i} \downarrow$	5.5	6.0	$\cdots$	9.5	10.0	10.5	11.0	11.5	12.0	12.5
5.5	321	337	$\cdots$	456	475	493	513	532	552	*573*
6.0	309	324	$\cdots$	441	459	478	497	516	*536*	556
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
9.5	227	240	$\cdots$	342	358	375	*391*	409	426	444
10.0	217	229	$\cdots$	329	345	361	*377*	394	412	429
10.5	206	219	$\cdots$	316	332	348	*364*	380	397	414
11.0	196	208	$\cdots$	304	319	334	***350***	366	383	400
11.5	186	198	$\cdots$	291	306	*321*	337	353	369	386
12.0	177	188	$\cdots$	279	294	*309*	324	340	356	372
12.5	167	178	$\cdots$	268	282	*296*	311	327	342	358

Notes: Y_1^i and $\bar{Y}_1^{-i}$ denote, respectively, the own efficiency level and the competitors' average efficiency level. Best replies are typed in italics, firm i's equilibrium product market profit is typed in bold face. Of course, these quantities were not emphasized in the instructions.

simultaneously, they do not yet know the average ex-post efficiency level of the other members in their group when they make their choices; thus, they have to form expectations about their competitors' average efficiency level. To calculate the payoffs corresponding to these expectations and on their own investment decisions, subjects can use product market profit and cost tables, as well as a calculator.

To illustrate the product market profit table, we now consider the treatment *NS-LE-ASYM*. Table 3 shows a part of the table that the subjects used. The first row gives the efficiency level of the subject's firm, whereas the first column gives the average efficiency level of the other firms. For example, the subjects' product market profit is 573 points for $Y_1^i = 12.5$ and $\bar{Y}_1^{-i} = 5.5$. Thus, subject i's product market profit is 573 points after investing 7 units (as the initial efficiency level is 5.5 units), under the assumption that the other firms do not invest. To obtain their net profit, subjects used the cost table to find out the relevant cost of an investment equal to 7 units (which are $3 \times 7^2 = 147$ points). In this fashion, subjects could, in principle, compute the best reply for a given expectation of average investments of the other firms. For illustrative purposes, Table 3 presents best replies (in italics) and the equilibrium product market profit (in bold face).

After 90 seconds, the subjects must take a definite decision. Finally, they are informed about actual investments of each group member and their own net profit.

In all *S*-treatments, the subjects' tasks are exactly the same, and they must also use the same tables. The only difference to the *NS*-treatments arises due to the presence of spillovers: The subjects' efficiency levels are not determined by the sum of their own initial efficiency level and their own investment only—they also depend on the spillovers from group members.[22]

Subjects were recruited using ORSEE (Greiner, 2004), and were randomly allocated to groups of six subjects upon arrival at the laboratory (partners-setting). Subjects were students from the University of Zurich and the Swiss Federal Institute of Technology in Zurich. A total of 120 subjects participated in the experiment, and none of them in more than one session. All experiments were computerized using the software "z-Tree" (Fischbacher, 2007) to run the experiment.

Before subjects played the experiment, they were given time to carefully read the instructions and to solve some simple examples to make sure that they understood the experiment correctly. There was no communication during the experiment.

An average session lasted 120 minutes. The net profits in points attained in the 16 replications of the games were converted to Swiss francs (1 point = CHF 0.80). On average, a subject earned CHF 46.55 (about $38) in the *NS*-treatment and CHF 59.85 (about $49) in the *S*-treatment, including a show-up fee of CHF 10.00 (about $8).

5 Experimental Results

This section presents tests of Hypotheses 1 through 4, which are all implied by Nash behavior. In Section 5.1, we shall first compare the experimental investment decisions to the Nash benchmarks. It will turn out that there is significant overinvestment relative to the Nash equilibrium, so that we cannot take the hypotheses for granted. In the remaining Sections 5.2 through 5.5, we therefore test each hypothesis in turn.

5.1 The Predictive Power of Nash Benchmarks

Table 4 presents some simple summary statistics of experimental investment decisions, along with the theoretical predictions. A comparison of average type-specific investments and Nash benchmarks suggests, except for type-1 firms, a tendency to overinvest relative to the Nash prediction (in Table 4, the corresponding deviations from the Nash equilibrium, Δ, are positive).

To test whether the deviation from the Nash prediction is statistically significant, we first introduce some notation. We let $\hat{y}^i_{t,k}$ denote subject i's period t investment decision, where the subscript k assigns the observation to the group, or industry, in which the subject operates. Similarly, we let $y^{i^*}_t$ denote the Nash prediction. The overinvestment relative to the Nash prediction, $\Delta^i_{t,k}$, can thus be expressed as

$$\Delta^i_{t,k} = \hat{y}^i_{t,k} - y^{i^*}_t.$$

Regressing overinvestment on a constant yields an estimate of 0.64 units with (robust) standard error 0.094 (see Table 5, Model I).[23] Thus, there is a highly sig-

[22] Specifically, subjects know that their own efficiency level is determined by the sum of their own initial efficiency level, own investment, and three times the average investment of the other group members. Formally, this can be seen by letting $\lambda = 0.6$ in Eq. (2).

[23] Standard errors are clustered on groups as the within group observations may not be independent from each other.

TABLE 4: Theoretical benchmarks and summary of investment decisions.

		Benchmarks		Experimental Investments			
Treatments		Nash	JPM	Average	Median	S.D.	Δ
No-Spillover							
SYM-LE	Type 5.5	5.34	0.86	5.70	5.00	1.58	0.36
SYM-HE	Type 11	5.57	0.90	6.33	6.00	1.79	0.76
ASYM-LE	Type 9	6.74	2.44	7.78	7.00	1.69	1.04
	Type 6.5	5.74	1.19	6.36	6.00	1.45	0.62
	Type 1	3.54	0.00	3.47	3.00	1.04	-0.06
ASYM-HE	Type 18	8.37	3.95	9.17	9.00	1.58	0.80
	Type 13	6.37	1.45	6.85	6.00	1.70	0.48
	Type 2	1.97	0.00	2.27	2.00	1.23	0.30
Spillover							
SYM-LE	Type 5.5	2.79	3.83	3.54	3.00	1.77	0.75
SYM-HE	Type 11	2.91	4.00	3.90	3.00	1.98	0.99
ASYM-LE	Type 9	3.32	4.32	4.36	4.00	1.81	1.04
	Type 6.5	2.94	3.97	3.46	3.00	1.49	0.52
	Type 1	2.10	3.20	2.08	2.00	1.37	-0.02
ASYM-HE	Type 18	3.97	4.99	5.22	4.00	2.32	1.25
	Type 13	3.21	4.28	4.25	4.00	1.98	1.04
	Type 2	1.55	2.73	1.89	2.00	1.05	0.34

