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DYNAMIC PATENT RACES WITH ABSORPTIVE CAPACITY: AN EXPERIMENTAL INVESTIGATION ON R&D BEHAVIOR

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Dynamic Patent Races with Absorptive Capacity: An Experimental Investigation on R&D Behavior*

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Abstract/Résumé

We report a laboratory experiment on dynamic patent races in an indefinite horizon with complete information. In a competitive environment, we analyze the R&D investment behavior of players who are randomly and anonymously paired in each race. We vary subjects' initial positions as leader/follower or symmetric/asymmetric, as well as the distance between the initial knowledge stock and the target. Our results show that individual average effort is highest for players in a tie position, followed by leaders, and lowest for followers. Starting as a follower (leader) leads to a lower (higher) chance of winning the race. Spillovers realized in the previous round significantly increase players' investment in the current round. Convergence toward equilibrium play becomes more pronounced in the second half of the sessions. Efficiency loss is significantly higher in races starting from a symmetric position than from an asymmetric position and is also significantly higher in the low treatment than in the high treatment.

Nous présentons une expérience de laboratoire sur les courses aux brevets dynamiques dans un horizon indéfini avec une information complète. Dans un environnement concurrentiel, nous analysons le comportement d'investissement en R&D des joueurs qui sont appariés de manière aléatoire et anonyme dans chaque course. Nous faisons varier les positions initiales des sujets (leader/suiveur ou symétrique/asymétrique), ainsi que la distance entre le niveau de connaissance initial et la cible. Nos résultats montrent que l'effort individuel moyen est le plus élevé pour les joueurs en position d'égalité, suivis par les leaders, et le plus faible pour les suiveurs. Commencer en tant que suiveur (leader) conduit à une chance plus faible (plus élevée) de gagner la course. Les retombées réalisées lors du tour précédent augmentent de manière significative l'investissement des joueurs dans le tour en cours. La convergence vers le jeu d'équilibre devient plus prononcée dans la seconde moitié des sessions. La perte d'efficacité est significativement plus élevée dans les courses commençant à partir d'une position symétrique qu'à partir d'une position asymétrique et est également plus élevée dans le traitement faible que dans le traitement élevé.

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1 Introduction

Innovation, as a key driver of growth, plays a crucial role in the evolution of the industrial leadership. It is one of the main factors in technological competition that can decisively improve a firm's competitiveness. Many long-established companies compete in expanding markets, striving to develop new inventions and secure patents. For example, Apple and Microsoft are engaging in a race to develop hand gesture system for notebooks, vehicles, home, appliance, and computers.

In general, strategic interactions occur between two or more competitors who invest costly resources in a patent race to increase their chance of winning. The winner gains legal monopoly power over the technological innovation through the patent system, while the loser receives nothing. By securing the patent, a firm can extract high profits from selling its technological invention in a market where rivals cannot copy or replicate it.

In this paper, we explore experimentally firms' R&D investment behavior based on a dynamic model of patent races similar to those in Fudenberg et al. (1983) and Halmenchlager (2006). In each period of an indefinite-horizon race, firms have to simultaneously and independently decide how much R&D effort to devote toward the accumulation of knowledge in order to reach a fixed critical level of experience and obtain a prize. Unlike previous experimental studies on patent races, our model incorporates firms' absorptive capacity – firms' ability to utilize, assimilate, and absorb external information to achieve organizational goals. The effective R&D level of each firm is determined by the sum of its own efforts in the past periods and a fraction of the rival's efforts, which spill over only when both firms make investments in the R&D process.

Subjects in each experimental session participate in ten sequences (races). We vary the initial knowledge position of each race to examine how players' R&D investment behavior change accordingly. Specifically, we design the races with symmetric and asymmetric initial positions. According to the unique Markovian perfect equilibrium we focus on, these two scenarios exhibit distinct dynamics theoretically: a symmetric initial position leads to intense competition and efficiency loss, and an asymmetric initial position results in less competition and no efficiency loss. This design allows us to test the extent to which participants' behavior aligns with theoretical predictions.

In addition, we vary the distance between the initial position and the race target, which we denote as low treatment (with a long distance to the target) and high treatment (with a short distance to the target). A real-life example of these treatments can be found in technology development where companies compete in short-term and long-term races. For instance, Intel and AMD are engaged in a tight race to develop AI and high-performance computing technologies. With advanced technology and significant R&D investments, their competition drives near-term breakthroughs. In contrast, Toyota and Tesla are competing in the electric vehicle (EV) market, which requires substantial upfront investment and long-term commitment. As a result, this longer race will continue to shape the future of AI and EV technologies.[1]

In summary, we employ a within-subject design in which we vary the initial position of the two players and the distance to the target in different patent races. Our experiment consists of 8 experimental sessions, with 4 sessions starting with the low treatment and switching to the high treatment, and another 4 sessions with the reverse order. Using this experimental design, we are interested in the following questions: 1) How does the starting position (leader vs. follower, symmetric vs. asymmetric, low vs. high initial position) affect the race outcome and the investment behavior? 2) What factors influence equilibrium play and efficiency level? 3) Does the realization of spillovers affect future investment behavior?

To the best of our knowledge, this is the first experimental study that tests a dynamic multi-period patent race model incorporating firms' absorptive capacity. It also contributes to the literature by providing new insights through a comparison of short and long patent races played by the same subjects.

Overall, we find that players' R&D investment behavior and race outcomes align with theoretical predictions. The individual average effort is highest for players in a tie position, followed by leaders, and lowest for followers. As theory predicts, the frequency of winning a race is highest for players starting as leaders and lowest for those starting as followers, in both low and high treatments. We find the effort level is overall higher in the high treatment, coupled with increased convergence toward equilibrium play in the second half of the sessions. Notably, a

[1] Information collected from the following links:
https://www.hivelr.com/2023/02/nvidia-nvda-porters-five-forces-industry-and-competition-analysis/
https://www.intc.com/news-events/press-releases/detail/1672/intel-reports-fourth-quarter-and-full-year-2023-financial
https://simplywall.st/narratives/intense-competition-will-force-amd-to-sacrifice-margins-in-favor-of-randd-spend
https://www.autoblog.com/2023/02/28/toyota-rethinking-long-term-ev-strategy-ceo-koji-sato/
https://markets.businessinsider.com/news/stocks/why-toyota-may-have-the-best-strategy-in-the-ev-race-1033078343

positive spillover realized from the previous round significantly increases players' incentive to invest in the current round.

We find that efficiency loss occurs in races with both symmetric and asymmetric initial positions, which is not entirely consistent with theoretical predictions. However, efficiency loss is significantly lower in races with asymmetric initial positions than in those with symmetric initial positions. Thus, the comparative statics remain aligned with theoretical expectations. In addition, efficiency loss is found significantly lower in the high treatment than in the low treatment.

The remainder of the paper is organized as follows: Section 2 discusses the related literature. Section 3 presents the theoretical model, and Section 4 describes the experimental design. Section 5 reports the experimental results, and Section 6 concludes. Appendices A–C provide additional details on the model, payoffs, and supplemental experimental results. Appendix D contains the experimental instructions.

2 Related literature

To better understand the forces that drive technological innovations, early models were provided by different economists. For instance, a R&D race model with knowledge accumulation is introduced by Doraszelski (2003), in which R&D efforts lead to a building up of knowledge stock and have an impact on hazard rate of a successful technological innovation.

An important strategic point is emphasized by different models in which firms have to anticipate the R&D efforts of their rivals in order to gain a competitive advantage and to develop the abilities to identify, assimilate and exploit external knowledge that can bring promising innovations (Cohen and Levinthal, 1990; Halmenschlager, 2006). These abilities have been largely considered as an important factor for the innovating firms since Cohen and Levinthal (1989) who emphasize that a firm can gain external information from other firms if it invests in its ability to absorb technological externalities.

Halmenschlager (2006) introduces the absorptive capacity into a dynamic patent race model with memory of past actions based on the work of Fudenberg et al. (1983). She finds that when the two firms are close in terms of their accumulated knowledge, the absorptive capacity allows the chance of catching up when the leader has a less aggressive response to the rival's reaction. When the follower doesn't conduct its R&D activity, the leader will not have the incentive to increase his effort since the rival is inactive and is far behind. In case of a tie, the firms gain the R&D effort from each other via the absorptive capacity and the pace of innovation increases.

Our paper is most related to the experimental studies on dynamic patent races in the form of multi-stage investment game.[2] Without considering the technological spillovers, Zizzo (2002) experimentally tests the patent race model of Harris and Vickers (1987) by taking into consideration technological uncertainty (the output and speed of technological development are uncertain) and dynamic uncertainty (investment in R&D can change as the race unfolds). Different from the predictions of Harris and Vickers (1987), Zizzo (2002) finds that the leaders do not invest more than the followers, and investment does not change as predicted with the change of the knowledge gap. Overall, the experimental evidence provides only limited support to the theory.

Based on Fudenberg et al. (1983), Silipo (2005) examines cooperation and break-up behavior in a dynamic patent race model in which firms have an option to choose R&D investment cooperatively or independently. Consistent with the model predictions, the experimental evidence shows that players in a symmetric initial position are more likely to cooperate than in an asymmetric position at the beginning of the race but break this cooperative relationship as they approach the finishing line.

Breitmoser et al. (2010) report an experiment on perpetual patent races with an indefinite time horizon and multiple awards, based on the theoretical papers by Aoki (1991), Hörner (2004) and Harris and Vickers (1987). Their main experimental results indicate that the subjects' behavior is less sensitive to the model parameters than Markov perfect equilibria predict. Instead, the quantal response equilibrium (QRE) based on Markov perfection is qualitatively and largely quantitatively consistent with the experimental observations.

Different from these papers, we experimentally test the theoretical patent race model of Fudenberg et al. (1983) and Halmenschlager (2006), with the consideration of the absorptive capacity, which has not been explored in the previous literature. We focus on examining the effect of the initial position on the firm's investment decisions, when the firm's type alters from leader to follower (or vice versa) and from symmetric to asymmetric position. Furthermore, we implement

[2] Some experimental studies on innovation employ different tasks. For instance, Sbriglia and Hey (1994) use a search task in which players need to find a letter combination by buying different letter trails under competition, Brüggemann and Meub (2017) examine the effects of innovation contests by a Scrabble-like creativity task in the lab (see Brüggemann and Bizer (2016) for a comprehensive survey). While these studies provide valuable insights into the innovation process and its policy implications, they lack clear theoretical predictions due to the complexity of the decision tasks.

races with varying distances between the initial position and the finishing line, which allows us to examine the effect of expected duration of the race on the investment behavior.

