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Competition in product design: An experiment exploring innovation behavior*

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May 2, 2007

Abstract

We experimentally investigate competition in innovation in a patent race scenario. Pairs of subjects compete as seller firms on a duopoly market, engaging in risky search investments. Successful innovation is rewarded through temporary monopoly rents. Throughout the interaction, subjects receive feedback on own and other's search success and profit margin. Partitioning subjects into subgroups of investor types reveals that the majority of subjects condition investments on the degree of competition as measured by sales shares, while for others no correlation is ascertained. Heterogeneity in individual risk attitudes and differing experiences with related search tasks may explain this finding. (JEL: D81, L11, O31)

Keywords: innovation, competition, imitation, patent race

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1 Introduction

We explore the dynamics of product market competition between duopolistic firms and assess their implication on firms' rate of innovative activity. Generally, the relationship between competition and innovation has long been of considerable concern to corporate and public decision makers and researchers alike. Above all, the question of interest is to identify the influence of competition on innovative success, be it to dissociate oneself from competitors while aiming for monopoly rents or to enhance productivity and induce economic growth (cf., Nadiri, 1993; Ahn, 2002).

Recent empirical studies (e.g., Aghion, Bloom, Blundell, Griffith, & Howitt, 2005) on the impact of economic policy reforms – focusing on the degree of competition in particular industries – have brought up convincing evidence that the degree of competition actually and significantly affects the rate of innovation. Further, it seems to be a popular view in many public administrations, e.g., the OECD, that increased competition can lead to both onetime and permanent gains in productivity. As a result, the distinction is commonly drawn between instantaneous gains from competition or static efficiency in the sense of a more efficient resource allocation and less slack,¹ and dynamic efficiency gains related to intensified innovative efforts and more innovations. While it is generally conceded that intense competition brings about static efficiency gains, the link between competition and dynamic gains sparks some controversy.

To bring some clarity to the question, some recent studies on industrial organization and endogenous growth have particularly addressed the relationship between product market competition and the rate of innovation. Nevertheless, the debate as to whether an imperfectly competitive monopoly or fierce competition in an atomistic market maximizes innovative output, is still ongoing. The various claims of a positive (cf., Geroski, 1995; Nickel, 1996; Lerner, 1997; Blundell, Griffith, & Reenen, 1999), negative (cf., Dixit & Stiglitz, 1977; Loury, 1979; Dasgupta & Stiglitz, 1980), or hump-shaped (cf., Aghion et al., 2005; Poldahl & Tingvall., 2005) relationship between competition and innovation each have their advocates as well as their critics.

While the first two claims are straightforward in their prediction that intensified competition encourages innovation² or diminishes it,³ the third is somewhat more

¹ Weak governance structures are identified as one source of inefficiencies, which tend to be remedied by intensified competition (Nickel, 1996).

² Innovations are pursued to remove current inefficiencies in the firm's processes and product portfolio ("replacement effect," Arrow (1962)) with the objective of recovering lost profit margins.

³ As the number of competitors increases, appropriability of monopoly rents by the innovating firm is less and less ensured. Moreover, the growing threat of Schumpeterian creative destruction

intricate. A firm in a (nearly) perfectly competitive market operates at marginal profitability and presumably lacks the financial resources to effectively pursue product and process innovations. If the firm is able to increase its market power, i.e., by setting a price above marginal cost, its rate of investing should equally increase. However, once the firm exceeds a critical level of market power, empirical evidence suggests that the growth trend will reverse and the investment rate decline.

In our study, we intend to accumulate experimental evidence from a competitive search scenario, which may allow us to verify the claimed hump-shaped (or inverted-U-shaped) relationship between innovation and competition. Discussing the incentive of firms to innovate, Aghion et al. (2005) argue that this is determined by the spread between the firms' rent prior and subsequent to the innovation whereby the former is more strongly threatened by competition than the latter. As a result, intense competition between "neck-to-neck" firms should encourage R&D investments.

In our design we will relax the assumption that subjects are able to compute the expected returns of their actions with certainty. All the same, we conjecture that neck-to-neck competition is capable of stimulating R&D investments, even in the described setting of incomplete information. In most realistic innovation scenarios firms find themselves in the similar situation of not being able to anticipate either the exact outcome of the search process search or the implied benefits thereof. Moreover, if the economic benefit of research investments was to be predicted with certainty or at least probabilistically, we would no longer be dealing with genuine innovations in the sense of Arrow (1991).

So far, little is known about the underlying processes which motivate firms to engage in risky innovative activities. In the literature on optimal innovation investments, in general, and on patent races, in particular, it is assumed that innovators can assess the profit of alternative innovation strategies.⁴ In competitive innovation scenarios such as patent races, the decision to invest primarily conditions on two aspects. First agents maximize their expected return for given respective probabilities and monetary returns of the various possible investment outcomes. An individual choice problem is thus solved, to which Fusfeld and Haklisch (1985) also refer as the "go-it-alone" or profit motive. Second, due to strategic interaction among competi-

(Schumpeter, 1942) dissuades risky search investments.

⁴ Seminal contributions such as Arrow (1962), Dasgupta and Stiglitz (1980), or Reinganum (1985) are based on this very idea: agents, endowed with complete information and perfect problem-solving capabilities, pursue an optimal R&D program maximizing the difference between the additional gross profits accruing from an innovation and the cost of achieving that innovation.

tors, each investor additionally has to anticipate the implication of others' choices on the own return on investment. Boone (2000), for example, extensively analyzes several factors of competitive pressure, or alternatively competitive threat, and discusses their impact on the firms' incentive to invest in innovations.

In the patent races analyzed by Beath, Katsoulacos, and Ulph (1988), the winner-follower outcome is stochastic. Reinganum (1985) focuses on the effect of variations in the intensity of the profit motive and Harris and Vickers (1985 and 1987) exclusively consider variations in the degree of the competitive threat. In the two latter studies, those firms with the stronger profit motive or a stronger perception of the competitive threat invest more in R&D and are ultimately more likely to win the patent race. In deterministic sequential patent races, such as the model of Vickers (1986), it is investigated under which conditions the strategic interaction between different innovators leads to specific winner-follower sequences. Sequential structures range from dominance sequences, where the same competitor always takes the lead, to so-called action-reaction sequences of leap-frogging, where the technological lead of one innovator in period t can trigger a change in technological leadership in period $t+1$ (see, e.g., Fudenberg, Gilbert, Stiglitz, & Tirole, 1983). Introducing uncertainty leads to (analytically non-tractable) stochastic innovation sequences leading Beath et al. (1988), in a number of simulation exercises to distinguish gradual catching-up sequences and continuous leap-frogging.