Notes: Average and median experimental investments, standard deviations (S.D.), and average deviations from the Nash equilibrium (Δ) based on 120 observations for each firm type.

nificant overall tendency to overinvest relative to the Nash benchmark. This result is also supported when we split the sample into early and late periods (see Table 5, Model II):[24] Although overinvestment significantly decreases by 0.34 units from 0.81 to 0.47 units in late periods, it remains persistent at the 1% confidence level.[25] Summing up, we have the following:

Observation 2. *There is significant, albeit small, overinvestment relative to the Nash benchmark that varies across treatments.*

It is important to note that this observation is essentially independent of the treat-

[24]Throughout the paper, early and late periods refer to the first and second replication of each *HE* and *LE* treatment, respectively, as subjects are twice in each role.

[25]The result is corroborated at the treatment level when controlling for spillovers and symmetry.

Table 5: Overinvestment.

	Model I	Model II	Model III
Variable	Dep. Var.: $\Delta^i_{t,k}$		Dep. Var.: $\Delta^{i,C}_{t,k}$
const	0.6372***	0.8083***	4.5394***
	(0.0943)	(0.1197)	(0.1309)
late		−0.3421***	
		(0.1035)	
spill			−4.9720***
			(0.1830)
sym			0.4152***
			(0.1007)

Notes: Overinvestment (Models I and II, respectively), and the observed deviation from the JPM prediction (Model III) at the overall level. Dependent variable in Models I and II is subject i's period t overinvestment in group k; in Model III, dependent variable is subject i's period t deviation from the JPM prediction in group k. 360 observations in each treatment; *** = Significant at the 1% level. Robust standard errors adjusted for clustering on groups in parenthesis.

ment and of the role (leader, follower, laggard) that an individual plays: In 14 of the 16 cases, the players' investments are (slightly) above the Nash prediction. In particular, overinvestment occurs in both the no-spillover and the spillover treatments. This is striking, because overinvestment in a game without spillovers corresponds to a behavior that is less cooperative than in the Nash equilibrium, whereas in the game with spillovers the overinvestment corresponds to more cooperative behavior.

A possible explanation for this phenomenon relies on the fact that investments are strategic complements in the case with spillovers but substitutes in the case without spillovers.[26] This difference in strategic incentives between spillover and no-spillover treatments could interact with the existence of reciprocal preferences such that overinvestment results in both cases.[27] Suppose, for example, that the population contains reciprocal and egoistic players and assume that the reciprocal players expect others to overinvest in the spillover treatment. Overinvestment in the spillover treatment means that the overinvesting players generate a benefit (positive externality) for the others, i.e., overinvesting is a kind behavior. Therefore,

[26]The role of strategic complementarity and substitutability for aggregate deviations from rationality or Nash equilibrium play has been examined by Haltiwanger and Waldmann (1985, 1989), Fehr and Tyran (2001, 2005), and Potters and Suetens (2005).

[27]There is ample evidence that social preferences play a role in strategic games in which players can affect each others payoffs (Fehr and Schmidt, 2006). Often social preferences take the form of preferences for reciprocity (Levine, 1998; Rabin, 1999; Duwfenberg and Kirchsteiger 2004; Falk and Fischbacher, 2006; Cox, Friedman and Gjerstad, 2007; Cox, Friedman and Sadiraj, forthcoming). An individual with reciprocal preferences responds to (the expectation of) kind acts with kind behavior and to (the expectation of) hostile behavior with hostility.

a reciprocal player will respond to this expectation with overinvestment. In addition, the selfish players will also overinvest because of strategic complementarity (i.e., they have pecuniary incentives to overinvest given that the reciprocal players overinvest relative to Nash). Thus, in the case of spillovers between the investing subjects, strategic complementarity and a positive fraction of reciprocal players may contribute to overinvestment.

In the no-spillover case the existence of reciprocal players may contribute to overinvestments relative to the Nash equilibrium because in these treatments investing imposes a negative externality on the other subjects. Therefore, investing according to or above the Nash equilibrium is likely to be viewed by the reciprocal subjects as unkind behavior that deserves retaliation whereas underinvestment relative to the Nash equilibrium is likely to be viewed as kind behavior because it reduces negative externalities. Note also, that due to strategic substitutability, egoistic players will never reciprocate kind acts of underinvestment; instead, they respond to underinvestment with overinvestments. Whether the selfish players play the Nash equilibrium or whether they even overinvest, reciprocal players are likely to interpret such behaviors as hostile and respond with retaliation, i.e., they will overinvest in order to punish the other investors. Thus, overinvestment in the no-spillover treatment could be the result of reciprocal players' retaliatory behavior.

Because investments are close to the levels prescribed by the Nash hypothesis, it seems conceivable that Hypotheses 1 through 4 will be confirmed. Nevertheless, as observations and predictions differ, we cannot take this for granted.

5.2 Increasing Dominance

To investigate our main hypothesis of increasing dominance, we now compare the investment behavior in the asymmetric treatments. We have the following result:

Result 1a (Dominance). *The higher a firm's initial efficiency level the larger is the firm's investment on average, that is, subjects' behavior exhibits increasing dominance. This result holds in each of the asymmetric treatments.*

Figures 1 and 2 provide a graphical representation of Result 1a (for treatments *NS* and *S*, respectively): On average, the more efficient firms invest more than less efficient firms.[28] This notion can be confirmed in Figure 3, which goes beyond Figures 1 and 2 by plotting the cumulative distribution of the subjects' investment choices instead of averages only. Inspection of the figure reveals that the cumulative distribution function of investments of leaders (followers) is below the graph of followers (laggards) in all treatments. This implies that the average investment of leaders exceeds the average investment of followers, and that followers invest more on average than laggards. To substantiate Result 1a, we estimate the following model:

$$\hat{y}^i_{t,k} = \beta_0 + \beta_1 \delta^i_{leader,k} + \beta_2 \delta^i_{laggard,k} + e^i_{t,k},$$

[28]The Nash benchmarks lie below the relevant lower bounds of the 95% confidence intervals for average investments, which again reflects the notion that subjects invest a significantly larger amount than prescribed by Nash behavior.