Aghion et al. (2018) report an experiment on the effect of product market competition on step-by-step innovations in a dynamic environment. They find that an increase in competition increases significantly the R&D investments by neck-and-neck firm; however, it decreases the R&D investments by laggard firms. Like our paper, their design also varies the relative position of the innovators and the expected time horizon of the races (finite vs. indefinite, short vs. long). However, their experiment is based on a growth model with step-by-step innovations and their theoretical benchmark is the steady state equilibrium, which differs significantly from Zizzo (2002), Silipo (2005), Breitmoser et al. (2010), and our model.

3 Model

We first provide a brief description of the theoretical model that our experimental design is based on. We consider a patent race game with an indefinite number of periods between two firms competing to discover a new technology. Once this new technology is available, it is going to be patented. We assume that the R&D process is deterministic. The firms aim to reach a critical knowledge level N and receive a prize Y.

In each period t, the two firms i and j simultaneously choose their R&D effort/investment, denoted as $x_i(t)$ and $x_j(t)$ respectively, among three levels: 0 (no R&D), 1 (low R&D) and 2 (high R&D). The corresponding cost is 0, c_1, and c_2, respectively. The chosen R&D effort contributes to the firm's cumulative knowledge level. Following Halmenschlager (2006), we assume that $c_2 > 3c_1$, which implies a diminishing return of the R&D process. We also assume that $\frac{Y}{2} > [\frac{(N+2)}{3}]c_2$. This assumption guarantees a positive payoff if the two firms maintain the high effort level in each period up to the end of the race and share the prize.

We consider absorptive capacity in the model, that is, the firms may benefit from spillovers of the other firm's R&D investment. The spillovers, $\varphi(x_i, x_j)$, are determined by the current effort level of both firm i and j and independent of past investments. Following Cohen and Levinthal (1989), we assume that a firm gains no spillover benefits if it makes no R&D effort in a given period. Specifically, in each period the firms gain one extra knowledge point if both invest at level 1 or 2, and no extra points otherwise (i.e., $\varphi\left(x_i, x_j\right) = \varphi\left(x_j, x_i\right) = 1$ if and only if both $x_i > 0$ and

$x_j > 0$).

The experience (or knowledge accumulation) of firm i at the beginning of period t, denoted by $\omega_i(t)$, is the sum of its past R&D investments, gained spillovers, and initial knowledge stock. Correspondingly, the remaining knowledge level needed for firm i to reach the finishing line is $k_i(t) = N - \omega_i(t)$. Firm i is considered the leader in period t if $k_i(t) < k_j(t)$, while the firms are considered neck and neck if $k_i(t) = k_j(t)$.

Three possible outcomes may arise for firm i at the end of the race: 1) Firm i is the unique winner if it reaches the finishing line with a higher knowledge level than its rival; 2) Both firms win the race, if they reach or pass the finishing line with the same level of knowledge; 3) Firm i is the loser if it does not attain the finishing line while the other firm does $\{ k_i(t+1) > 0 \text{ and } k_j(t+1) \leq 0\}$ or if it reaches the line with a lower level of knowledge than its rival $\{k_i(t+1) > k_j(t+1) \text{ and } k_i(t+1) \leq 0\}$. In any case, the firm needs to pay the accumulated cost incurred during the R&D procedure. The firm gains the entire prize if it is the sole winner and shares the prize with the other firm equally if both are winners.

We focus on the subgame perfect Markovian Nash equilibrium, in which $(k_i(t), k_j(t))$ are the state variables.[3] We focus on the determination of the subgame-perfect Markovian Nash equilibrium. The following proposition from Halmenschlager (2006) describes the firms' equilibrium behavior. (Appendix A provides the detailed formulas for the dynamics of the knowledge stock and payoff function.)

Proposition 1:

The unique subgame perfect Markovian equilibrium strategy is characterized as follows:

Case 1: (x_1, x_2) = (1,0) if $k_2 \geq k_1 + 2$;

Case 2: (x_1, x_2) = (2,2) if $k_1 = k_2$;

Case 3: x_1= [1, 2] and x_2= [0, 2] if $k_2 = k_1 + 1$.

The proof can be found in Halmenschlager (2006).

Proposition 1 describes firms' optimal R&D efforts in each period, depending on the current gap between their knowledge stocks. In Case 1, when the knowledge gap between the follower and

[3] For a given state, the equilibrium strategies assume that all future strategies are also equilibrium strategies starting at the resulting states.

the leader is greater than 2, the leader maintains a low R&D effort until the end of the race, while the follower exits the competition. In Case 2, both firms choose a high effort level when they are neck and neck. In Case 3, when the leader is one unit ahead of the follower, the leader adopts a mixed strategy between high and low effort levels, while the follower randomizes between no effort and high effort. In equilibrium, the follower catches up with positive probability.

Below, we provide two numerical examples illustrating the R&D investments, spillovers, and the dynamics of the knowledge stocks of different cases described in Proposition 1: one with symmetric initial knowledge levels (Case 2) and the other with asymmetric initial knowledge levels (Case 1).

Example 1: Equilibrium path for the case $(\omega_1(1), \omega_2(1)) = (0,0)$, N=16

t	1	2	3	4	5	6	7
$x_1(t)$	2	2	2	2	2	2	
$x_2(t)$	2	2	2	2	2	2	
$\omega_1(t)$	0	3	6	9	12	15	18
$k_1(t) = N - \omega_1(t)$	16	13	10	7	4	1	-2
$\omega_2(t)$	0	3	6	9	12	15	18
$k_2(t) = N - \omega_2(t)$	16	13	10	7	4	1	-2
$\varphi(x_1(t), x_2(t))$	1	1	1	1	1	1	
Cost for every player	c_2	c_2	c_2	c_2	c_2	c_2	

Example 2: Equilibrium path for the case $(\omega_1(1), \omega_2(1)) = (2,0)$, N=16

t	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
$x_1(t)$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
$x_2(t)$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
$\omega_1(t)$	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
$k_1(t) = N - \omega_1(t)$	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
$\omega_2(t)$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$k_2(t) = N - \omega_2(t)$	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
$\varphi(x_1(t), x_2(t))$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Cost for player 1	c_1	c_1	c_1	c_1	c_1	c_1	c_1	c_1	c_1	c_1	c_1	c_1	c_1	c_1	

In the sections below, both numerically and experimentally, we focus on the pure strategy equilibrium behaviour (Case 1 and Case 2 in Proposition 1), as the predictions on the R&D investment in each period in these two cases are precise, and the equilibrium path is determined by the initial knowledge level. In contrast, Case 3 involves mixed strategies and dynamic features that can lead to multiple equilibrium paths even with the same initial knowledge level, making it less suitable as a theoretical benchmark for the experimental data.

4 Experimental design, hypotheses, and procedure

4.1 Experimental design

Our experimental sessions consist of 10 R&D races with an indefinite number of periods between two players. We employ a within-subject design and vary the initial knowledge stocks in different races. In one dimension, we focus on comparisons between symmetric initial positions vs. asymmetric initial positions. In the other dimension, we vary the distance to the finishing line, which we denote as low treatment (long distance) and high treatment (short distance).

The comparison between symmetric and asymmetric initial positions allows us to test Proposition 1 directly, which predicts that, in the symmetric case, competition is more severe with both firms making a high effort and resulting in a shorter race, while in the asymmetric case (with a knowledge gap of at least 2), competition is less severe with one firm giving up the race and the leading firm making a low effort. The comparison between the low and high treatments, however, relies more on behavioral hypotheses. The predicted firm investments in Proposition 1 depend solely on the current difference in knowledge levels, k_1 compared to k_2, and are independent of the distance to the finish line. However, when the initial position is at a low level, firms may exhibit behavioral differences, as it is more challenging to identify the equilibrium path when the race is expected to be longer.

Table 1: The set of sequences with their associated initial positions

Race		1	2	3	4	5	6	7	8	9	10
treatment	L-H	(0,0)	(2,0)	(0,2)	(4,0)	(0,4)	(8,8)	(10,8)	(8,10)	(12,8)	(8,12)
	H-L	(8,8)	(10,8)	(8,10)	(12,8)	(8,12)	(0,0)	(2,0)	(0,2)	(4,0)	(0,4)

Table 1 summarizes the initial knowledge stocks of the 10 races used in the experiment. Specifically, we design the races with symmetric low initial positions at (0, 0), symmetric high initial positions at (8, 8), asymmetric low initial positions at (0, 2) and (0, 4), and asymmetric high initial positions at (8, 10) and (8, 12). In each race, subjects were randomly re-matched to avoid potential reputation effects. Races with the same asymmetric initial gap were always played twice in each session, with subjects switching the initial position across the two races. For instance, if a subject in race 2 has an initial position of 2, then he will have an initial position of 0 in race 3. This design allows subjects to experience both leader and follower roles at the beginning of the race, reducing the impact of initial roles on earnings. Based on the equilibrium path, the 10 races are expected to take about 80 periods in total, with each period lasting approximately one minute in our program.

We conducted 8 experimental sessions. Four sessions, denoted as the L-H treatment, start with the low initial positions (Low treatment) for the first 5 races and switch to the high initial positions (High treatment) for the remaining 5 races. The other four sessions, denoted as the H-L treatment, follow the reverse order.

In all the races, we choose the critical level of knowledge N=16, the prize Y=20, and the cost c_0 = 0 ECU, c_1 = 0.2 ECU, c_2= 0.8 ECU to satisfy the assumptions $\frac{Y}{2} > [\frac{(N+2)}{3}]c_2$ and $c_2 > 3c_1$, for the uniqueness of the subgame perfect Markovian equilibrium.

Given these parameter values and the initial knowledge stocks in each race, we calculate the equilibrium payoff at the individual level and group level (for the pair), as well as the individual minimum and maximum payoffs and the group efficient payoff, as summarized in Table 2. Generally, the maximum payoff is achieved in a path where both players invest at the low effort until the end of the race (in the asymmetric case) or close to the end of the race (in the symmetric case) so the spillover is mostly generated while the group efficient outcome can be achieved with different paths. Notice that the symmetric initial positions will lead to an efficiency loss in equilibrium, which is higher in the low treatment due to the excess competition between the two firms who invest at the high level. In contrast, if the race has asymmetric initial positions, such as Example 2 in Section 3, in equilibrium the follower will give up from the beginning of the race, so the equilibrium outcome will coincide with the efficient outcome. Appendix B provides the details on the firms' investments in equilibrium for each race and how we calculate the payoffs in Table 2.

Table 2: The different types of payoffs of each race

Treatment	Initial Experience (IE)	Individual Equilibrium payoff	Group Equilibrium payoff	Individual Maximum payoff	Individual Minimum payoff	Group Efficient payoff
Low	(0,0)	(5.2, 5.2)	10.4	18.2	-4.2	16.8
Low	(2,0)	(17.2, 0)	17.2	18.6	-4.0	17.2
Low	(4,0)	(17.6, 0)	17.6	18.8	-3.2	17.6
High	(8,8)	(7.6, 7.6)	15.2	19.0	-1.8	18.4
High	(10,8)	(18.8, 0)	18.8	19.4	-1.6	18.8
High	(12,8)	(19.2, 0)	19.2	19.6	-1.6	19.2

4.2 Hypotheses

Based on the model and experimental design, we outline the following hypotheses.