In contrast to such models, we do not assume that competitors are able to anticipate the future benefits from innovations by applying backward induction. If subjects, by contrast, use search heuristics, will this lead to unpredictable investment patterns, or will behavioral regularities endure? Bounded rationality would require participants to mentally represent the dynamic investment problem by neglecting certain complicating aspects, which does not exclude that they search in predictable ways. Thus, what we study is the structure and the determinants of innovative investments in a competitive interaction scenario, characterized by risky investment choices and strategic uncertainty.⁵

Rather than asking the question whether regularly observed search patterns converge to or actually reach optimality, we confront subjects with a complex decision environment, relying on an extensive and unordered search space. Subjects have to determine which (mix) of the two generic strategies of risky innovative investments and risk-free imitations suits their preferences best. Given the complexity

⁵ See Knight (1921) and Shackle (1968) for seminal contributions on the issue of choice under risk and uncertainty.

of the task, analytic optimization by means of Bayesian reasoning becomes unfeasible, urging participants to rely on boundedly rational decision heuristics. After describing our model, we will provide a simulation analysis to demonstrate how such heuristics could be defined and evaluated.

The subsequent data analysis focuses on behavioral regularities in non-price competition. We will show by regression analysis that the decision to innovate conditions to a certain extent on proxies of competitive pressure. While we do not find clear-cut support for a hump-shaped relation between competition and innovation when using (relative) firm size as a proxy for the former, we discern a significant positive impact of the difference in the rivals' periodic revenues (a measure of relative profits) on the rate of investing.

Clearly, our competitive search scenario does not allow us to offer new insights into how to detect the genuinely new. Rather, we investigate interacting agents who engage in innovative activities with the aim of introducing something superior to the status quo. More specifically, we focus on search patterns for higher quality and, consequentially, more profitable product designs, and on how such search processes condition on information about the own and the other's search success and economic performance. To the best of our knowledge, this is one of the first attempts to explore interaction in innovative behavior experimentally.⁶

The remainder of this paper is structured as follows. Section 2 introduces the various elements of our model of competitive innovation. The second of three subsections of this section describes the practical procedures, while the third reports central results from a simulation analysis of the above-described model. Section 3 contains the data analysis, stating observed behavioral regularities and reporting on the behavior of subgroups of participants with distinct investment preferences. Finally, in section 4 we discuss our main findings and conclude.

2 Experimental model and numerical benchmark

In our model, innovations exclusively relate to product improvements, and competition is restricted to a duopoly market without price competition. More specifically,

⁶ Isaac and Reynolds (1988 and 1992) experimentally investigate patent tournaments in terms of price competition. Zizzo (2002) sets up a patent race for a single patent. However, in neither case competition takes place in the product space. Less related are experimental studies of stopping heuristics in search problems where one attempts to select the most suitable candidate when candidates can only be evaluated sequentially (see, e.g., Zwick, Rapoport, Lo, & Muthukrishnan, 2003, for the so-called secretary problem).

the search space comprises product-enhancing innovations for which an exhaustive search is (prohibitively) costly. Subjects are symmetric with respect to search costs and rent appropriation.

2.1 Search space and demand model

In the experiment, pairs of subjects design a “product” A that is composed of multiple aspects, which in turn feature several mutually exclusive design choices. Each (product) aspect a_1, \dots, a_n allows for several specifications $m_j = ||a_j|| \geq 2$ (with $j = 1, \dots, n$) which constitute the unordered set $a_j^1, \dots, a_j^{m_j}$. Thus, in each period t , the subjects $i = 1, 2$ actively select or maintain one specification $x_{i,j}$ per aspect from the various alternatives $a_j^1, \dots, a_j^{m_j}$ for all aspects a_1, \dots, a_n .

Generally, it should be the subjects’ goal to identify the exogenously given consumer preferences⁷ a_1^*, \dots, a_n^* . The better they match their product configuration A_i (defined by $x_{i,1}, \dots, x_{i,n}$) with the ideal specification a_j^* of the respective aspects (with $j = 1, \dots, n$), the higher their payoff will be.⁸ To align the own product specification A_i with the predefined ideal (product) profile, subjects can, at a cost of $c(> 0)$ per search attempt, simultaneously explore some or all of the n aspects. Throughout the repeated interaction, subjects are free to identify and adopt the ideal specifications of the various aspects while being regularly updated on the competitor’s past search and economic performance. For any choice $x_{i,j}$ of the subjects, $i = 1, 2$, we define the former’s distance to the aspect a_j^* by

$$\delta_{i,j}(x_{i,j}, a_j^*) = \begin{cases} 0 & \text{if } x_{i,j} = a_j^* \\ 1 & \text{otherwise.} \end{cases}$$

Positive demand is attracted if the subject has specified at least one aspect correctly. We arbitrarily define that each correctly specified aspect increases demand by two units, while misspecified aspects do not yield any demand. This setting may be interpreted as the competition between two firms which are active in n independent markets (one for each aspect), and to which they may only enter after meeting the ideal aspect specification. $\phi_{i,j}^t(x_{i,j}^t, x_{-i,j}^t)$ denotes the demand which subject i

⁷ In the instructions, we frame the search task as the firm’s objective to best serve a set of stable, but initially unknown consumer preferences.

⁸ The ideal specification for aspect a_j is discovered when it is matched by subject i ’s selected specification for that aspect ($x_{i,j} = a_j^*$ with $j = 1, \dots, n$).

attracts through aspect a_j in period t .⁹ We define

$$\phi_{i,j}^t(x_{i,j}^t, x_{-i,j}^t) = [1 - \delta_{i,j}^t(x_{i,j}^t, a_j^*)] [1 + \delta_{-i,j}^t(x_{-i,j}^t, a_j^*)] .$$

If subjects coincide in correctly specifying an aspect, the total demand for this is split equally between them. Conversely, if only one subject correctly specifies an aspect, he appropriates the entire demand for this aspect. For simplicity, we abstract from production costs¹⁰ and assume a uniform and constant cost $c(> 0)$ for investing in innovative activities. These costs represent switching costs and are only incurred if subject i selects a truly novel specification for aspect a_j , whereas he may return to any previously selected aspect specification at no charge.