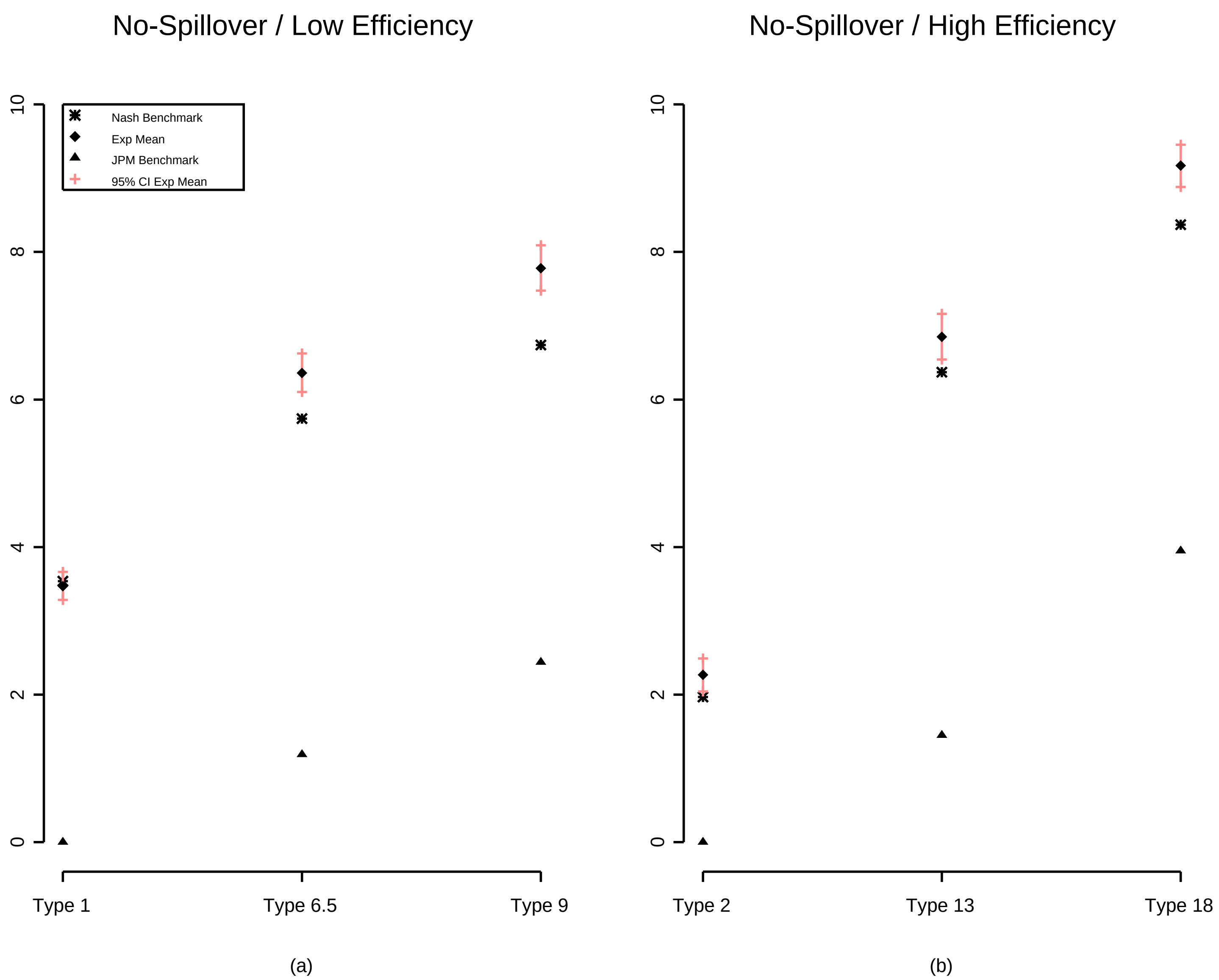

Figure 1: Average investments in the *NS-LE* treatment with the corresponding 95% confidence intervals, along with the theoretical benchmarks (in panel a, panel b displays *NS-HE* treatment).