Race Outcomes

Hypothesis 1: (*Starting position effect as leader vs. tie vs. follower)*

The probability to win a race is highest (lowest) when the player starts as a leader (follower).

Hypothesis 2: (*Low initial knowledge versus high initial knowledge effect)*

Fixing the initial position and the knowledge gap at the beginning of the race, the frequency of winning a race has no significant difference between the low and high treatment.

Investment Behavior

Hypothesis 3: *(Effort level based on the position of the round)*

In each round within the race, the effort level is highest in a tie position, second highest as a leader, and lowest as a follower.

Hypothesis 4: *(Effort level between low and high treatments)*

Fixing the position of each round, the effort levels in the low and high treatments are not significantly different.

Hypothesis 5: *(Spillover effect)*

The spillovers in the previous round have significant effect on the players' investment behavior in the current round.

Efficiency Loss

Hypothesis 6: *(Symmetric vs. asymmetric starting position of the race)*

In each treatment, the efficiency loss in a race with a symmetric initial position is significantly higher than with an asymmetric initial position.

Hypothesis 7: *(Efficiency loss between low and high treatments)*

In the symmetric initial position, the percentage of efficiency loss is higher in the low treatment compared to the high treatment. In the asymmetric initial position, there is no significant difference between the low and high treatment.

4.3 Experimental procedure

Each session consisted of 10 sequences, as presented in Table 1. In each sequence, subjects were randomly and anonymously matched to compete in the R&D race and remained paired with the same opponent throughout the sequence. Subjects were explicitly informed of the matching protocol. Before proceeding to the next sequence, each pair had to wait until the other pairs finished their races.

In each round of a sequence, matched players simultaneously decided whether to invest 0, 1, or 2 points, which cost respectively c_0, c_1 and c_2. Before making a decision, each player could observe their own and their matched player's past choices, accumulated knowledge, and the total costs in all the previous rounds. The spillover was granted only if both players invested 1 or 2 points in a given round. Prior to proceeding to the next round, each player had to wait for their matched opponent to complete their decision.

In every sequence, the prize of 20 ECU was awarded to the player whose accumulated knowledge first reaches or exceeds 16 points. In that case, the winner received 20 ECU minus the accumulated costs, and his opponent received no prize but still had to pay the accumulated costs. If both players reached 16 points in the same round, they share the prize, each receiving 10 ECU minus the costs.

When one player or both players in a pair reach or pass 16 points, a sequence ends. Otherwise, the sequence will continue into next round, in which the total points and the total costs accumulated in all previous rounds of the same sequence will carry over into the next round. In order to avoid the race lasting forever when no one invests, we impose a stopping rule that, if two players within a group choose zero for three consecutive rounds, the competition is terminated, and the prize is lost. The outcome from every sequence will not be transferred to the next sequence as the races reset at the start of a new sequence.

At the end of the session, subjects were paid their total earnings from all the sequences, as well as a 10$ show-up fee. The total payoffs from the sequences were converted into Canadian dollars at a known and fixed rate of 1 ECU = CAD$0.25. The experiment took place at the Claude Montmarquette Experimental Economics Lab (CMEEL) at CIRANO (Centre Interuniversitaire de Recherche en Analyse des Organisations). It was programmed and conducted with the z-Tree software. Participants were recruited using ORSEE (Greiner, 2015). Each session lasted approximately 2 hours, including the first 45 minutes for instructions and quiz. At the end, the participants were paid privately in cash and left the laboratory one at a time.

5 Experimental results

In this section, we present our empirical results and compare them to the theoretical predictions. We first provide the race outcomes, then we discuss subjects' behavior, its consistency with the equilibrium behavior and the efficiency loss.

5.1 Race outcomes

We first present the summary of the races in each session. As shown in the following table, a total of 94 subjects participated in 8 experimental sessions. Out of 470 races, 50 races ended with 2 winners, 415 races ended with 1 winner and 5 races ended with no winner. Subjects earned on average, $29.48 including the $10 show-up fee.

Table 3: Session Summary

Session	Treatment	No. of Subjects	No. of Races with 2 winners	No. of Races with 1 winner	No. of Races with no winner	Total number of races
1	L-H	10	6	41	3	50
2	L-H	14	10	60	0	70
3	L-H	10	5	45	0	50
4	L-H	12	6	54	0	60
5	H-L	12	7	52	1	60
6	H-L	14	8	62	0	70
7	H-L	10	5	44	1	50
8	H-L	12	3	57	0	60
Total	N/A	94	50	415	5	470

Figure 1: Number and percentage of winners given the starting position

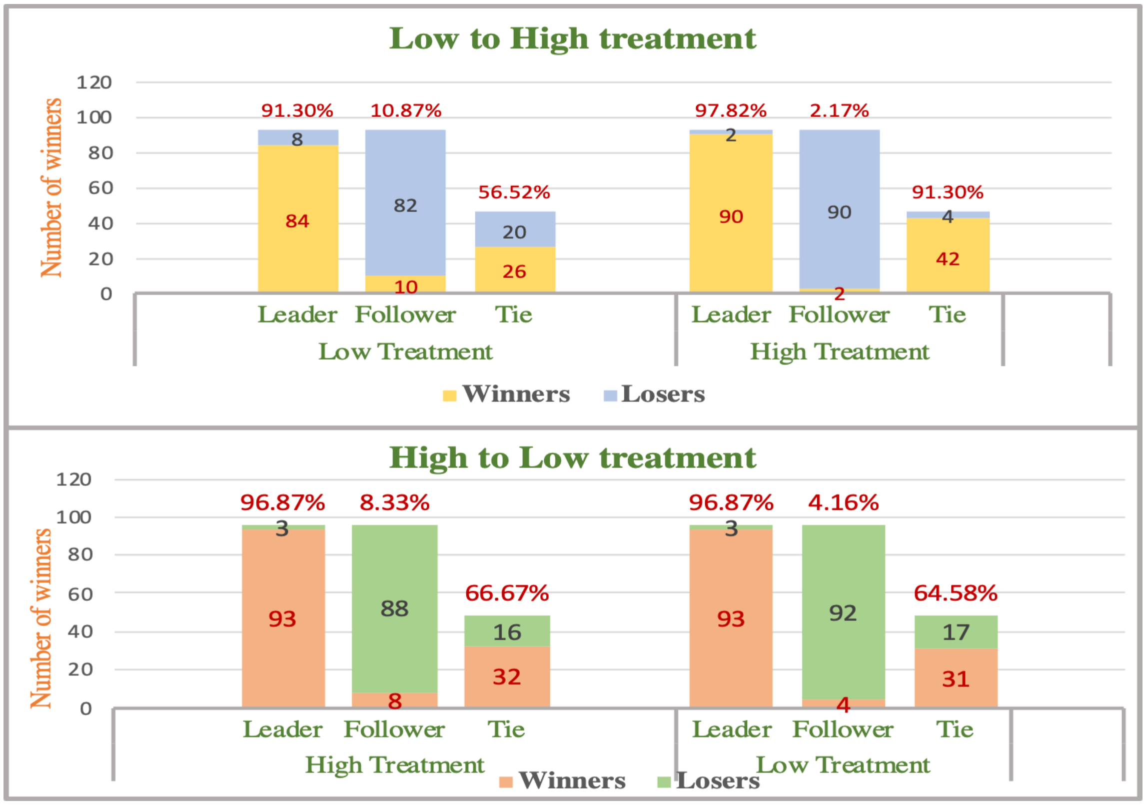


Figure 1 shows the number and percentage of winners given players' initial status as a leader, follower, or in a symmetric position, in the low and high treatments. The results indicate that initial status has a decisive impact on the likelihood of winning the race. Players who start as leaders have the highest winning frequency, approximately 95%, while those who start as followers have the lowest, providing strong support for Hypothesis 1. This pattern holds across both the low and high treatments and remains consistent regardless of the treatment order. Confirmed by two-tailed Wilcoxon signed-rank tests ($p<0.001$ for all pairwise comparisons between initial positions, with 94 observations in both the low and high treatments), we summarize the following Finding 1.

Finding 1: The frequency of winning a race is highest when players start as leaders, second highest when they start in a symmetric position, and lowest when they start as followers. This pattern holds for both the low and high treatments.

Next, we examine whether the race outcomes depend on the distance between the initial experience and the critical knowledge level, as well as the order between the low and high treatment. Interestingly, when the session starts with the low initial experience and moves to high initial experience (L-H treatment, Session 1 to 4), we find that the race outcomes are more consistent with the equilibrium predictions in the high treatment. Specifically, the frequency of winning a race as a leader (follower) in the initial position is significantly higher (lower) in the high treatment than in the low treatment ($p < 0.1$, two-tailed Wilcoxon signed rank test). Most prominently, when the starting position is symmetric, the frequency of winning a race in the high treatment is 91.3% compared to 56.5% in the low treatment and the difference is significant ($p < 0.01$), indicating that the competition in the high treatment is more severe and it is more likely that both players win the race and share the prize.

This effect between the low and high treatment, however, is interacting with the order whether the low or high treatment is played first. When the session starts with the high initial experience and switches to the low initial experience (H-L treatment, Session 5-8), we find that, given any starting position, there is no significant difference in the frequency of winning between the low and high treatment.

Finding 2: In the L-H treatment, race outcomes given the high initial positions exhibit greater consistency with the equilibrium predictions compared to those given the low initial positions. In contrast, in the H-L treatment, the race outcomes do not differ significantly between the low and high initial experience, given any starting position.

Finding 2 partially rejects Hypothesis 2. Theoretically, the predicted winner only depends on players' initial position, as a leader/follower or in a symmetric position, but it is not related to the distance between the initial experience and the finishing line. Our results in the L-H treatment, however, suggest that the outcome converges to the prediction when the distance is shorter. Given that such effect only holds in the L-H treatment, we cannot exclude the possibility that subjects learn over time about the equilibrium play, and they learn better when playing long races first.

5.2 Investment Behavior

In both the low and high treatments, the maximum individual average effort reaches the upper limit of 2. In the low treatment, the minimum, lower quartile, median, and upper quartile of individual average effort are 0.596, 0.851, 1.137, and 1.464, respectively. In the high treatment, the corresponding values are 0.681, 1, 1.266, and 1.583, all of which are higher than those in the low treatment (see Figure B.1 in the online appendix).

To further investigate whether players' investment behavior depends on their position in each round of the race, we present in Figure 2 the mean individual average effort, both conditional and unconditional on players' positions at the start of each round (leader, follower, or tie) in the low and high treatments.