The variable $\gamma_{i,j}^t$ marks the switching costs which are incurred by subject i when choosing a specification of aspect a_j for the first time at point t in the interval $1 \leq t \leq T$:

$$\gamma_{i,j}^t(x_{i,j}^t) = \begin{cases} 2 & \text{if } x_{i,j}^t \notin \bigcup_{\bar{t}=1}^{t-1} x_{i,j}^{\bar{t}} \\ 0 & \text{otherwise.} \end{cases}$$

The (undiscounted) overall profit π_i of subjects $i = 1, 2$, which results from their interaction during $t = 1, \dots, T$ periods, then is

$$\pi_i = \sum_{j=1}^n \left[\sum_{t=1}^T \phi_{i,j}^t(x_{i,j}^t, x_{-i,j}^t) - \gamma_{i,j}^t(x_{i,j}^t) \right] .$$

At the end of each period, both subjects receive feedback on their competitor's product configuration A_{-i} . In absence of further restrictions, this would allow to imitate the other's correctly specified aspects without having to invest in extensive search oneself. To protect the innovator, i.e., the one who first discovered the correct aspect specification a_j^* of aspect a_j in period $t < T$, we introduce a transitory monopoly (patent) right of $k(> 0)$ periods. During the patent phase from t to $t + k$, imitation of a_j^* is not allowed. Once the patent phase has expired, the competitor may choose a_j^* at the cost of two units which, in this context, represent switching or imitation costs. If the subjects independently identify a_j^* at the same time, they can both freely choose a_j^* afterwards.

⁹ In the following, $-i$ denotes the respective other subject in the group.

¹⁰ Alternatively, interpret the constant sales price as the constant net revenue (price minus unit production costs) before the costs of search are applied.

2.2 Laboratory protocol

The experiment was conducted at the computer laboratory of the Max Planck Institute of Economics and involved a total of 72 undergraduate students from the University of Jena, the majority of them majoring in business administration or economics. Four sessions were conducted, each of them comprising two sequences of a patent race with 15 periods each. Initially, subjects were randomly paired and henceforth interacted in partners design throughout the first sequence. Prior to the start of the second sequence, subjects were randomly matched with a different co-player, with whom they would then interact until the end of the session. General comprehension of the rules method was ensured by means of a pre-experimental control questionnaire.¹¹ Subjects were provided with pen and paper so they could take notes, which the majority of participants actually did.

In the experiment, pairs of subjects competed in simultaneously searching for the correct specification of eight distinct aspects. To ease the subjects' task of understanding the structure of the search space, we provided them with an intuitive framing, prompting them to design a "product," namely an automobile, which was comprised of multiple components. For each component, in turn, a number of alternatives was available. Whenever the correct specification of an aspect was found, demand for the overall product increased by either one or two units. Subjects were free to modify their current set of choices in each period while they could equally maintain any subset or the entire set of their design choices in the preceding period. A modification of overall design choice could involve any and any number of the eight distinct aspects.

At the end of each period, subjects received feedback on their design choices, on the success of their search investments (i.e., whether oneself or the co-player was been awarded a patent), and on the economic performance in the respective period (i.e., in terms of newly assigned and further active patents and periodic profits). All the above-stated information was made known to both players.

The following parameters were used: Subjects each received an endowment of 40 units at the beginning of each sequence. Beyond this initial allocation, there were no further endowments. Although it was theoretically possible in the experiment to entirely deplete one's account, thus reaching bankruptcy, it never occurred that participants ran out of money. They could use this money to invest in eight distinct

¹¹ Prior to the start of the experiment, any open questions and obscurities were privately clarified at the participant's place.

aspect which altogether defined their own “product.” There were two types of aspects which differed in riskiness. While one type of aspects comprised 8 alternative specifications ($m_j = 8$), the other type only contained half as many alternatives ($m_j = 4$), rendering the latter more attractive in terms of their profitability of research. If a patent was awarded, it shielded its owner from imitation for a duration of $k = 4$ periods. Accumulated earnings were converted into euros at the exchange rate of 1 unit = €0.08.

It took participants about 65 minutes to finish the two patent race sequences, during which they, on average, earned an amount of €18.78 (sd. €3.16). The spread between the highest (€25.70) and the lowest (€7.54) realized payoff indicates that search success varied considerably among participants.

2.3 Deriving a numerical benchmark

The complexity of the decision task is due to the very large search space and the uncertainty of $a^* = (a_1^*, \dots, a_n^*)$. The task becomes even more involved when the number of aspects and of options within the aspects increase. One particular obstacle to optimization is to quantify the utility which is derived from a “failed” investment. In this case, search does not yet yield the ideal aspect specification, but reduces the number of feasible options in that aspect by one, thereby improving the chance of a subsequent search success. Since all innovation attempts are made public, the benefit of decreasing the search space by discarding invalid options constitutes a public good, which is henceforth enjoyed by both competitors.

To evaluate the quality and consistency of observed investment decisions, we ran a simulation of our search model to establish a numerical benchmark. The objective of this exercise was to investigate the distributions of several key variables related to the outcome of the interactive search process.¹² By intentionally making the decision problem too challenging for any formal optimization calculus on the subjects’ part, we wanted to encourage them to rely on effective search heuristics. In their approaches of boundedly rational reasoning, Simon (1955), Rubinstein (1998), and Gigerenzer and Todd (1999) suggest decision heuristics generating adequate outcomes that are only slightly inferior to optimality, but require significantly less cognitive effort. In our framework, subjects had to form a simple mental model which effectively reduces the complexity of the search task.

¹² Inspected variables included the mean search duration in aspects comprising four or eight options, the relationship between the subject’s risk attitude and his sequence profit, and the magnitude of information spillovers.