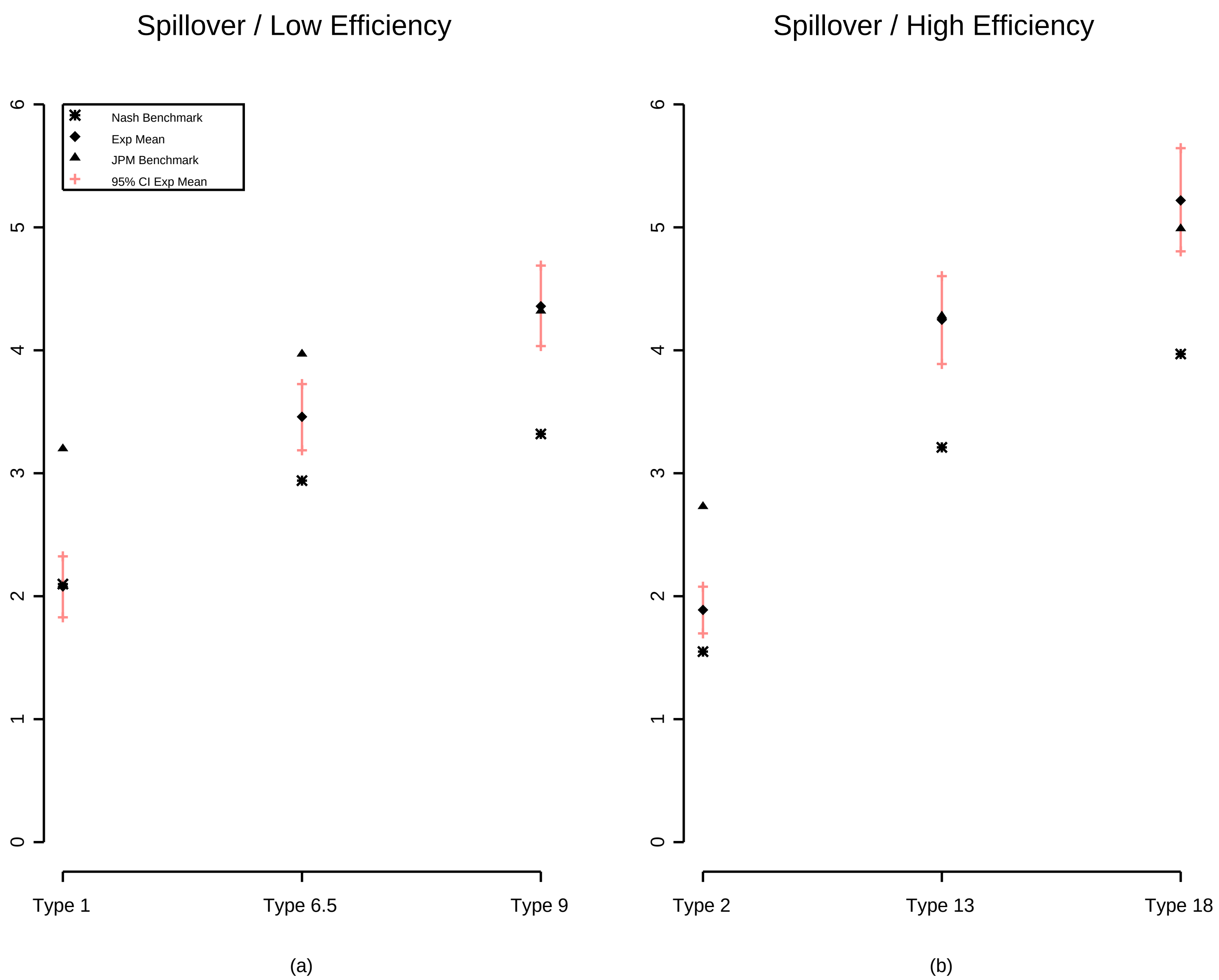

FIGURE 2: Average investments in the *S-LE* treatment with the corresponding 95% confidence intervals, along with the theoretical benchmarks (in panel a, panel b displays *S-HE* treatment).

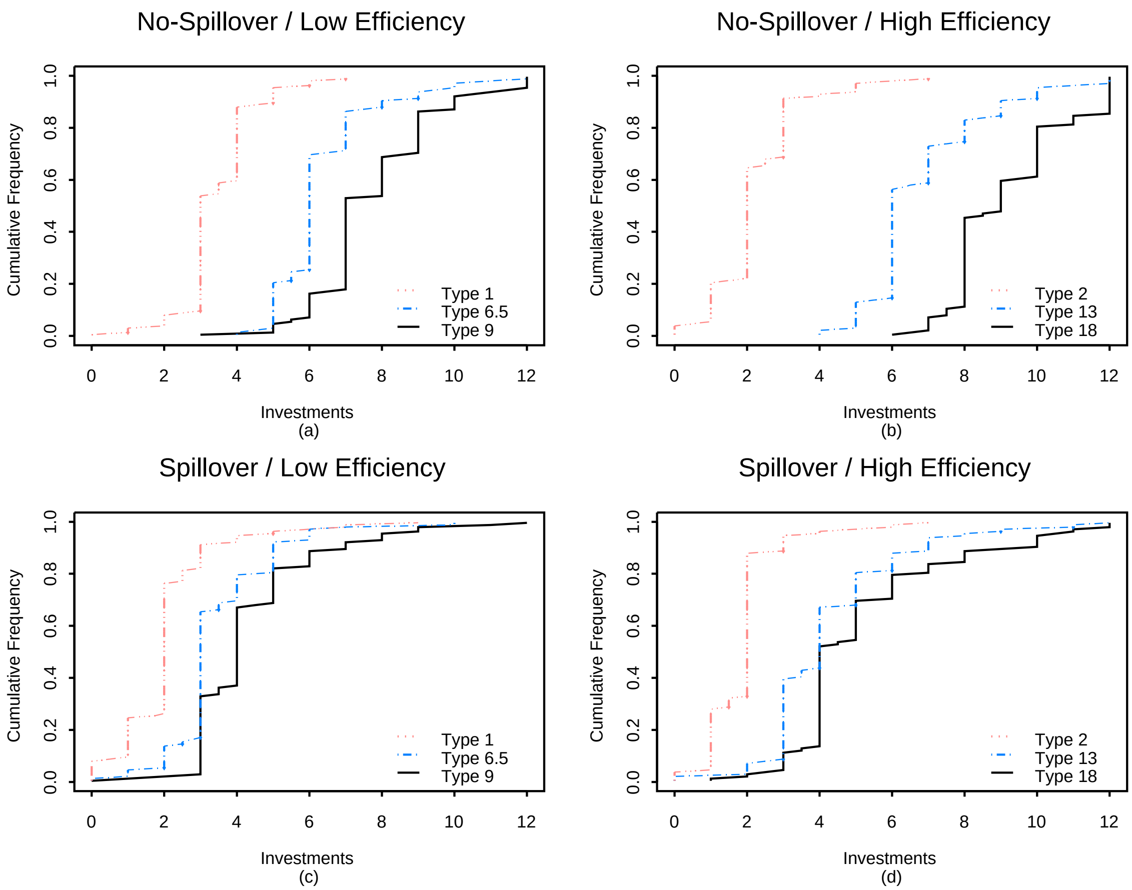

FIGURE 3: Cumulative distribution of investment choices in asymmetric treatments.

where $e^i_{t,k}$ is a residual that is assumed to be independent across groups k. For each subject i in group k, the preceding equation relates the investment decision in each period t to a constant and two dummy variables that take value 1 if subject i's investment decision is taken in the role of a leader and a laggard, respectively.[29]

Table 6 gives the parameter estimates for each asymmetric treatment. To illustrate, consider the treatment *NS-LE*. By construction, the estimate of the constant term, which is equal to 6.36 units, reflects the average investment of a follower (see Table 4). The estimated coefficient on the dummy variable *leader* indicates that, on average, a subject invests 1.42 units more as leader than as follower, amounting to a total average investment of 7.78 units (refer, again, to Table 4). As the estimated coefficient is significantly different from zero (p–value < 0.001), we conclude that the average investment of leaders significantly exceeds the average investment of followers. The estimated coefficient on the dummy variable *laggard* can be interpreted similarly: A subject invests on average 2.89 units less as laggard than as follower. Thus, laggards invest 3.47 units on average, and the difference to the followers' investment of 6.36 units is significant (at the 1% confidence level).

[29]Recall that each subject is twice in each of the three possible roles, and that there are 6 subjects in each group. As there are 10 groups, we have a total of 360 observations in each treatment.

Table 6: Estimation results for the increasing dominance hypothesis.

	Asymmetric Treatments			
Variable	*NS-LE*	*NS-HE*	*S-LE*	*S-HE*
const	6.3625***	6.8525***	3.4563***	4.2458***
	(0.1433)	(0.2142)	(0.1345)	(0.2327)
leader	1.4208***	2.3142***	0.9063***	0.9792***
	(0.1232)	(0.1204)	(0.1585)	(0.2365)
laggard	−2.8875***	−4.5858***	−1.3792***	−2.3583***
	(0.1508)	(0.2025)	(0.1196)	(0.2202)

Notes: Dependent variable is subject i's period t investment decision in group k ($\hat{y}^i_{t,k}$). 360 observations in each treatment; *** = Significant at the 1% level. Robust standard errors adjusted for clustering on groups in parenthesis.