Using pairwise signed-rank tests, we find that the differences in individual average effort across positions are statistically significant and align with Proposition 1, providing support for Hypothesis 3 ($p<0.01$ in 16 out of 18 tests, see Table B.1 in the online appendix for p-values). This result is robust in both the low and high treatments and is consistent regardless of the treatment order, as summarized in Finding 3.

Finding 3: The individual average effort is the highest for the players who are in a tie position, second highest for the leaders and lowest for the followers, in both the low and high treatments and regardless of the treatment order.

Table 4 reports the p-value of Wilcoxon signed rank tests comparing the individual average effort, both conditional or unconditional on players' position in each round between the low and high treatment. Overall, without accounting for potential order effects between L-H and H-L treatments, we find that players' individual average effort is significantly higher in the high treatment than in the low treatment ($p<0.01$ when unconditional on position, $p<0.1$ for each position).

Figure 2: Mean of individual average effort given players' status in each round in the low and high treatment

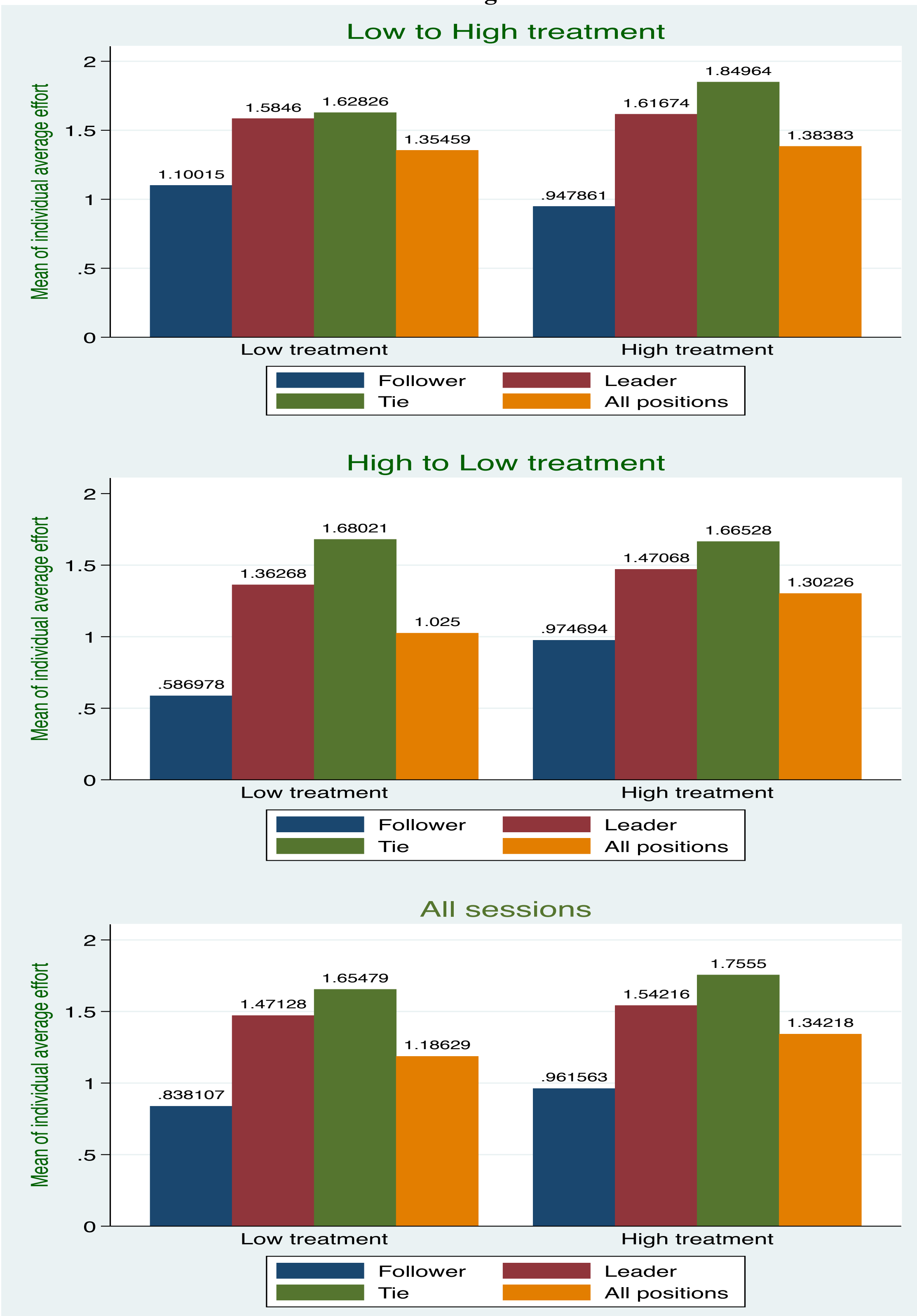


Table 4: p-value of signed rank tests on individual average effort (low vs. high treatment)

	L-H treatment	H-L treatment	All sessions
Follower	0.052 Low>High	0.000 Low<High	0.058 Low<High
Leader	0.788 Low ≈ High	0.031 Low<High	0.084 Low<High
Tie	0.002 Low<High	0.911 Low ≈ High	0.05 Low<High
Unconditional on positions	0.438 Low ≈ High	0.000 Low<High	0.000 Low<High
Gap: Leader vs. Follower	0.069 Low<High	0.01 Low>High	0.587 Low ≈ High
Gap: Tie vs. Follower	0.001 Low<High	0.004 Low>High	0.968 Low ≈ High
Gap: Tie vs. Leader	0.014 Low<High	0.122 Low ≈ High	0.689 Low≈High

Taking a closer look at the L-H treatment and H-L treatment separately, we find different patterns when the order of the treatment changes. For the L-H sessions, the individual average effort in the high treatment, compared to the low treatment, is significantly higher for the players who are in a tie position ($p = 0.002$), but lower for the followers ($p = 0.052$) and not significantly different for the leaders ($p = 0.788$). When unconditional on positions, overall, there is no significant difference between the low and high treatment ($p = 0.438$). However, for the H-L sessions, the individual average effort in the high treatment is significantly higher than in the low treatment except when players are in the tie position ($p<0.01$ when unconditional on position or as a follower, $p<0.05$ as a leader).

These different patterns suggest that players' behavior may be affected by the order of the treatments. Therefore, we further look at the gap in terms of individual average effort of the players who are at different starting positions (leaders vs. followers, tie vs. followers, and tie vs. leaders). As shown in Figure 2 and Table 4, we find that regardless of whether the treatment is L-H or H-L, all the gaps become significantly larger in the second half of the session except that between the leaders and the players who are in a tie position in the H-L treatment ($p = 0.122$). Based on the above test results, we formulate the following Finding 4.[4]

[4] Table B.2 in Appendix B presents regression results that further support Finding 4.

Finding 4: Overall, effort levels are higher in the high treatment. The difference in effort levels across positions is more significant in the second half of the sessions in both L-H and H-L treatments, indicating evidence of learning over time.

Next, we further examine how players' investment behavior is affected by the realization of spillovers in the previous round, using panel data OLS regression models as presented in Table 5. The variable "effort" is the dependent variable which is equal to 0, 1, or 2. "Know_gap" is players' knowledge gap compared to their partner at the start of each round, which is negative (positive) when the player is a follower (leader) and 0 otherwise. "Leader" and "Follower" are dummy variables, which is equal to 1 if the players are leaders and followers, respectively, at the start of a round and is 0 otherwise. "Spillover(t-1)" is a dummy variable indicating whether spillover is realized in the previous round of the same sequence. We include two interaction terms "Leader_spillover" which is "Leader * Spillover(t-1)" and "Follower_spillover" which is "Follower* Spillover(t-1)".

Table 5: OLS regressions on spillover effect

Dependent variable	**All Data**		**L-H treatment**		**H-L treatment**	
Effort	**(1)** All sessions	**(2)** All sessions	**(3)** Low treatment	**(4)** High treatment	**(5)** Low treatment	**(6)** High treatment
know_gap	0.058***	0.017***	0.060***	0.105***	0.053***	0.087***
	(0.002)	(0.004)	(0.005)	(0.012)	(0.002)	(0.009)
Spillover(t-1)	0.810***	0.329*	0.718***	0.787***	0.933***	0.594***
	(0.030)	(0.137)	(0.064)	(0.072)	(0.038)	(0.073)
leader		-0.387**				
		(0.140)				
leader_spillover		0.161				
		(0.144)				
follower		-1.150***				
		(0.136)				
follower_spillover		0.667***				
		(0.146)				
Constant	0.745***	1.511***	0.855***	0.813***	0.633***	0.890***
	(0.033)	(0.133)	(0.070)	(0.069)	(0.033)	(0.066)
N	3864	3864	1262	408	1744	450

Notes: Clustered standard errors (by subject) in parentheses; Subject-period as one unit of observation;
* p<0.05, ** p<0.01, *** p<0.001

Overall, conditional on all positions (Regression 1) and regardless of whether the player is a leader or a follower or in a symmetric position (Regression 2), we find that there is a positive and a significant relationship between the spillovers in the previous period and the effort in the current period, indicating that getting an external technological benefit constitutes an important incentive for the players to provide more investment. In the L-H treatment (Regressions 3 and 4), the effect of the spillovers on the R&D investment is larger in the high treatment compared to the low treatment while the opposite is true for the H-L treatment (Regressions 5 and 6), which indicates that the spillover effect is larger in the second half of the sessions.

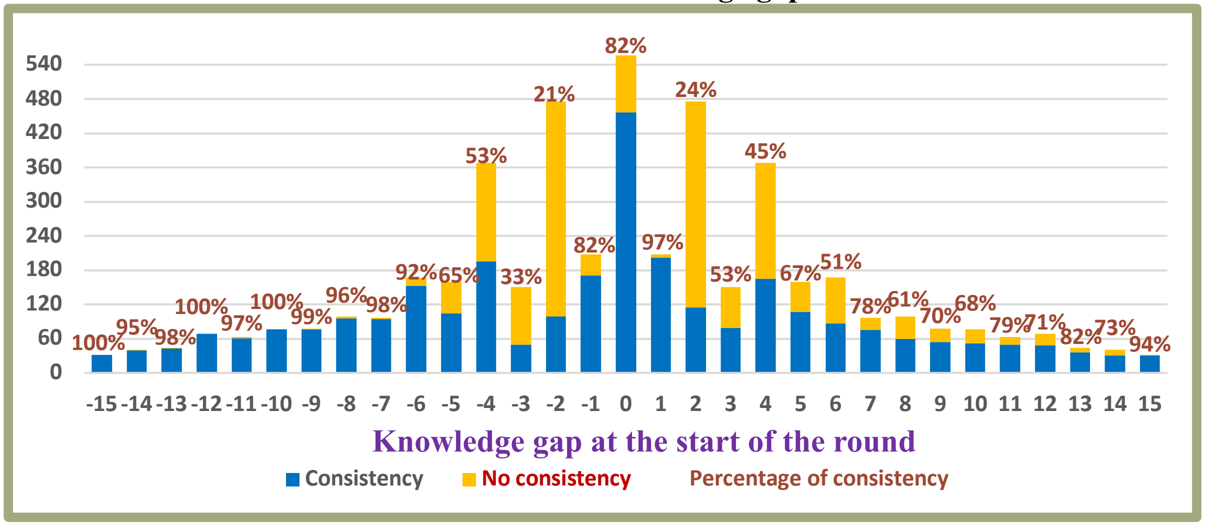
Finding 5: Regardless of whether the treatment is L-H or H-L or both, the spillovers in the previous round significantly increase the players' investment in the current round.