Consider the following model simplifications: Subjects may entertain heterogeneous preferences and also differ in their attitude toward risk, which is captured by an individual parameter arbitrarily labeled as their “risk type.” This (henceforth denoted by r) may range from 1 to 8, meaning that the subject is unwilling to invest in costly search if the number of remaining choice options in aspect a_j ($m_j = ||a_j||$) exceeds r . The risk type is presumed to be an idiosyncratic constant which cannot be changed and is supposed to dictate the subject’s decision making.¹³ Further, assume that subjects do not take the remaining duration of a sequence into account when deciding whether to invest. As long as the investment risk satisfies the subject’s risk type, he will invest irrespective of the number of remaining interaction periods.

The simulation exercise, which we briefly summarize in the following, is based on a sample of 10,000 competitive interactions between paired agents and conforms to both, our model specification and the above-stated simplifications.¹⁴ If at least one of the agents is of risk type $r_o = 8$, it almost always (in 99% of all cases) follows that all eight aspect specifications are correctly identified throughout the race. The entire product specification is typically revealed by the end of period 7 ($\mu = 6.9$, $\sigma = 1.8$). Moreover, agents generally derive a positive income from investing in all aspects, irrespective of whether the latter comprise four or eight choice options. This incentive, of course, varies in the agent’s degree of risk aversion.

The following statistics from the simulation may serve as a guideline: Agents on average expend an amount of $\mu = 3.82$, $\sigma = 1.96$ ($\mu = 5.94$, $\sigma = 4.48$) on investigating aspects which initially feature 4 (8) options (henceforth labeled as aspects $m_j = 4$ or $m_j = 8$) and thereby derive a gross income of $\mu = 13.88$, $\sigma = 4.71$ ($\mu = 12.14$, $\sigma = 5.32$). In terms of net profits, e.g., after deducting incurred search costs, this translates into $\mu = 10.04$, $\sigma = 4.85$ ($\mu = 6.14$, $\sigma = 5.94$). Due to the substantial volatility in net profits, their realizations are spread over the interval of $[-6, 20]$ or, respectively, $[-12, 18]$. However, a net loss is incurred in less than 1% (10%) of all investments in $m_j = 4$ ($m_j = 8$) aspects.

We estimate a linear regression to quantify the effect of the own and the other’s risk type on the own sequence profit (see Table 1). The model considers the own (r_o) and the other’s (r_c) risk type, and their interaction term ($r_o \times r_c$). We find that both r_o and r_c positively contribute to the own sequence profit. The striking negative interaction effect between r_o and r_c points to a detrimental conflict of simultaneous

¹³ Alternatively, think of the subject’s risk type as his minimally required winning probability for taking part in a lottery which features at most $(r - 1)$ blanks and exactly one winning lot.

¹⁴ The simulation was scripted and conducted using the statistics package R. To obtain a copy of the script, please contact the corresponding author.

Table 1: *A linear model explaining sequence profit as being conditional on subjects' risk type*

Covariate	Estimate	Std.error	p-value
<i>Intercept</i>	13.06	0.721	< 0.001
r_o	13.49	0.142	< 0.001
r_c	7.71	0.141	< 0.001
$r_o \times r_c$	-1.40	0.028	< 0.001
adj. R^2 : 0.61			

Table 2: *Simulation-based payoff matrix*

π_{row}, π_{column}		r_{column}							
r_{row}		1	2	3	4	5	6	7	8
	1	40,40	40,40	40,40	66,94	66,94	66,94	66,94	84,121
	2	40,40	40,40	40,40	66,94	66,94	66,94	66,94	84,121
	3	40,40	40,40	40,40	66,94	66,94	66,94	66,94	84,121
	4	94,66	94,66	94,66	80,80	80,80	80,80	80,80	100,108
	5	94,66	94,66	94,66	80,80	80,80	80,80	80,80	100,108
	6	94,66	94,66	94,66	80,80	80,80	80,80	80,80	100,108
	7	94,66	94,66	94,66	80,80	80,80	80,80	80,80	100,108
	8	121,84	121,84	121,84	108,100	108,100	108,100	108,100	108,108

high-risk types.

Table 2 presents the interacting agents' average sequence profits, the former being grouped by their risk type, and arranges the data in the style of a payoff matrix. Assuming that an agent can deliberately and strategically choose his risk type and subsequently maintains the latter throughout the sequence, e.g., like adhering to one particular strategy in a repeated game, one immediately derives the unique "equilibrium" of this simple game.¹⁵ In "equilibrium," both agents prefer to adopt the risk type of $r^* = 8$ over all other risk types. We thus find that the unique solution of this simple simultaneous-move game is an equilibrium in dominant strategies.

¹⁵ Clearly, our numerically derived prediction may only be applied when risk neutrality of subjects can be reasonably assumed, since we deliberately chose not to consider the variance of sequence payoffs.