Similarly, inspection of Table 6 reveals that average experimental investment decisions satisfy the increasing dominance hypothesis in all asymmetric treatments even though subjects do not choose Nash investments, which confirms Hypothesis 1.

Interestingly, the following result shows that the subjects' tendency to overinvest relative to the Nash prediction even reinforces increasing dominance.

Result 1b (Increasing Overinvestment). *The pattern of overinvestment relative to the Nash prediction reinforces increasing dominance as more efficient firms overinvest more than less efficient firms.*

The fact that overinvestment tends to increase with the firm-type can be seen most directly in Table 4. To test for significance of the result, we estimate the model

$$\Delta^i_{t,k} = \beta_0 + \beta_1 \delta^i_{leader,k} + \beta_2 \delta^i_{laggard,k} + e^i_{t,k}.$$

Estimates are presented in Table 7. Consider again the treatment *NS-LE* to illustrate: By construction, the estimate of the constant term, which is equal to 0.62 units, reflects the subjects' average overinvestment in the role of a follower. As the estimated coefficient on the dummy variable *leader* is highly significant, the leaders' average overinvestment of 1.04 units thus exceeds that of laggards. Also, the subjects overinvest on average 0.69 units less as laggards than as followers (and therefore *underinvest* relative to the Nash prediction). As this difference in average overinvestment is again significant at the 1% confidence level, Result 1b is confirmed.

Using similar reasoning, Table 7 shows that more efficient firms overinvest more than less efficient firms in treatment *S-LE* (at the 1% confidence level). The estimated differences in the *HE*-treatments also support Result 1b. Although not all differences are statistically significant, the p–values of the hypothesis tests that types do not matter suggest to reject this hypothesis in all treatments at the 10% confidence level, and in three cases at the 1% confidence level. Thus, the tendency towards self-reinforcing dominance is more pronounced than theory would predict.

Table 7: Estimation results for the increasing overinvestment hypothesis.

	Asymmetric Treatments			
Variable	*NS-LE*	*NS-HE*	*S-LE*	*S-HE*
const	0.623***	0.483*	0.516***	1.036***
	(0.143)	(0.214)	(0.135)	(0.233)
leader	0.421***	0.314**	0.526***	0.219
	(0.123)	(0.120)	(0.159)	(0.237)
laggard	−0.688***	−0.186	−0.539***	−0.698**
	(0.151)	(0.203)	(0.120)	(0.220)
p–value that types do not matter	0.003	0.057	0.000	0.007

Notes: Dependent variable is subject i's period t overinvestment in group k ($\Delta^i_{t,k}$). 360 observations in each treatment; * = Significant at the 10% level; ** = Significant at the 5% level; *** = Significant at the 1% level. Robust standard errors adjusted for clustering on groups in parenthesis.

5.3 The Technological Gap

We now investigate the effect of altering the technological gap between the firms. As detailed in the model section, aggregate investments in the subgame-perfect Nash equilibrium are predicted to be equal in the symmetric and asymmetric treatments (Hypothesis 2). Figure 4 therefore compares the two treatments. To illustrate, consider the *NS-LE*-treatments (Panel a). For each type, the figure gives the difference between its investment in the asymmetric *NS-LE*-treatment and in the corresponding symmetric treatment. The theoretical prediction is that types 9 and 6.5 invest more in the asymmetric case than in the symmetric case, whereas type 1 invests less. The experimental observations reflect the theoretical prediction not only qualitatively, but also quantitatively. Panels (b) through (d) provide a similar picture.[30] In spite of the substantial effect of asymmetry for the individual types, the right-hand columns in the figures suggest that the higher investments of high types and the lower investments of low types roughly cancel out, as Hypothesis 2 would predict.

To test this, we employ the following model:

$$\hat{y}_{t,k} = \beta_0 + \beta_1 \delta_{sym,k} + e_{t,k},$$

where $e_{t,k}$ is a residual that is assumed to be independent across industries k (but not necessarily across the two replications). For each industry k, the preceding equation

[30]For the *S-LE*-treatments, theory predicts slightly higher investments in the asymmetric case, whereas average investment in the experiment is slightly higher in the symmetric case. Clearly, however, the deviations are very small in both treatments.

FIGURE 4: Predicted investment change in the asymmetric treatments relative to the corresponding symmetric treatment and the actual average investment change.

relates aggregate investments, denoted $\hat{y}_{t,k}$,[31] to a constant and a dummy variable taking value 1 if the observation is generated in a symmetric industry structure.[32]

Table 8 gives the parameter estimates for each comparison. As illustration, we consider the comparison Δ^{HE} in the no-spillover treatment (i.e., the comparison of the treatments *NS-ASYM-HE* and *NS-SYM-HE*). The estimate of the constant term, which is equal to 36.57 units, reflects average aggregate investment at the industry level in the asymmetric industry configuration. The estimated coefficient on the dummy variable *sym* indicates that average aggregate investment in a symmetric industry configuration is 1.40 units higher, amounting to an average aggregate investment of 37.97 units. As shown in the table, the estimated coefficient is not significantly different from zero at reasonable confidence levels (in the case under consideration, the p–value is equal to 0.187). Therefore, there is no statistical evidence

[31] Experimental aggregate investments in group k are defined as $\hat{y}_{t,k} = \sum_i \hat{y}^i_{t,k}$.

[32] The total of 80 observation in each comparison can be obtained by recalling that each subject is twice in each role, and there are 10 groups in each treatment. In symmetric treatments, where subjects find themselves only in one role, there are 20 aggregate outcomes. In asymmetric treatments there are 60 aggregate outcomes, as there are three different roles for each subject.

Table 8: Estimation results for the comparison of aggregate investments.

	No-Spillover Treatments		Spillover Treatments	
Variable	Δ^{HE}	Δ^{LE}	Δ^{HE}	Δ^{LE}
const	36.5717***	35.2417***	22.7167***	19.7917***
	(0.5269)	(0.4706)	(0.6921)	(0.5490)
sym	1.4003	−1.0417	0.6833	1.4208
	(1.0537)	(0.9412)	(1.3843)	(1.0880)

Notes: Δ^{HE} and Δ^{LE} denote the comparison of the corresponding symmetric and asymmetric industry structures. Dependent variable is aggregate investment in industry k in period t ($\hat{y}_{t,k}$). 80 observations in each comparison; *** = Significant at the 1% level. Robust standard errors adjusted for clustering on groups in parenthesis.

suggesting that average aggregate investments are different in the two treatments.