5.3 Equilibrium Consistency

In this subsection, we examine the consistency between investment behavior in our experimental data and equilibrium predictions. For each player's investment choice in each round of each sequence, we define a dummy variable that takes a value of 1 if the player's investment behavior, conditional on the knowledge gap at the beginning of that round, aligns with the predictions of Proposition 1, and 0 otherwise. The overall consistency frequency is 62.4% when pooling all decision rounds across all players.

Figure 3 presents the frequency of this dummy variable being 1 or 0 given each knowledge gap at the start of the round. In our data, the knowledge gap ranges from -15 to 15. The consistency frequency is high when the knowledge gap is large in absolute value ($|k| \geq 5$) and is higher for followers ($k \leq -5$, with an average frequency of 94%) than for leaders ($k \geq 5$, with an average frequency of 72%) in this range. Additionally, we observe high consistency with the equilibrium prediction when the players are in a tie position ($k = 0$), where both firms are predicted to exert high effort. When the absolute value of the knowledge gap is 1, leaders' behavior aligns more closely with the mixed strategy equilibrium prediction than that of the followers, indicating that the followers not only randomize between choosing zero and the high effort level as predicted but also tend to invest at the low effort level. Finally, we observe that consistency is relatively low when the knowledge gap falls within the intermediate range ($2 \leq |k| \leq 4$).

Figure 3: Frequency of investment behavior consistent with equilibrium predictions conditional on knowledge gap



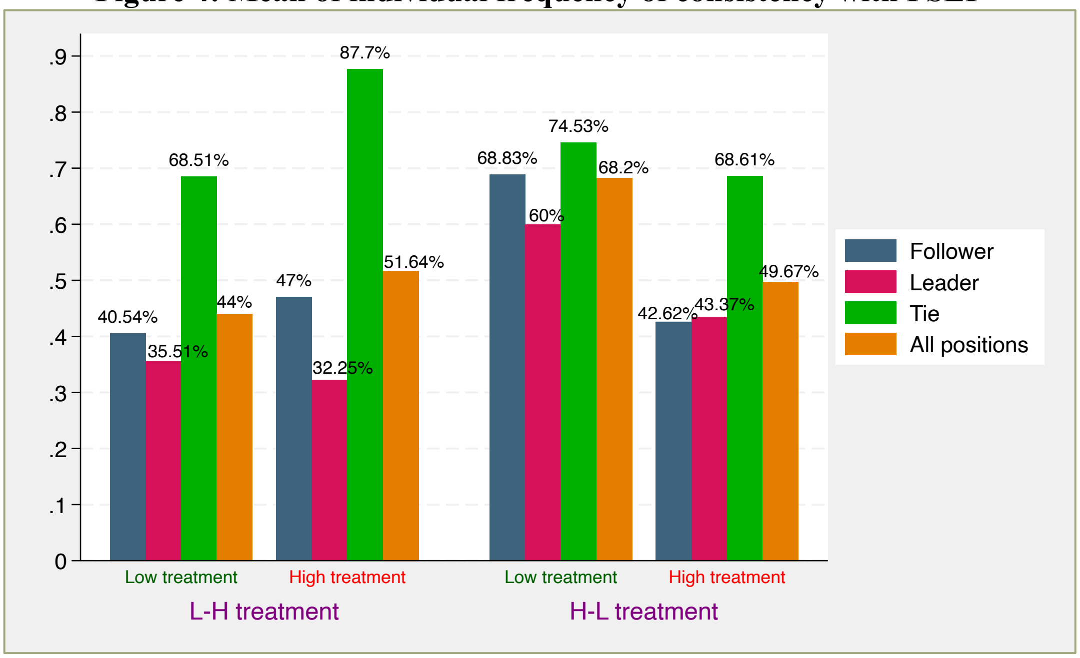
To better understand the investment behavior when the knowledge gap falls within the range $2 \leq |k| \leq 4$, we calculate the frequency of each effort level at each knowledge gap in this range, as shown in Table 6. The equilibrium predicts that when the knowledge gap is greater than or equal to 2 in absolute value, the follower should give up the competition, while the leader should invest at a low effort up to the end of the race. However, we find when the knowledge gap is equal to -2 or 2, the high effort is chosen 73% of the time by leaders and 61% of the time by followers, indicating excessive competition compared to equilibrium predictions. Followers appear to be trying to catch up, while leaders attempt to secure the leading position. As the knowledge gap increases (-3 and -4 for followers, 3 and 4 for leaders), the frequency of high effort drops significantly, by more than 20% on average. Followers switch to choosing zero effort more frequently, and correspondingly, leaders shift toward low effort. This trend suggests a convergence toward equilibrium behavior.

Table 6: Frequency for each effort level conditional on knowledge gap

Knowledge gap at the start of each round	-4	-3	-2	2	3	4
Effort =0	53%	33%	21%	3%	3%	4%
Effort =1	16%	21%	18%	24%	53%	45%
Effort =2	31%	47%	61%	73%	44%	51%

Next, we further examine consistency at the individual level, by focusing on the comparison with the pure strategy equilibrium predictions (PSEP). We calculate each player's individual frequency of consistency by dividing the total number of rounds in which their investment behavior aligns with the PSEP by the player's total number of decision rounds where $|k| \neq 1$. In Figure 4, we present the mean of individual frequency of consistency with the PSEP, both conditional and unconditional on players' position at the start of each round (as leader, follower, or tie position) in the low and high treatment, respectively.

Figure 4: Mean of individual frequency of consistency with PSEP



Based on Wilcoxon signed rank tests, we find that, regardless of whether the order of the treatment is L-H or H-L, in general the players' behavior is more consistent with the PSEP in the second half of the sessions ($p < 0.01$ for both L-H and H-L treatments). In the L-H treatment, the learning effect is more significant for the followers ($p<0.1$) and for the players in a tie position ($p<0.01$). While in the H-L treatment, it is more significant for the followers and the leaders ($p<0.01$). We summarize the consistency results in Finding 6. Table B.3 and B.4 in Appendix B provide the complete Wilcoxon signed rank test results and additional regression results that support the finding.

Finding 6: Overall, players' investment behavior is consistent with equilibrium predictions more than 62% of the time. The behavior is significantly more consistent with the PSEP in the second half of the session than in the first half, regardless of whether the treatment is L-H or H-L.

5.4 Efficiency Loss

Efficiency loss is one important concern in our patent race environment. In this subsection, we evaluate the efficiency level that players achieve in the experiment by comparing the actual group payoff in each race to the corresponding group efficient payoff presented in Table 2.

We find a general deviation from the efficient outcome, which may arise for several reasons: First, players learn over time about equilibrium play (Finding 4), leading to efficiency loss in races starting with asymmetric positions; Second, even when players follow the equilibrium strategy, races starting in a tie position are predicted to incur efficiency loss; Finally, inefficiency occurs when players choose zero effort in three consecutive rounds, causing races to end with no winner.

Based on the group-level percentage of efficiency loss in each race, we calculate the session-level average percentage of efficiency loss for different initial positions (IP), separately for the Low and High treatments, and present the mean in Figure 5.

Figure 5: Mean of session-level average percentage of efficiency loss

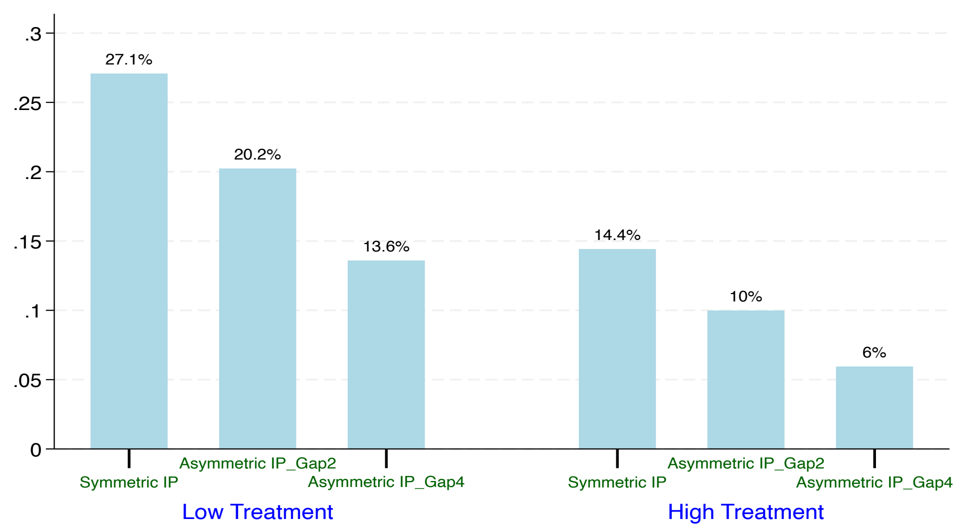


Figure 5 shows several patterns on the percentage of efficiency loss. First, fixing the initial knowledge gap, the percentage of efficiency loss is smaller in the high treatment than in the low treatment. Notice that this pattern partially supports Hypothesis 7, which states that the percentage of efficiency loss is higher in the low treatment for symmetric IP and no differences between the low and high treatments for asymmetric IP. Second, the percentage of efficiency loss decreases as the initial knowledge gap increases. Even though the positive efficiency loss for asymmetric IP does not align with theoretical predictions, the pattern of comparative statics is behaviorally intuitive. When the asymmetry of the initial knowledge gap is more significant, the players tend to adhere more closely to the equilibrium strategy. However, when the initial knowledge gap is 2, the two players engage in excessive competition. Third, while the percentage of efficiency loss for the symmetric IP is high, 27.1% in the low treatment and 14.4% in the high treatment, it is still lower than the theoretical predictions of 38% and 17%, respectively. This can occur when the race that starts in a tie position evolves to an asymmetric position during the race, leading to lower efficiency loss and reduced competition compared to the prediction.