3 Results

3.1 Regular investment behavior

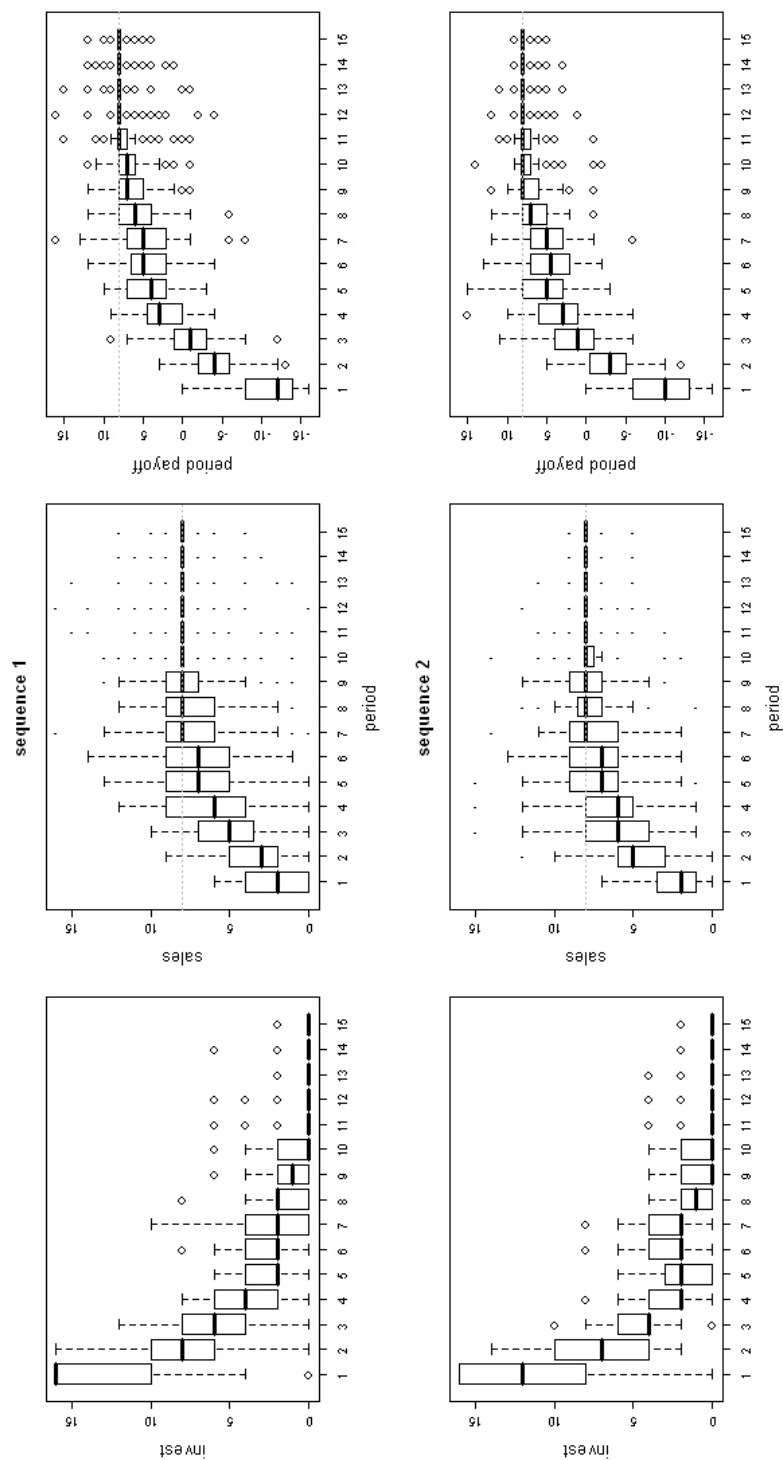
Let us first analyze the aggregate investment choices. Figure 1 shows the distribution of investments across all periods of the two sequences and illustrates subjects' revenues and period profits. Initial investments in each sequence start out at an elevated level (left panel). The median investor expends either the maximally possible amount (16 in sequence 1), or remains only slightly beneath the investment limit (12 in sequence 2). In the following periods, the intensity of investments declines at a decreasing rate before stabilizing at a low level at the end of the first half of the sequence. Any expiring patents of the rival are usually imitated without delay, accounting for the elevated investment activity around periods 6 and 7. Thereafter, investment activity drops to a marginal level for the remainder of the sequence. Since our model does not provide continued investment opportunities once a patent has been granted in a given aspect, any further activity in this domain is useless. In a companion paper to this study (Cantner, Nicklisch & Weiland, 2005), we lift this constraint by introducing sequential patenting (allowing agents to pursue search throughout the entire sequence).

The middle and right panels of Figure 1 depict the evolution of revenues and period profits throughout the sequence. The two plots are, of course, closely related as period profits and revenues only differ in the vertical shift due to search costs. Initially, revenues and period profits rise monotonically and at a decreasing rate until both subjects are in control of an equitable market share (of eight units), usually reached around period 9. Note that the decline in the spread between the rivals' profit margin nicely illustrates the rent erosion effect of competition in the absence of enforced property rights.

Result 1: The rate of investing is maximal at the start of the patent race and declines continuously at a decreasing rate. Revenues and period profits initially increase rapidly and then converge (at a decreasing rate) toward equitable sharing maximal demand with no search costs.

Let us now focus attention on the role of leadership during the race. More specifically, we explore whether and, if so, to which extent a subject's relative position of being ahead or behind in terms of accumulated profits is governed by path-dependency. We find that the current leader's probability of maintaining his rank

Figure 1: *Investments, sales, and period profits across periods and sequences*



throughout the remaining sequence monotonically increases across periods at a diminishing rate. At the end of the first period, it is not yet possible to discern the more probable, eventual winner of the patent race. Yet, at any later point of time, it becomes increasingly obvious that the current leader will eventually win the race. The empirical probability of eventually winning the race if one is currently ahead of one's competitor equals 74% in period 3, 84% in period 6, and 94% in period 9. Thereafter, we do not observe any switch in leadership. We can therefore state that in most cases the relative position of the paired rivals does not switch throughout a sequence, if each is willing to neglect the turmoil in the first two periods of the competitive race. Switches in the leader-follower structure, which are also referred to as "leap-frogging," are extensively discussed in the economic literature on development and firm competition (cf., Fudenberg et al., 1983; Aoki, 1991). Our data thus suggest that "success breeds success." Similarly, in an empirical analysis of 301 German firms in the manufacturing sector, Flaig and Stadler (1994) prove a significant state dependence of the current innovation output of the firm on the magnitude of its realized innovations in the preceding year. If a follower has not been able to achieve a turnaround in the first half of the sequence, he will in all likelihood remain behind.

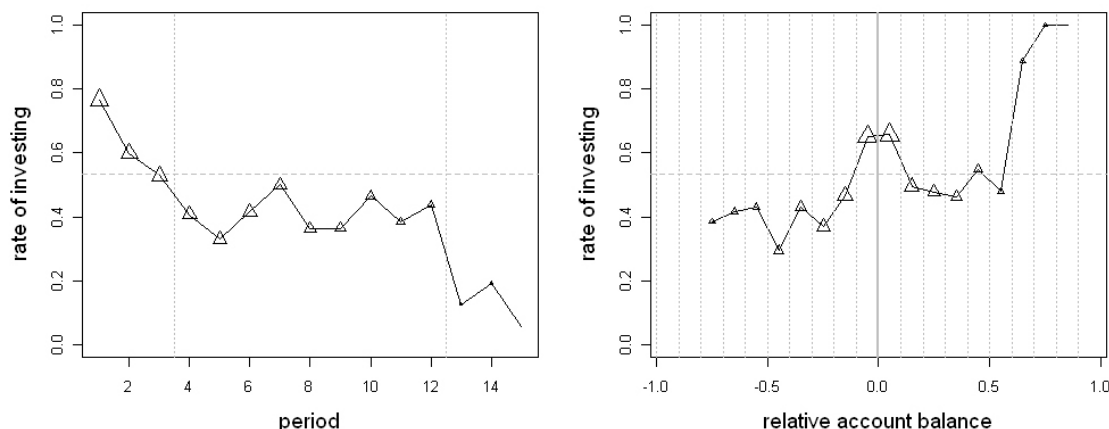
Result 2: Leap-frogging in the sense of switching from leader to follower and vice versa is rare. Moreover, the relatively short time window for investing in search rules out further competitive dynamics in the second half of a sequence.