The statistical results are very similar in the other comparisons.[33] Thus, individuals seem to have well understood incentives to invest: Switching from a symmetric to an asymmetric industry structure induces subjects to invest less (more) when their efficiency level is lower (higher) in the asymmetric treatment than in the symmetric treatment, as predicted by the theoretical model.

We summarize the insights on average aggregate investments as follows.

Result 2 (Technological Gap). *In the asymmetric industry, leaders, followers, and laggards change their investment levels relative to the symmetric industry in the predicted direction in both the low-efficiency and the high-efficiency treatment. Moreover, these changes cancel out at the aggregate level, leaving aggregate investment unaffected.*

5.4 Appropriability

Here, we investigate the effects of introducing spillovers on investment behavior. Table 4 shows that average investments of each firm type are considerably lower in the S-treatments than in the NS-treatments. We now aim at exploring this finding more thoroughly.

We approach Hypothesis 3 using the following model:

$$\hat{y}^i_{t,k} = \beta_0 + \beta_1 \delta^i_{spill,k} + e^i_{t,k},$$

where $e^i_{t,k}$ is a residual that is assumed to be independent across groups k. This equation relates each subject i's period t investment decision to a constant and a

[33] Observe that, except for the case Δ^{LE} in the NS-treatment, average aggregate investments are slightly higher in the symmetric treatments.

dummy variable that takes value 1 if individual i's observation is assigned to an S-treatment.[34]

Estimating the model, we obtain in the NS-treatments, that subjects invest on average 5.99 units (which is the estimate of β_0). The estimate of β_1 is equal to -2.41 units with associated p–value < 0.001, implying that average investment in the S-treatments, which amounts to 3.59 units, is significantly lower. Therefore, Hypothesis 3 is confirmed, which leads to the following result:

Result 3 (Appropriability). *Average investments in the spillover treatment are significantly lower than in the no-spillover treatment.*[35]

5.5 Deviation from the Cooperative Outcome

We shall now test whether subjects overinvest in the no-spillover treatments and underinvest in the spillover treatments relative to the joint-profit maximizing benchmark, as predicted by Hypothesis 4.

To investigate these claims, we let y_t^{i**} denote the corresponding JPM benchmark, so that the observed deviation from the JPM prediction can be expressed as

$$\Delta_{t,k}^{i,C} = \hat{y}_{t,k}^i - y_t^{i**}.$$

We estimate the model

$$\Delta_{t,k}^{i,C} = \beta_0 + \beta_1 \delta_{spill,k}^i + \beta_2 \delta_{sym,k}^i + e_{t,k}^i,$$

where $e_{t,k}^i$ is a residual that is assumed to be independent across groups k.[36]

Estimation results are presented in Table 5 (Model III). By construction, the estimate of β_0 gives average overinvestment relative to the cooperative investment decisions in asymmetric NS-treatments. Standard calculations yield that average overinvestment relative to the JPM benchmark amounts to 4.95 units in NS-treatments, which is a highly significant deviation.[37] Thus, subjects deviate from the JPM benchmark by overinvesting in the presence of negative externalities.

It can be seen from Table 4 that average deviations from the JPM benchmarks are much less pronounced and not unidirectional in the S-treatments. Therefore, a more detailed investigation of the deviations is called for. In *symmetric* treatments, simple analysis yields that subjects on average underinvest 0.02 units. Surprisingly,

[34] Note that each of the 8 stage-games is replicated twice and that there are 6 subjects in each group. As there are 10 groups in each treatment, we have a total of 1,920 observations.

[35] In fact, the result also holds at the type-level, as a comparison of figures 1 and 2 suggests.

[36] Recall that the dummy variable $\delta_{spill,k}^i$ takes value 1 if the observation belongs to group k in an S-treatment (and zero otherwise). Analogously, $\delta_{sym,k}^i$ takes value 1 in symmetric treatments.

[37] As subjects significantly overinvest relative to the Nash benchmark in the NS-treatments, they do so a fortiori relative to the JPM benchmark. In addition, inspection of Table 4 unambiguously leads to the conclusion that average investments are substantially higher than the relevant JPM benchmarks for all firm-types in the NS-treatments.

average investment is not significantly different from the JPM benchmarks. Therefore, experimental investment decisions maximize industry profits.[38] In *asymmetric* treatments, however, subjects underinvest relative to the JPM benchmark. In contrast to symmetric treatments, there is significant underinvestment of 0.43 units.[39] Relating to Hypothesis 4, we thus have the following result:

Result 4 (Deviation from JPM). *Subjects significantly overinvest relative to the JPM benchmark in the no-spillover treatments. In the spillover treatments, subjects approximately choose JPM investment levels in symmetric treatments. In asymmetric treatments, subjects significantly underinvest relative to the JPM benchmarks.*

Hence, this result partially supports Hypothesis 4. Clearly, restricting attention to outcomes at the individual level is a very strong test of the theoretical predictions. Surprisingly, however, estimating the model using overinvestment at the group level does not qualitatively affect the findings reported in Result 4.[40] We therefore have the following observation:

Observation 3. *From a joint-profit maximizing perspective, aggregate investments are inefficiently high in the no-spillover treatments. In the spillover treatments, in contrast, aggregate investments turn out to be approximately efficient in symmetric treatments and inefficiently low in asymmetric treatments.*

6 Conclusions

Theoretical models explain why markets should be expected to display self-reinforcing dominance under appropriate conditions, but it is hard to identify these mechanisms in real-world markets. We therefore use a laboratory experiment to find out whether subjects' behavior reflects the crucial strategic effects. We introduce a two-stage investment model which predicts that more efficient firms should invest more into cost reduction than their lagging competitors, thus providing a reason why initial market dominance might be self-reinforcing. It turns out that there is significant overinvestment relative to the Nash benchmark. However, the overinvestment is small, and the increasing dominance hypothesis is confirmed. Moreover, the deviations from the equilibrium follow an interesting pattern. Overinvestment is higher for more efficient types, so that the increasing dominance prediction is reinforced.