In order to examine whether these patterns are significant, we conduct the pairwise Wilcoxon signed rank tests using the session-level average percentage of efficiency loss.[5] The test results confirm the significant difference between the low and high treatment conditional on each initial knowledge gap ($p < 0.05$ for all the two-tailed pair-wise tests, 8 obs.). Furthermore, given the low or high treatment, the average percentage of efficiency loss generally becomes significantly lower as the initial knowledge gap increases from the symmetric position to IP = 2 and from IP = 2 to IP = 4 ($p < 0.05$ for 5 two-tailed pair-wise tests, 8 obs.), except the comparison between IP = 2 and IP = 4 in the high treatment (p = 12%, 8 obs.). We summarize these two patterns in Finding 7.

Finding 7: Conditional on each initial knowledge gap, the average percentage of efficiency loss is significantly higher in the low treatment than in the high treatment. In both low and high treatments, the average percentage of efficiency loss decreases as the initial knowledge gap increases.

6 Conclusion

In a setting of dynamic patent races with absorptive capacity, we provide experimental evidence on how different initial knowledge levels and relative positions of competitors influence

[5] In the z-Tree program, we randomly matched players and randomly assigned the group number to each pair of players in each race, so we cannot use the paired signed rank test using the group-level data on efficiency loss.

R&D investment behavior and race outcomes. Each subject participated in ten sequences (races), with half featuring a short distance to the target (“low treatment”) and the other half with a long distance to the target (“high treatment”). Our primary focus is on strategic decision-making within the competition.

Overall, our experimental results support the unique Markovian perfect equilibrium of the model. As predicted by theory, the likelihood of winning the race is highest for leaders and lowest for followers. The individual average effort is highest for players in a tie position, followed by leaders, and lowest for followers, in both low and high treatments, regardless of treatment order. Additionally, efficiency loss is significantly higher in races starting with a symmetric position compared to those starting asymmetrically and is higher in the low treatment than in the high treatment. The comparative statics of efficiency loss aligns with theoretical predictions.

Beyond the theoretical model, our results provide empirical insights into behavioral patterns. Examining the first and second halves of the sessions, we observe a general learning trend in players' investment behavior. In the latter half of the experiment, participants' actions align more closely with pure strategy equilibrium predictions, regardless of whether the treatment order is from low to high or high to low. Furthermore, we find that a positive spillover realized in the previous round notably boosts players’ motivation to make investment in the subsequent round.

In this paper, the experimental design does not account for asymmetric information between players or different monetary rewards. For future research, we are interested in investigating how different reward mechanisms affect players’ competition behavior in dynamic patent races and how informational asymmetry between players influences the R&D outcome.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT in order to improve language and readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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Online Appendix A: More details about the model

Dynamics of the knowledge stock

The experience for firm i at the beginning of period $(t+1)$, denoted by $\omega_i(t+1)$, is the summation of firm i's R&D investment and the spillovers in the past periods plus the initial experience (or initial knowledge stock), which can be represented by the following expression:

$$\omega_i(t+1) = \sum_{\tau=1}^{t}\{x_i(\tau) + \varphi(x_i(\tau), x_j(\tau))\} + \omega_i^1,$$

where $\omega_i^1 \geq 0$ is the firm i's initial experience.

Dynamics of the state variable

The state variable in period $(t+1)$ depends on the state variables in period t and the R&D investment and spillovers in period t by the following rule

$$(k_i(t+1), k_j(t+1)) = (k_i(t) - x_i(t) - \varphi[x_i(t), x_j(t)], k_j(t) - x_j(t) - \varphi[x_i(t), x_j(t)]).$$

Stationary Markov strategy

The R&D choice of the firm is specified by a stationary Markov strategy χ_i that depends on the remaining stock of knowledge that the firm has to accumulate:

$$\chi_i\colon (k_i,\ k_j) \in \{1, \dots, N\}^2 \to \chi_i(k_i,\ k_j) = x_i, \text{ with } x_i \in \{0, 1, 2\}.$$

Payoffs

The possible outcomes of firm i are determined by the following net profit function:

$$\pi_i(t) = \begin{cases} Y - AC_i(t) \quad \text{if } k_i(t+1) < k_j(t+1) \text{ and } k_i(t+1) \leq 0; & \textbf{(Case1)} \\ Y/2 - AC_i(t) \quad \text{if } k_i(t+1) = k_j(t+1) \text{ and } k_i(t+1) \leq 0; & \textbf{(Case 2)} \\ -AC_i(t) \quad \text{if } \{k_i(t+1) > k_j(t+1) \ \&\ k_i(t+1) \leq 0\} \text{ or } \{k_i(t+1) > 0 \ \&\ k_j(t+1) \leq 0\} & \textbf{(Case 3)} \end{cases}$$

where $AC_i(t)$ is the accumulated cost of firm i up to time t with t denoting the time of discovery.

Online Appendix B: Additional experimental results

Figure B.1: Box plots for the individual average effort in the low and high treatment

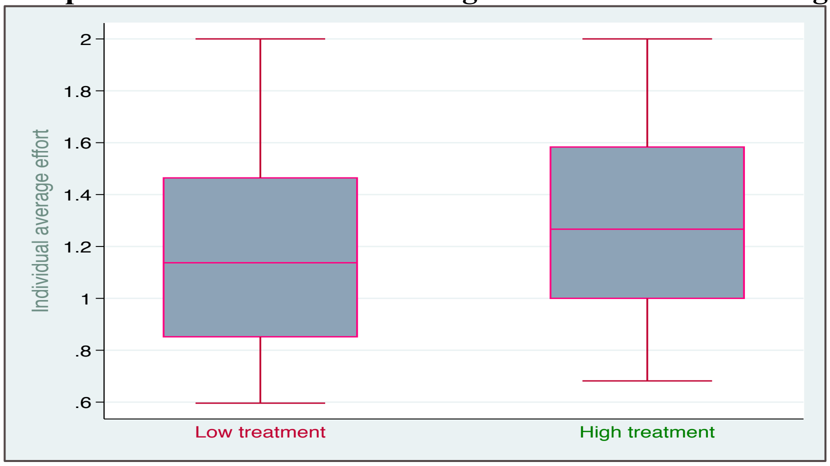

Table B.1: p-value of signed rank tests on individual average effort (Comparison between different positions)

Treatment	Comparison	L-H treatment (Session 1 to 4)	H-L treatment (Session 5 to 8)	All sessions
Low treatment	Follower vs. Leader	0.000	0.000	0.000
	Follower vs. Tie	0.000	0.000	0.000
	Leader vs. Tie	0.566	0.000	0.001
High treatment	Follower vs. Leader	0.000	0.000	0.000
	Follower vs. Tie	0.000	0.000	0.000
	Leader vs. Tie	0.000	0.017	0.000

In order to further analyze the individual R&D investment behavior in a multivariate framework, we use panel data OLS regression models on the level of effort and present the results in Table B.2. The variable "effort" is the dependent variable which is equal to 0, 1, or 2. "Know_gap" is the players' knowledge gap compared to their partner at the start of each round, which is negative (positive) when the player is a follower (leader) and 0 otherwise. "Leader" and "Follower" are dummy variables, which is equal to 1 if the players are leaders and followers, respectively, at the start of a round and is 0 otherwise. "High_treatment" is equal to 1 if it is the high treatment and 0 otherwise, and "High_low" is equal to 1 if the treatment is from high to low, 0 otherwise. We also include the interaction terms "Leader_ht" which is "Leader * high_treatment", "Follower_ht" which is "Follower*high_treatment", "High_low* high_treatment".

In all the regressions, we find knowledge gap at the start of each round has a significant effect on the effort level, but the coefficient is quite small. The results in Table B.2 are consistent with Figure 2 and Table 4. Regardless of whether the treatment is L-H or H-L or both (Regressions 1, 2 and 3), the effort is significantly the highest for the players who are in a symmetric position, the second highest for the leaders and the lowest for the followers. Conditional on all sessions and all players' positions (Regression 5), we find that the effort in the high treatment is significantly higher than the effort in the low treatment ($p < 0.001$) as shown in Figure 2 and Table 4. In the L-H treatment (Regression 1), the effort level for the players who are in a symmetric position is significantly higher in the high treatment compared to the low treatment, but such effect disappears in the H-L treatment (Regression 2).

Table B.2: OLS regressions on individual effort

Dependent variable: **Effort**	**(1)** L-H treatment	**(2)** H-L treatment	**(3)** All sessions	**(4)** All positions	**(5)** All positions
Know_gap	0.054***	0.029***	0.040***	0.057***	0.057***
	(0.010)	(0.005)	(0.004)	(0.004)	(0.004)
Leader	-0.385***	-0.658***	-0.534***		
	(0.088)	(0.059)	(0.054)		
Leader_ht	-0.171	0.320**	0.098		
	(0.109)	(0.101)	(0.077)		
Follower	-0.429**	-1.109***	-0.788***		
	(0.137)	(0.114)	(0.094)		
Follower_ht	-0.426***	0.463***	0.039		
	(0.094)	(0.110)	(0.087)		
High_treatment	0.228***	-0.112	0.052	0.024	0.161***
	(0.066)	(0.074)	(0.052)	(0.047)	(0.032)
High_low				-0.328***	
				(0.070)	
High_low*high_treatment				0.254***	
				(0.060)	
Constant	1.705***	1.816***	1.764***	1.340***	1.167***
	(0.069)	(0.046)	(0.042)	(0.054)	(0.039)
N	2130	2674	4804	4804	4804

Notes: Clustered standard errors (by subject) in parentheses; Subject-period as one unit of observation; * p<0.05, ** p<0.01, *** p<0.001

Table B.3: p-value of signed rank tests on individual frequency of consistency with PSEP (low vs. high treatment)

	L-H treatment	H-L treatment
Follower	0.098 Low<High	0.000 High<Low
Leader	0.220 Low ≈ High	0.001 High<Low
Tie	0.002 Low<High	0.729 Low ≈ High
All positions	0.005 Low< High	0.000 High<Low

To examine whether players' behaviors align with the PSEP in a multivariate framework, we estimate marginal-effect Probit regression models on the consistency level. The regression results for each model are presented in Table B.4. The dependent variable, "consistency," is a dummy variable equal to 1 if the firm's choice in a period aligns with the equilibrium predictions and 0 otherwise. The independent variables are defined the same as in Table B.2.