3.2 Determinants of the rate of investing

To investigate the pattern of diminishing investments across time more closely, we separately compute the mean propensity of the sample population to engage in risky search for every single period.¹⁶ More exactly, we declare an investment in a given aspect to be risky if the aspect contains at least two so far unexplored elements.¹⁷ Figure 2 (left panel) reveals that the rate of investing in risky search substantially diminishes over time. Three phases of the patent race can be distinguished: an initial phase of elevated investment propensity (periods 1-3), an ensuing phase with an attenuated but nondecreasing investment rate (periods 4-12), and a terminal

¹⁶ The computation involves the investment choices of all participants and refers to all aspects, in which the correct specification has not yet been revealed.

¹⁷ This procedure reduces the number of observations from 5,365 to 5,029.

Figure 2: *Investment propensity contingent on period and relative account balance*

phase during which the rate of investing converges to zero (periods 13-15).

The differences between the three phases can be rationalized: initially, rivals are symmetric with an identical endowment and no patents. Since early patents entail continuous positive cash flows for their owners, subjects have a strong incentive to invest in search right from the start of the patent race.¹⁸ Subsequently, the rate of investing decreases and stabilizes at around 40-50%, since slightly less than half of all available risky investments are actually pursued.¹⁹ Toward the end of the sequence, most of the still actively searching subjects refrain from investing as the attainable cash flows from investing in search of an aspect shrink over time and may not justify any further investment.

In the right panel of Figure 2, the choice of investing in risky search is related to the rivals' (relative) account balance. The latter statistic was chosen because, in our view, the relative distance in account values constitutes a suitable proxy for the intensity of competition in the patent race.²⁰ The "relative account" statistic (henceforth *relAcc*) of a subject with respect to his rival is defined as the difference between his and the latter's account balance, divided by the sum of their account balances.²¹ A first inspection of Figure 2 reveals that the mass of observations is

¹⁸ Cash flows result from an initial sequence of monopoly rents, followed by a steady stream of revenues which are derived from equal market shares. Moreover, monopoly rents are the only effective means for a subject to leave the competitor behind.

¹⁹ As the sequence progresses, the number of remaining (sensible) investment opportunities decreases sharply. The triangle size equals the natural logarithm of the number of available risky investment choices in the period.

²⁰ A second proxy for competitive intensity, i.e., the spread in the rivals' revenue level in the preceding period, will be introduced shortly.

²¹ Consequently, *relAcc* lies between (0, 1] $[-1, 0]$ for the leading (lagging) competitor.

found in the range of $relAcc \in [-0.5, 0.5]$.²² Inspecting the correlation between the rate of investing and associated values of $relAcc$ reveals that the two variables are very weakly, yet significantly related ($\rho = 0.086$ with $p < 0.001$, Pearson’s product-moment correlation). Another feature in the relation between competition (proxied by $relAcc$) and the rate of investing is a pronounced peak in investment propensity (at the level of 65%) within the interval of $relAcc \in [-0.1, 0.1]$. Contrasting investment rates within and outside of this range confirms that the vertical shift between the two samples is highly significant ($p < 0.001$, binomial test for equality of proportions).

This provides strong experimental evidence that “neck-to-neck” competition, as discussed in Aghion et al. (2005) and Palokangas (2006), induces subjects to challenge the current leader (if one is behind) or to defend the own leading position. Such an effect is hardly consistent with rationality since the relative position of competitors is irrelevant for the returns from investments. Thus, the significant shift in the subjects’ investment behavior can be attributed to psychological effects (e.g., being dissatisfied with the own performance when lagging behind). Although we do not provide any monetary incentive other than the account balance itself, becoming the temporary or eventual leader in the patent race seems to be a strong motive. This finding leads us to conjecture that at least a minority of subjects is negatively affected when they are lagging behind in a competitive environment. In our view, such subjects intensify their investment activity in order to appropriate additional income.

In the following, we provide an overview of those factors which were found to have a significant impact on the subject’s propensity to invest. For this purpose, we fit a mixed effects logit model²³ to those cases in which the choice set contains at least two options, implying that an investment may potentially fail. The filter applies to a coefficient but not to the dependent variable. The considered dataset is therefore neither truncated nor censored. As explanatory variables consider the period, the probability of a search success, being the leader or follower in the race, the difference in periodic income, and a dummy for *sequence*₂ to account for learning (see Table 3).

The first two coefficients, the linear and the quadratic *period* term, are both highly significant. Jointly, they describe a monotonic decline of the investment

²² The triangle size in Figure 2 is determined by the natural logarithm of the observation count.

²³ This regression method allows to control for individual heterogeneity and repeated measurements of a single subject’s behavior.

Table 3: *Mixed effects model explaining investment choice*

Covariate	Estimate	Std.error	p-value
<i>Intercept</i>	1.838	0.201	< 0.001
<i>period</i>	-0.386	0.04	< 0.001
<i>period</i> ²	0.026	0.003	< 0.001
<i>risky</i>	-0.114	0.017	< 0.001
<i>leader</i>	0.406	0.09	< 0.001
<i>spread</i>	0.060	0.012	< 0.001
<i>sequence</i> ₂	-0.159	0.068	0.019

propensity across periods, with the rate of decline diminishing over time. Thus, other factors held constant, subjects invest most intensively early in the race and subsequently invest with less and less zeal. As expected, the estimate of the coefficient *risky*, i.e., the number of remaining risky decision alternatives in an aspect, is negative in its direction. This shows that subjects are aware of the fact that the profitability of research decreases with the number of remaining options.