Our set-up also allows us to compare aggregate investments in neck-to-neck situations with those in asymmetric leader-laggard structures, confirming the prediction that total investments should be the same in both cases, as long as the average efficiency level is the same in both cases. An interesting extension of our analysis would consider settings where theory predicts differences in both cases, which can happen, for instance, when subjects compete in prices.

[38] The test's p–value is 0.918.

[39] The test's p–value is 0.003.

[40] The statistical details are available from the authors upon request.

Our results also show that spillovers reduce investments in accordance with theory. Finally, the relation between subjects' decisions and joint-profit maximization is less clear than theory would suggest; in particular, in settings with spillovers, the difference between observed investments and joint-profit maximizing investment levels is insignificant.

Apart from that, however, the conformance between theory and experiments is striking. In spite of the unfamiliar kind of strategic problem, the Nash equilibrium yields surprisingly good predictions. Having confirmed this, it would be interesting to see whether the observed regularities still hold when the product-market stage is modeled explicitly. Deviations in the output stage could have interesting repercussions for investment behavior. Suppose, for instance, that, in the product-market stage, leaders choose higher output levels than in the Cournot equilibrium and, laggards respond by choosing lower outputs. Anticipating this, the leader should set higher outputs than in equilibrium, and the laggard should set lower outputs. Such deviations would reinforce increasing dominance.

Appendix

A.1 Equilibrium under Non-Cooperative Behavior

Firm i's net profit under non-cooperative behavior is given by

$$\Pi^i(\mathbf{y};\mathbf{Y}_0,\alpha,\lambda,\kappa) = \left(\frac{\alpha + IY_0^i - \sum_{j\neq i} Y_0^j + (I+\lambda(1-I))\, y^i + (2\lambda-1)\sum_{j\neq i} y^j}{I+1}\right)^2 - \kappa\left(y^i\right)^2. \quad \text{(A.1)}$$

In the subsequent analysis, we require that firm i's objective function Π^i satisfies the second-order and stability conditions, i.e.

$$\Pi^i_{ii} < 0 \quad \text{and} \quad \left|\Pi^i_{ii}\right| > \left|\sum_{j\neq i}\Pi^i_{ij}\right|, \quad \text{(A.2)}$$

respectively, where subscripts denote partial derivatives. Letting

$$\alpha^i \equiv \alpha + IY_0^i - \sum_{j\neq i} Y_0^j$$

in (A.1), firm i's first-order condition reads

$$\Pi^i_i(\cdot) = \frac{I+\lambda(1-I)}{(I+1)^2}\left(\alpha^i + (I+\lambda(1-I))y^i + (2\lambda-1)\sum_{j\neq i} y^j\right) - \kappa y^i = 0.$$

Letting further

$$\beta_1 = \left(\frac{I+\lambda\,(1-I)}{I+1}\right)^2 - \kappa, \quad \beta_2 = \frac{(2\lambda-1)\,(I+\lambda(1-I))}{(I+1)^2}, \quad \text{and} \quad \beta_3 = \frac{I+\lambda(1-I)}{(I+1)^2},$$

firm i's first-order condition may equivalently be rewritten as

$$\beta_1 y^i + \beta_2 \sum_{j \neq i} y^j + \beta_3 \alpha^i = 0. \tag{A.3}$$

Solving for y^i yields

$$R^i(\mathbf{y}^{-i}) = -\frac{\beta_3}{\beta_1}\alpha^i - \frac{\beta_2}{\beta_1}\sum_{j \neq i} y^j,$$

which is firm i's best-response function given that rivals invest $\mathbf{y}^{-i}$. Noting that $\beta_1 = \Pi^i_{ii}$ and that $\beta_2 = \Pi^i_{ij}$, respectively, we may conveniently rewrite firm i's reaction function as

$$R^i(\mathbf{y}^{-i}) = \phi^i - \frac{\Pi^i_{ij}}{\Pi^i_{ii}}\sum_{j \neq i} y^j, \quad \text{with} \quad \phi^i \equiv -\frac{\beta_3}{\beta_1}\alpha^i. \tag{A.4}$$

Thus, using (A.2),

$$\text{sign}\left(\frac{\partial R^i(\mathbf{y}^{-i})}{\partial y^j}\right) = \text{sign}\left(\Pi^i_{ij}\right).$$

As $\text{sign}\left(\Pi^i_{ij}\right) = \text{sign}\left(\beta_2\right)$, the fact that

$$\frac{I + \lambda(1 - I)}{(I+1)^2} > 0; \quad \text{for all } \lambda,$$

implies $\text{sign}\left(\Pi^i_{ij}\right) = \text{sign}\left(2\lambda - 1\right)$.

In matrix notation, the system of first-order conditions as given in (A.3) reads

$$\begin{pmatrix} \beta_1 & \beta_2 & \cdots & \beta_2 \\ \beta_2 & \beta_1 & \ddots & \vdots \\ \vdots & \ddots & \ddots & \beta_2 \\ \beta_2 & \cdots & \beta_2 & \beta_1 \end{pmatrix} \begin{pmatrix} y^1 \\ y^2 \\ \vdots \\ y^I \end{pmatrix} = -\beta_3 \begin{pmatrix} \alpha^1 \\ \alpha^2 \\ \vdots \\ \alpha^I \end{pmatrix},$$

which we may conveniently rewrite as $M\mathbf{y} = -\beta_3 \boldsymbol{\alpha}$. Using the stability condition given in (A.2), which can be restated as $|\beta_1| > (I-1)|\beta_2|$, the matrix M has a dominant diagonal. Thus, M is known to be nonsingular and M^{-1} exists, whence follows that $\mathbf{y} = -M^{-1}\beta_3\boldsymbol{\alpha}$.