Table B.4: Marginal effect Probit regressions on consistency with PSEP

Dependent variable: **Consistency**	**(1) L-H treatment**	**(2) H-L treatment**	**(3) All sessions**	**(4) All sessions**
Leader	-0.456***	-0.294***	-0.389***	
	(0.075)	(0.082)	(0.059)	
Leader_ht	-0.323***	0.001	-0.147*	
	(0.099)	(0.089)	(0.073)	
Follower	-0.349***	-0.178*	-0.274***	
	(0.074)	(0.072)	(0.056)	
Follower_ht	-0.249*	-0.112	-0.165*	
	(0.101)	(0.075)	(0.065)	
High_treatment	0.313***	-0.189*	0.027	0.090**
	(0.088)	(0.079)	(0.067)	(0.027)
High_low				0.281***
				(0.050)
High_low* high_treatment				-0.315***
				(0.042)
N	1918	2470	4388	4388

Notes: Clustered standard errors (by subject) in parentheses; Subject-period as one unit of observation; data with |k|=1 is excluded; * p<0.05, ** p<0.01, *** p<0.001

The results in Table B.4 are consistent with Figure 4, which shows that the behavior of players in a tie position aligns with PSEP more than the behavior of leaders and followers. Regression 1 (L-H treatment) indicates overall higher consistency during the high treatment phase compared to the low treatment phase. However, regression 2 (H-L treatment) suggests that players in the high treatment are less likely to align their choices with equilibrium predictions compared to the low treatment. Conditional on all sessions, Regression 4 provides evidence of a learning effect, as players increasingly align with equilibrium play in the second half of the session, regardless of whether the treatment is L-H or H-L.

Online Appendix C: Payoffs and paths of choices

In this appendix, we present with details on how we calculate the different payoffs summarized in Table 2. Under each initial experience, we show the paths of choices for the two firms and we denote the payoff of each firm by V_i, i ={1,2}.

<u>Case 1: $(\omega_1(1), \omega_2(1)) = (0, 0)$:</u>

Table C.1: Individual equilibrium payoffs for Case 1

t	1	2	3	4	5	6	7
$x_1(t)$	2	2	2	2	2	2	
$x_2(t)$	2	2	2	2	2	2	
$\omega_1(t)$	0	3	6	9	12	15	18
$k_1(t) = N - \omega_1(t)$	16	13	10	7	4	1	-2
$\omega_2(t)$	0	3	6	9	12	15	18
$k_2(t) = N - \omega_2(t)$	16	13	10	7	4	1	-2
$\varphi(x_1(t), x_2(t))$	1	1	1	1	1	1	
Cost for every player	c_2	c_2	c_2	c_2	c_2	c_2	

$V_1 = V_2 = 10 - (6 * 0.8) = 5.2$ ECU

Table C.2: Individual Maximum payoff and Group efficient payoff for Case 1

t	1	2	3	4	5	6	7	8	9	10
$x_1(t)$	1	1	1	1	1	1	1	1	1	
$x_2(t)$	1	1	1	1	1	1	1	0	0	
$\omega_1(t)$	0	2	4	6	8	10	12	14	15	16
$k_1(t) = N - \omega_1(t)$	16	14	12	10	8	6	4	2	1	0
$\omega_2(t)$	0	2	4	6	8	10	12	14	14	14
$k_2(t) = N - \omega_2(t)$	16	14	12	10	8	6	4	2	2	2
$\varphi(x_1(t), x_2(t))$	1	1	1	1	1	1	1	0	0	
Cost for player 1	c_1	c_1	c_1	c_1	c_1	c_1	c_1	c_1	c_1	

$V_1 = Y - (9 * c_1) = 20 - (9 * 0.2) = 18.2$ ECU , $V_2 = -7 * 0.2 = -1.4$

$V_1 + V_2 = 16.8$: this is **the efficient outcome**.

Table C.3: Individual Minimum payoff for Case 1

t	1	2	3	4	5	6	7
$x_1(t)$	2	2	2	2	2	2	
$x_2(t)$	2	2	2	2	2	1	
$\omega_1(t)$	0	3	6	9	12	15	18
$k_1(t) = N - \omega_1(t)$	16	13	10	7	4	1	-2
$\omega_2(t)$	0	3	6	9	12	15	17
$k_2(t) = N - \omega_2(t)$	16	13	10	7	4	1	-1
$\varphi(x_1(t), x_2(t))$	1	1	1	1	1	1	
Cost for player 2	c_2	c_2	c_2	c_2	c_2	c_1	

$V_2 = -(5 * c_2) - c_1 = -(5 * 0.8) - 0.2 = -4.2$ ECU

Case 2: $(\omega_1(1), \omega_2(1)) = (8, 8)$:

Table C.4: Individual equilibrium payoffs for Case 2

t	1	2	3	4
$x_1(t)$	2	2	2	
$x_2(t)$	2	2	2	
$\omega_1(t)$	8	11	14	17
$k_1(t) = N - \omega_1(t)$	8	5	2	-1
$\omega_2(t)$	8	11	14	17
$k_2(t) = N - \omega_2(t)$	8	5	2	-1
$\varphi(x_1(t), x_2(t))$	1	1	1	
Cost for every player	c_2	c_2	c_2	

$V_1 = V_2 = 10 - (3 * 0.8) = 7.6$ ECU

Table C.5: Individual Maximum payoff and Group efficient payoff for Case 2

t	1	2	3	4	5	6
$x_1(t)$	1	1	1	1	1	
$x_2(t)$	1	1	1	0	0	
$\omega_1(t)$	8	10	12	14	15	16
$k_1(t) = N - \omega_1(t)$	8	6	4	2	1	0
$\omega_2(t)$	8	10	12	14	14	14
$k_2(t) = N - \omega_2(t)$	8	6	4	2	2	2
$\varphi(x_1(t), x_2(t))$	1	1	1	0	0	
Cost for player 1	c_1	c_1	c_1	c_1	c_1	

$V_1 = Y - (5 * c_1) = 20 - (5 * 0.2) = 19$ ECU , $V_2 = -3 * 0.2 = -0.6$

$V_1 + V_2 = 18.4$: this is **the efficient outcome**.

Table C.6: Individual Minimum payoff for Case 2

t	1	2	3	4
$x_1(t)$	2	2	2	
$x_2(t)$	2	2	1	
$\omega_1(t)$	8	11	14	17
$k_1(t) = N - \omega_1(t)$	8	5	2	-1
$\omega_2(t)$	8	11	14	16
$k_2(t) = N - \omega_2(t)$	8	5	2	0
$\varphi(x_1(t), x_2(t))$	1	1	1	
Cost for player 2	c_2	c_2	c_1	

$V_2 = -(0.8 * 2) - 0.2 = -1.8$ ECU

Case 3: $(\boldsymbol{\omega_1(1), \omega_2(1)}) = (\mathbf{2, 0})$:

Table C.7: Individual equilibrium payoffs for Case 3

t	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
x_1(t)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
$x_2(t)$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
$\omega_1(t)$	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
$k_1(t)$ $= N - \omega_1(t)$	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0
$\omega_2(t)$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$k_2(t)$ $= N - \omega_2(t)$	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
$\varphi(x_1(t), x_2(t))$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Cost for player 1	c_1	c_1	c_1	c_1	c_1	c_1	c_1	c_1	c_1	c_1	c_1	c_1	c_1	c_1	

$V_1 = Y - 14c_1 = 17.2$ ECU and $V_2 = 0$

Table C.8: Individual Maximum payoff and Group efficient payoff for Case 3

t	1	2	3	4	5	6	7	8
$x_1(t)$	1	1	1	1	1	1	1	
$x_2(t)$	1	1	1	1	1	1	1	
$\omega_1(t)$	2	4	6	8	10	12	14	16
$k_1(t) = N - \omega_1(t)$	14	12	10	8	6	4	2	0
$\omega_2(t)$	0	2	4	6	8	10	12	14
$k_2(t) = N - \omega_2(t)$	16	14	12	10	8	6	4	2
$\varphi(x_1(t), x_2(t))$	1	1	1	1	1	1	1	
Cost for player 1	c_1	c_1	c_1	c_1	c_1	c_1	c_1	

$V_1 = Y - (7 * c_1) = 20 - (7 * 0.2) = 18.6$ ECU, $\quad V_2 = -7 * 0.2 = -1.4$

$V_1 + V_2 = 17.2$: this is **the efficient outcome**.

Table C.9: Individual Minimum payoff for Case 3

t	1	2	3	4	5	6
$x_1(t)$	2	2	2	2	2	
$x_2(t)$	2	2	2	2	2	
$\omega_1(t)$	2	5	8	11	14	17
$k_1(t) = N - \omega_1(t)$	14	11	8	5	2	-1
$\omega_2(t)$	0	3	6	9	12	15
$k_2(t) = N - \omega_2(t)$	16	13	10	7	4	1
$\varphi(x_1(t), x_2(t))$	1	1	1	1	1	
Cost for player 2	c_2	c_2	c_2	c_2	c_2	

$V_2 = -(0.8 * 5) = -4$ ECU

Case 4: $(\boldsymbol{\omega_1(1), \omega_2(1)}) = (\mathbf{4, 0})$:

Table C.10: Individual equilibrium payoffs for Case 4

t	1	2	3	4	5	6	7	8	9	10	11	12	13
x_1(t)	1	1	1	1	1	1	1	1	1	1	1	1	
$x_2(t)$	0	0	0	0	0	0	0	0	0	0	0	0	
$\omega_1(t)$	4	5	6	7	8	9	10	11	12	13	14	15	16
$k_1(t) = N - \omega_1(t)$	12	11	10	9	8	7	6	5	4	3	2	1	0
$\omega_2(t)$	0	0	0	0	0	0	0	0	0	0	0	0	0
$k_2(t) = N - \omega_2(t)$	16	16	16	16	16	16	16	16	16	16	16	16	16
$\varphi(x_1(t), x_2(t))$	0	0	0	0	0	0	0	0	0	0	0	0	
Cost for player 1	c_1	c_1	c_1	c_1	c_1	c_1	c_1	c_1	c_1	c_1	c_1	c_1	

$V_1 = Y - 12c_1 = 17.6$ ECU and $V_2 = 0$

Table C.11: Individual Maximum payoff and Group efficient payoff for Case 4

t	1	2	3	4	5	6	7
$x_1(t)$	1	1	1	1	1	1	
$x_2(t)$	1	1	1	1	1	1	
$\omega_1(t)$	4	6	8	10	12	14	16
$k_1(t) = N - \omega_1(t)$	12	10	8	6	4	2	0
$\omega_2(t)$	0	2	4	6	8	10	12
$k_2(t) = N - \omega_2(t)$	16	14	12	10	8	6	4
$\varphi(x_1(t), x_2(t))$	1	1	1	1	1	1	
Cost for player 1	c_1	c_1	c_1	c_1	c_1	c_1	

$V_1 = Y - (6 * c_1) = 20 - (6 * 0.2) = 18.8$ ECU , $V_2 = -6 * 0.2 = -1.2$

$V_1 + V_2 = 17.6$: this is **the efficient outcome**.