The positive estimate of the dummy *leader* signifies that being ahead of one's rival strongly encourages further investing. Thus, an earlier satisfactory performance intensifies further search. Further, the coefficient of *spread*, marking the difference in the rivals' per period revenues, is also positive.²⁴ If we assume competition to be fiercest when the revenue spread between competitors is marginal or zero, the degree of competition increases the rate of investing for followers, at least more than it inspires leaders. We also tested for the significance and economic relevance of the rivals' relative account balance (*relAcc*)²⁵ whose coefficient, however, turned out to be insignificant. Likewise, Cohen, Levin, and Mowery (1987) came to the same conclusion that overall firm size does not significantly impact on their R&D intensity, after empirically investigating data from the Federal Trade Commission's Line of Business Program and a series of further surveys. Finally, we derive from the negative estimate of the covariate *sequence*₂ that learning in the first sequence induces subjects to invest slightly less in the second sequence. Most notably, the rate of investing in the first period of sequence 2 is significantly lower than its equivalent in sequence 1.

Result 3: The decision to invest in risky search significantly conditions on generic factors determining the expected return of an investment and

²⁴ The statistic is computed as the own periodic revenues minus the other's revenues.

²⁵ Already in section 5.1 this variable was found to be a poor predictor of the rate of investing.

Table 4: *Investor type characteristics*

Description	Investor type	
	A	B
	“Bold”investor	“Cautious” investor
Rate of investing at		
low risk (2-4 items)	0.93	0.57
high risk (5-8 items)	0.88	0.53
Population share (%)	27.8	72.2
wins sequence (%)	62.5	37.5
sequence payoff	112.9	97.5

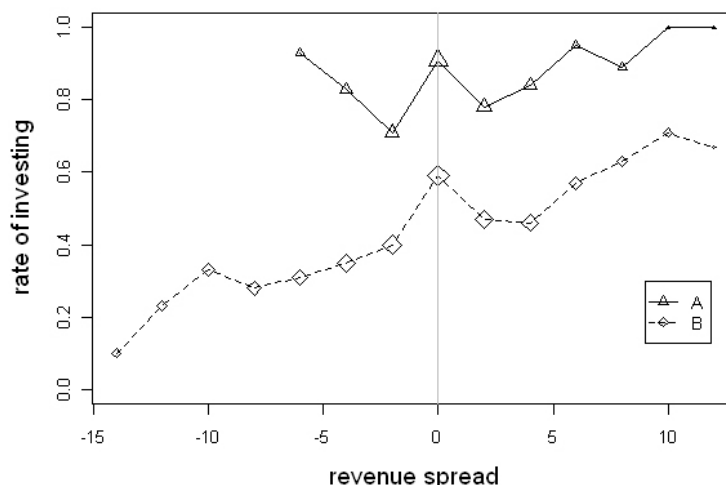
on particular measures of the subject’s relative performance.

3.3 Distinguishing bold and cautious investors

Up to now, we have explored aggregate behavior. Although this uncovered regularities in search behavior, the findings cannot be used to identify behavioral patterns which are shared by distinct groups of subjects. In particular, when asking whether subjects react uniformly to changes in the degree of competition or whether there are subgroups of participants employing distinctly different strategies in handling competitive pressure, one should try to classify participants.

For this purpose we perform a cluster analysis on the dataset of individual investment choices, whereby we use the subject’s average rate of investing in aspects containing 2-4 or 5-8 choice options, respectively, as the clustering criteria. More specifically, we partition the data into two clusters “around medoids” (PAM), which represents a more robust version of K-means. As a result, we identify a minority group of subjects (28%) who invest in risky search irrespective of the prevailing degree of competition. The majority of participants (72%), by contrast, condition on the intensity of the rivalry. Table 4 briefly characterizes both investor types.

Bold investors (type *A*) invest in about 90% of all cases, in which there is a profit opportunity, essentially neglecting the investment’s expected risk of failure. We arbitrarily rate the investment risk as high (low) if there are 5-8 (2-4) remaining choice options in the respective aspect. Cautious investors (type *B*) pursue active and costly search more sporadically, taking up only about 50% of all profit opportunities and, on average, more often rely on imitation. In line with the results from

Figure 3: *Investment rate contingent on revenue spread and investor type*

our simulation we find that vigorous investing leads to superior profits, as shown by the significantly higher sequence payoffs of boldly over cautiously investing agents.²⁶

Finally, Figure 3 illustrates the relationship between the intensity of competition (the rivals' spread in revenues) and the rate of investing. While a linear association between the two aspects can be identified for the cautious investor type, the smaller group of bold investors is generally unaffected by the degree of competitive pressure. The independence between competition and innovation for the bold investor type is not surprising, as the mean investment propensity of that group equals 92% (87%) for low (high) risk investments. It is, however, remarkable that investors who do not condition on aspects of competition represent nearly one third (27.8%) of the sample population.

Result 4: The majority of subjects conditions their choice of investing on the state of competition, prompting leaders (followers) to invest less (more) with more intense competition. Yet about one third of the population pursues an unconditional and vigorous investment strategy, entirely ignoring the degree of competition.

²⁶ The difference in payoffs between the two investor types is highly significant ($p = 0.003$, one-sided MWU test).

4 Discussion

In our scenario of competitive innovation, pairs of subjects may either actively search or remain passive, hoping to opportunistically benefit from information spillovers. The main objective has been to collect individual choice data in a controlled experiment, allowing us to evaluate conflicting conjectures on the relationship between competition and the rate of innovative activity. Like the patent race models suggested by Harris and Vickers (1987) our experimental design features both uncertainty and strategic interaction. Yet, unlike their and several other preceding models of competitive innovation, obtaining a patent in our model does not terminate interaction, but rather represents a temporary success in an ongoing race.

We identify several factors guiding the decision to innovate, some of them related to generic aspects of the investment task (objective criteria), while others condition on the rival's performance as a point of reference (relative criteria). The objective investment criteria are the probability of a search success and the remaining time span in which rents from investment can be appropriated. The relative criteria are related to the relative stance of competitors, e.g., being the leader or the follower in the race, and the difference in the rivals' revenues. With respect to the former, we find that being ahead in competition induces the leader to invest even more vigorously. This conforms to the prediction of well-known theoretical models on competitive innovation like those by Grossman and Shapiro (1987) and Harris and Vickers (1987).