Lemma A.1. *The inverse of M is given by*

$$M^{-1} = \frac{\beta_2}{(\beta_1 - \beta_2)(\beta_1 - \beta_2 + I\beta_2)} \begin{bmatrix} \frac{\beta_1}{\beta_2} + (I-2) & -1 & \cdots & -1 \\ -1 & \frac{\beta_1}{\beta_2} + (I-2) & \ddots & \vdots \\ \vdots & \ddots & \ddots & -1 \\ -1 & \cdots & -1 & \frac{\beta_1}{\beta_2} + (I-2) \end{bmatrix}.$$

Proof. Letting I denote the identity matrix, it suffices to show that $M^{-1}M = I$. For the diagonal elements, we obtain

$$\frac{\beta_2}{(\beta_1 - \beta_2)(\beta_1 - \beta_2 + I\beta_2)}\left(\beta_1\left(\frac{\beta_1}{\beta_2} + (I-2)\right) - \beta_2(I-1)\right) = 1.$$

Similarly, we obtain for the off-diagonal elements that

$$\frac{\beta_2}{(\beta_1 - \beta_2)(\beta_1 - \beta_2 + I\beta_2)} \left(-\beta_1 + \beta_2 \left(\frac{\beta_1}{\beta_2} + (I-2) \right) - (I-2)\beta_2 \right) = 0.$$

□

Using Lemma A.1, firm i's equilibrium investment can computed to be

$$y^{i^*} = -\frac{\beta_2\beta_3}{(\beta_1 - \beta_2)(\beta_1 - \beta_2 + I\beta_2)} \left(\left(\frac{\beta_1}{\beta_2} + (I-2) \right) \alpha^i - \sum_{j\neq i} \alpha^j \right).$$

Simplifying the term in brackets on the right hand side yields

$$\begin{aligned} \left(\frac{\beta_1}{\beta_2} + (I-2) \right) \alpha^i - \sum_{j\neq i} \alpha^j &= \left(\frac{\beta_1}{\beta_2} + (I-1) \right) \alpha^i - \sum_i \alpha^i \\ &= \left(\frac{\beta_1}{\beta_2} + (I-1) \right) \left(\alpha + (I+1) Y_0^i - \sum_i Y_0^i \right) \\ &\quad - \left(I\alpha + \sum_i Y_0^i \right), \end{aligned}$$

so that firm i's equilibrium investment can be rewritten as

$$y^{i^*} = -\frac{\beta_3 \left((\beta_1 - \beta_2)\alpha + (\beta_1 - \beta_2 + I\beta_2)(I+1) Y_0^i - (\beta_1 + I\beta_2) \sum_i Y_0^i \right)}{(\beta_1 - \beta_2)(\beta_1 - \beta_2 + I\beta_2)}. \tag{A.5}$$

Lemma A.2. *Under (A.2), both*

$$\beta_1 - \beta_2 < 0 \quad \textit{and} \quad \beta_1 - \beta_2 + I\beta_2 < 0.$$

Proof. By (A.2), $\beta_1 < 0$. If $\beta_2 \geq 0$, we immediately have $\beta_1 - \beta_2 < 0$. If $\beta_2 < 0$,

$$|\beta_1| > (I-1)|\beta_2| > |\beta_2| \Longleftrightarrow -\beta_1 > -\beta_2.$$

Thus, $\beta_1 - \beta_2 < 0$.

Similarly, if $\beta_2 \leq 0$, (A.2) implies $\beta_1 + (I-1)\beta_2 < 0$. If $\beta_2 > 0$, we have

$$|\beta_1| > (I-1)|\beta_2| \Longleftrightarrow -\beta_1 > (I-1)\beta_2.$$

Thus, $\beta_1 + (I-1)\beta_2 < 0$. □

With Lemma A.2 in mind and noting that $\beta_3 > 0$, $y^{i^*} > 0$ if and only if the numerator of (A.5) is negative, i.e.,

$$(\beta_1 - \beta_2)\alpha + (\beta_1 - \beta_2 + I\beta_2)(I+1) Y_0^i - (\beta_1 + I\beta_2) \sum_i Y_0^i < 0, \quad \text{for all } i,$$

or equivalently, if and only if

$$\alpha > \frac{(\beta_1 + I\beta_2) \sum_{j\neq i} Y_0^j - \left(I\beta_1 + (I^2 - I - 1) \right) Y_0^i}{\beta_1 - \beta_2}, \quad \text{for all } i.$$

Thus, equilibrium investments are positive if and only if net demand α is sufficiently large relative to the initial efficiency levels $(Y_0^1, \ldots, Y_0^I)$.[41]

[41] Note that in the case of symmetric firms with initial efficiency level $Y \geq 0$, the restriction on α boils down to $\alpha + Y > 0$, or equivalently, to $a > c - Y$.

A.2 Proofs of Propositions 1 through 4

Proof of Proposition 1. From (A.5), it follows that

$$y^i - y^j = \frac{\beta_3 (I+1)}{\beta_1 - \beta_2} \left(Y_0^j - Y_0^i \right).$$

As $\beta_3 > 0$, the claim follows from Lemma A.2. This completes the proof.

Proof of Proposition 2. (i) Let $y \equiv \sum_i y^i$ denote aggregate investment. From (A.5), we obtain

$$y = -\frac{\beta_3 \left(I\alpha + \sum_i Y_0^i \right)}{\beta_1 - \beta_2 + I\beta_2}.$$

Hence, the numerator is determined by $\sum_i Y_0^i$ only. This completes the proof. (ii) follows immediately from Proposition 1 and part (i) of this proposition.

Proof of Proposition 3. From the discussion in Footnote 15, player i's optimal investment $y^{i^*}(\lambda = 0.5)$ is independent of rivals' actions. Note that condition (6) implies

$$\frac{\partial \Pi^i(\lambda < 0.5)}{\partial y^i} > \frac{\partial \Pi^i(\lambda = 0.5)}{\partial y^i} > \frac{\partial \Pi^i(\lambda > 0.5)}{\partial y^i}.$$

Hence, for arbitrary $\lambda < 0.5$ and arbitrary actions of the competitors, the best response is above $y^{i^*}(\lambda = 0.5)$, whereas for arbitrary $\lambda > 0.5$, the best response is below $y^{i^*}(\lambda = 0.5)$. This completes the proof.

Proof of Proposition 4. We prove the statement for $\lambda \in (0.5, 1]$. In a Nash equilibrium, $\partial \Pi^i(\mathbf{y}^*)/\partial y^i = 0$. Therefore,

$$\frac{\partial \Pi(\mathbf{y}^*)}{\partial y^i} = \frac{\partial \Pi^i(\mathbf{y}^*)}{\partial y^i} + \sum_{j \neq i} \frac{\partial \Pi^j(\mathbf{y}^*)}{\partial y^i} = (I-1)(2\lambda - 1) > 0,$$

where the last two steps follow from Observation 1. As $\partial \Pi(\mathbf{y}^*)/\partial y^i > 0$, for all i, concavity implies $\partial \Pi(\mathbf{y})/\partial y^i > 0$, for all $\mathbf{y} < \mathbf{y}^*$. Thus no $\mathbf{y} \leq \mathbf{y}^*$ can maximize the firms' joint profit, whence follows for all i that $y^{i^{**}}(\lambda) > y^{i^*}(\lambda)$. The proof for the case $\lambda \in [0, 0.5)$ is analogous, and therefore omitted. This completes the proof.

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