Table C.12: Individual Minimum payoff for Case 4

t	1	2	3	4	5
$x_1(t)$	2	2	2	2	
$x_2(t)$	2	2	2	2	
$\omega_1(t)$	4	7	10	13	16
$k_1(t) = N - \omega_1(t)$	12	9	6	3	0
$\omega_2(t)$	0	3	6	9	12
$k_2(t) = N - \omega_2(t)$	16	13	10	7	4
$\varphi(x_1(t), x_2(t))$	1	1	1	1	
Cost for player 2	c_2	c_2	c_2	c_2	

$V_2 = -(0.8 * 4) = -3.2$ ECU

Case 5: $(\omega_1(1), \omega_2(1)) = (10, 8)$:

Table C.13: Individual equilibrium payoffs for Case 5

t	1	2	3	4	5	6	7
x_1(t)	1	1	1	1	1	1	
$x_2(t)$	0	0	0	0	0	0	
$\omega_1(t)$	10	11	12	13	14	15	16
$k_1(t) = N - \omega_1(t)$	6	5	4	3	2	1	0
$\omega_2(t)$	8	8	8	8	8	8	8
$k_2(t) = N - \omega_2(t)$	8	8	8	8	8	8	8
$\varphi(x_1(t), x_2(t))$	0	0	0	0	0	0	
Cost for player 1	c_1	c_1	c_1	c_1	c_1	c_1	

$V_1 = Y - 6c_1 = 18.8$ ECU and $V_2 = 0$

Table C.14: Individual Maximum payoff and Group efficient payoff for Case 5

t	1	2	3	4
$x_1(t)$	1	1	1	
$x_2(t)$	1	1	1	
$\omega_1(t)$	10	12	14	16
$k_1(t) = N - \omega_1(t)$	6	4	2	0
$\omega_2(t)$	8	10	12	14
$k_2(t) = N - \omega_2(t)$	8	6	4	2
$\varphi(x_1(t), x_2(t))$	1	1	1	
Cost for player 1	c_1	c_1	c_1	

$V_1 = Y - (3 * c_1) = 20 - (3 * 0.2) = 19.4$ ECU , $V_2 = -3 * 0.2 = -0.6$

$V_1 + V_2 = 18.8$: this is **the efficient outcome**.

Table C.15: Individual Minimum payoff for Case 5

t	1	2	3
$x_1(t)$	2	2	
$x_2(t)$	2	2	
$\omega_1(t)$	10	13	16
$k_1(t) = N - \omega_1(t)$	6	3	
$\omega_2(t)$	8	11	14
$k_2(t) = N - \omega_2(t)$	8	5	
$\varphi(x_1(t), x_2(t))$	1	1	
Cost for player 2	c_2	c_2	

$V_2 = -0.8 - 0.8 = -1.6$ ECU

Case 6: where $(\omega_1(1), \omega_2(1)) = (12, 8)$:

Table C.16: Individual equilibrium payoffs for Case 6

t	1	2	3	4	5
x_1(t)	1	1	1	1	
$x_2(t)$	0	0	0	0	
$\omega_1(t)$	12	13	14	15	16
$k_1(t) = N - \omega_1(t)$	4	3	2	1	0
$\omega_2(t)$	8	8	8	8	8
$k_2(t) = N - \omega_2(t)$	8	8	8	8	8
$\varphi(x_1(t), x_2(t))$	0	0	0	0	
Cost for player 1	c_1	c_1	c_1	c_1	

$V_1 = Y - 4c_1 = 19.2$ ECU and $V_2 = 0$

Table C.17: Individual Maximum payoff and Group efficient payoff for Case 6

t	1	2	3
$x_1(t)$	1	1	
$x_2(t)$	1	1	
$\omega_1(t)$	12	14	16
$k_1(t) = N - \omega_1(t)$	4	2	0
$\omega_2(t)$	8	10	12
$k_2(t) = N - \omega_2(t)$	8	6	4
$\varphi(x_1(t), x_2(t))$	1	1	
Cost for player 1	c_1	c_1	

$V_1 = Y - (2 * c_1) = 20 - (2 * 0.2) = 19.6$ ECU , $V_2 = -2 * 0.2 = -0.4$, $V_1 + V_2 = 19.2$: this is **the efficient outcome**.

Table C.18: Individual Minimum payoff for Case 6

t	1	2	3
$x_1(t)$	2	2	
$x_2(t)$	2	2	
$\omega_1(t)$	12	15	18
$k_1(t) = N - \omega_1(t)$	4	1	-2
$\omega_2(t)$	8	11	14
$k_2(t) = N - \omega_2(t)$	8	5	2
$\varphi(x_1(t), x_2(t))$	1	1	
Cost for player 2	c_2	c_2	

$\overline{V_2 = -0.8 - 0.8 = -1.6}$

Appendix D: Instructions (L-H treatment)

This is an experiment in the economics of strategic decision making. You will receive $10 for showing up in the session. Your additional earnings will depend on your own decisions and other participants' decisions as explained below. The instructions are simple. If you follow them closely and make appropriate decisions, you can earn an appreciable amount of money. During the experiment, please remain silent and do not use your mobile device. If you have any questions, or need assistance of any kind, please raise your hand and an experimenter will come to assist you.

During the experiment, your additional earnings will be calculated using Experimental Currency Units (ECU). At the end of the experiment, the total amount of ECUs you have earned will be converted to Canadian Dollars at the rate of 1 ECU = $0.25 and will be paid to you in cash, in addition to the show-up fee.

Overview of the experiment

In this experiment, you will play 10 sequences in total. At the beginning of each sequence, you will be randomly and anonymously matched with another participant in this room with equal probability. You will not know whether or not you play with this participant in any previous sequence. Neither will you observe the choices made by your matched player in any previous sequence.

Specifics

Each sequence consists of multiple rounds, in which you and your matched player make investment decisions and accumulate points in order to compete for a prize that is worth 20 ECU. In each round, you and your matched player independently and simultaneously decide whether to invest 0, 1, or 2 points, which costs respectively c_0 = 0, c_1 = 0.2 and c_2= 0.8 ECU, as summarized in the following table:

Points	Costs
0	c_0 = 0 ECU
1	c_1 = 0.2 ECU
2	c_2 = 0.8 ECU

At the end of each round, the points you invested in the round will be added to your accumulated points of the sequence. In each round, you and your matched player may earn one extra point from investment if both of you invest 1 or 2 points. If one of you or both of you choose to invest 0 point, no extra point will be earned. The following table shows all the possible cases for the extra point:

Your choice / Your partner's choice	0	1	2
0	(0,0) => no extra point	(0,1) => no extra point	(0,2) => no extra point
1	(1,0) => no extra point	(1,1) => one extra point	(1,2) => one extra point
2	(2,0) => no extra point	(2,1) => one extra point	(2,2) => one extra point

In each round, before you make your decision, you will be able to observe the choice of yourself and your matched player in the previous rounds, as well as your accumulated points and your matched player's accumulated points. After both you and your matched player submit the decision for the current round, you will observe the choice made by yourself and your matched player in this round, whether or not you receive the extra point, and the updated accumulated points.

When one player or both players in a pair reach or pass a level of accumulation of 16 points, a sequence ends. Otherwise, the sequence will continue into next round, in which the total points and the total costs accumulated in all previous rounds of the same sequence will carry over into the next round.

At the end of every sequence, you will receive the prize of 20 ECU if the following two conditions are satisfied:

(1) Your accumulation of points reaches or passes 16;

(2) Your accumulation of points is higher than the accumulation of points of your matched player.

In the case that you and your matched player reach or pass 16 points in the same round with the same accumulated points, you will share the prize and each of you receives 10 ECU.

<u>Examples:</u>

<u>Example 1:</u> At the end of the current round, you accumulated less than 16 points while your matched player accumulated at least 16 points, your matched player wins.

<u>Example 2:</u> At the end of the current round, you accumulated less than 16 points while your matched player accumulated 17 points, your matched player wins.

<u>Example 3:</u> At the end of the current round, you and your matched player both accumulated 16 points, both of you win and share the prize.

<u>Example 4:</u> At the end of the current round, you and your matched player both accumulated less than 16 points, the sequence continues to the next round.

Payoffs from a sequence:

- If you are the only winner, you will earn 20 ECU less the total costs you bared to accumulate 16 points.
- If both you and your matched player are winners, you will earn 10 ECU less the costs you bared to accumulate 16 points.
- If your matched player is the only winner, you get no prize from the game but still need to pay the costs that have occurred.
- Note that if neither you nor your matched player invest at least 1 point for three consecutive rounds, the sequence will be ended and neither of you will win the prize.

At the beginning of each sequence, you and your partner have an initial position, which is exogenously varied: In some sequences you will start in an asymmetric position, and in some other sequences you will start in a symmetric position. Your initial position will be shown on the screen when the sequence starts. The following table indicates the initial position for each pair in every sequence:

Sequences	1	2	3	4	5	6	7	8	9	10
Initial position for every player in every sequence	(0,0)	(2,0)	(0,2)	(4,0)	(0,4)	(8,8)	(10,8)	(8,10)	(12,8)	(8,12)

Earnings:

At the end of the session, the program will calculate your entire earnings from participation in all the sequences. Your final payment will be equal to the earnings from the 10 sequences plus the $10 show-up fee. You will be paid in private and in cash at the end of the experiment.

Comments:

- ❖ You cannot change your choice once you have made it;
- ❖ Do not discuss your decisions or your results with anyone at any time during the experiment.
- ❖ Do not get up from your seat before the end of the experiment.
- ❖ Your ID# is private. Do not reveal it to anyone.

Now, please fill out the short enclosed quiz before we start the experiment. The aim of the quiz is to make sure that the key concepts covered in the instructions are clear for you. Your answers in the quiz will not affect your earnings directly.

Thank you for participating and good luck!

Quiz:

Please answer the following questions. If you have any questions, please contact one of the conductors of the study.

- ➢ You will be randomly and anonymously matched with another participant in the room in every round.   True or False

- ➢ At the beginning of a round, you are randomly and anonymously paired with another participant. You choose one point to invest while your matched partner chooses 2 points. What is the value of the spillover in this case?
  What is your cost in this round?

- ➢ At the beginning of a round, you are randomly and anonymously paired with another participant. You choose zero point to invest while your matched partner chooses one point.

What is the value of the spillover in this case?
What is your cost in this round?

- At the end of a sequence, your accumulated points are greater than your partner's accumulated points and your accumulated cost is equal to 2.8 ECU.
  What is the value of the prize that you get?
  What is your payoff?

- At the end of a sequence, your accumulated points are equal to your partner's accumulated points and your accumulated cost is equal to 4.8 ECU.
  What is the value of the prize that you get?
  What is your payoff?

- At the end of a sequence, your accumulated points are lower than your partner's accumulated points and your accumulated cost is equal to 4.2 ECU.
  What is the value of the prize that you get?
  What is your payoff?

- Your final earnings will be determined by your payoffs in all the sequences. True or False