Further, the spread in the rivals' revenues turns out to be a significant promoter of innovative investments, but also calls for a differentiated interpretation of the effect of competition on the latter. The observed investment choices are in line with the notion that followers intensify their search efforts with more competition, measured by how close competitors are. Our data are less easily reconciled with Aghion et al. (2005)'s empirical regularity of a decreasing rate of investing for highly profitable firms. We fail to replicate the presumed positive relation between competition and innovation for industry leaders, since a growing spread in the rivals' revenues – which, in our view, signifies less competition – increases innovative activity rather than decreasing it. As long as the expected costs of search can be covered by the expected return of an innovation, leaders in our experiment invest with ever-growing zeal.

A rather homogeneous group of subjects, representing about one third of the sample population, does not conform to any of the leader-follower interaction pre-

dictions of the theoretical models on industrial dynamics. Members of this group persistently invest in search independently of the race's progress, the likelihood of search successes, and the prevailing degree of competition. Initially, this could be explained by risk neutrality since an early investment pays off in the rest of the sequence. But later in the race, subjects seem to be spurred by the tournament character of the interaction, inspiring them with a desire to win. Of course, a stable preference like curiosity could also explain such bold investment behavior. Hopefully, follow-up studies, based on the experimental prototype developed here, can shed additional light on when and why certain investor types behave differently in competitive innovation (see already Cantner, Nicklisch, & Weiland, 2005).

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A Experimental instructions

The following instructions were originally written in German.

Thank you for participating in our experiment. We kindly ask you to refrain from any public announcements and attempts to communicate directly with other participants. In case you violate this rule, we have to exclude you from the experiment. If you have any questions, please raise your hand, and one of the experimenters will come to your place and answer your questions. In the experiment you will repeatedly - namely in periods $t = 1$ to $t = 15$ - interact with one other participant who has received the same instructions as you have. In each period t of the interaction, both of you are asked to specify for a product - namely a car - 8 different components (color, engine type, ...), which we call components a_1 to a_8 . For components a_1 to a_4 , there are eight different alternatives (e.g., for colors green, blue, red,...), and for component a_5 to a_8 , there are four alternatives which you and the other participant can select.

We will now describe how your choice of vector a and the other's choice determine what you will earn in a given period. To do so let us refer to

$$\begin{aligned}\hat{a} &= (\hat{a}_1, \dots, \hat{a}_8) \text{ as your own choice,} \\ \tilde{a} &= (\tilde{a}_1, \dots, \tilde{a}_8) \text{ as the other's choice,} \\ a^* &= (a_1^*, \dots, a_8^*) \text{ as the ideal choice.}\end{aligned}\tag{1}$$

For your choice $a = \hat{a}$ in period t , you will receive

$$\delta_i(\hat{a}_i^t, a_i^*) = \begin{cases} 1 & \text{ECU if } a_i^t = a_i^* \\ 2 & \text{ECU if } \tilde{a}_i^t = a_i^* \text{ and } a_i^t \neq a_i^* \\ 0 & \text{ECU if } a_i^t \neq a_i^*. \end{cases}\tag{2}$$

Thus, if you miss all eight ideal components a_i^* by your eight choices \hat{a}_i^t , your success is 0. If you have chosen the right component ($\hat{a}_i^t = a_i^*$), then you will receive from that choice 1 ECU, if the other has done so, too ($\tilde{a}_i^t = a_i^*$) and 2 otherwise ($\tilde{a}_i^t \neq a_i^*$). Altogether you will therefore receive $D_t = \sum_{i=1}^8 \delta_i(\hat{a}_i^t, a_i^*)$. Thus, in one period you can earn at most $8 \times 2 = 16$ ECU, which requires $\hat{a}^t = a^*$ and $\tilde{a}_i^t \neq a_i^*$ for $i = 1, \dots, 8$. However, you will not receive any income in period t , if $\hat{a}_i^t \neq a_i^*$ for $i = 1, \dots, 8$.

It is important to note that if you are the first to discover the ideal specification

a_i^* of component $i = 1, \dots, 8$ by your choice $\hat{a}_i^t = a_i^*$, say in period t , then the other cannot choose a_i^* in the next 4 periods. Similarly, if the other is first in finding a_i^* by $\tilde{a}_i^t = a_i^*$ in a period t , then you cannot choose a_i^* in the next 4 periods. If both of you find a_i^* at the same time, you can both choose a_i^* afterwards.

Also keep in mind that you have to pay 2 ECU every time when you try out a new alternative a_i^j of any of the 8 components. This rule holds only for new alternatives. You are free to leave one component unspecified, as well. This option is free, but you will then definitely not earn any profit for this component. Your total success score $D = \sum_{t=1}^{15} D_t(\hat{a}^t, \tilde{a}^t)$ in all periods $t = 1, 2, \dots, 15$ determines your earnings from which your switching costs K are subtracted. At the start of the experiment, you will receive an endowment of 40 ECU, so that after 15 periods your profit equals $40 + D - K$ ECU. At the end of the experiment, your accumulated profit will be exchanged into Euro at the rate of $1ECU = 0.08Euro$ and will be privately disbursed to you. There is the unlikely possibility to go bankrupt in this experiment if you spend the entire endowment on exploration without finding any ideal specification. In this case you will not receive any profit for the 15 periods.

After each period t you will be informed about

- your own and the other's success ($D_t(\hat{a}^t, \tilde{a}^t)$ and $D_t(\tilde{a}^t, \hat{a}^t)$) in period t ,
- your own and the other's choice ($\hat{a}^t = (\hat{a}_1^t, \dots, \hat{a}_8^t)$ and $\tilde{a}^t = (\tilde{a}_1^t, \dots, \tilde{a}_8^t)$) in period t ,
- the optimal alternatives found in the last five periods (which are unavailable to you, if the other was the first in finding it, and which are ruled out for the other if you were the first to find them), and
- your and the other's accumulated profit from all the periods so far.

After receiving this information feedback, we will start the new period $t + 1$ in which your partner and the ideal choice $a^* = (a_1^*, \dots, a_8^*)$ will remain the same. After 15 periods, the first sequence is finished and a new sequence of 15 periods starts in which you will be matched with a different participant and which will feature a new, randomly determined ideal choice a^* .

Before the first period starts, we kindly ask you to answer several questions concerning the rules of this experiment. Please answer them correctly. An experimenter will come to your place and explain things when answers are wrong.