Can Communication Mitigate Strategic Delays in Innovation Adoption?*

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ABSTRACT

Innovation is at the core of growth and welfare, however, evidence suggests that innovation adoption is at a slower pace than the technological progress justifies. We explore whether communication could mitigate the slow innovation adoption. We model innovation adoption as a risky investment with irreversible costs under pure informational externalities. Agents choose adoption timing, where the earliest investor bears the costs while all agents learn the investment returns. The informational externalities create free-riding incentives for agents, resulting in strategic delays in innovation adoptions. We show that introducing communication into this setting leads to earlier investments, mitigating strategic delay. We test our model predictions in a laboratory experiment. We find that communication leads to significantly earlier investment times when there are 2 players. Half of the subjects coordinate on the asymmetric equilibrium of early pioneers and their followers by opting out of communication half of the time, while the other half communicates and coordinates on earlier adoption times. When there are 4 players, communication helps subjects to coordinate and reduce strategic delay significantly in the first half of the experiment, while coordination failures emerge in the second half of the experiment when subjects get more experienced, sweeping away the beneficial effect of communication at the aggregate level.

KEYWORDS: Innovation; Investment timing; Communication; New technology adoption; Coordination; Informational Externalities, Experiments

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“*We see all around us in real life faulty ropes instead of steel hawsers, defective draught animals instead of show breeds, the most primitive hand labor instead of perfect machines...*”

Schumpeter (1934). The Theory of Economic Development. Harvard University Press. p. 14-15

I. Introduction

Innovation is at the core of growth and welfare. One of the pillars of innovation is the adoption of new technologies. The timing of new technology adoption is a fundamental issue in understanding productivity growth (Hoppe, 2002). Krugman (1994) attributes the slowdown in the US productivity growth in the early 70s, among other reasons, to the delay between the generation and the exploitation of new technologies. The adoption of new technologies by firms or individuals being at a slower pace than the technological progress justifies is a well-documented empirical observation (Oster 1982, Sumrall 1982, Smith and Ulu 2012).

One of the critical determinants of innovation adoption decisions is the uncertainty about the profitability of the new product, service, or technology, namely the returns to the adoption investment. This uncertainty could be resolved at no cost by observing the experience of early adopters. Consider the situation when a new product, a novel medical procedure, or a sustainable production technology is released. Consumers learn about new products and services from friends and neighbors (Liu et al., 2014), health professionals learn about the benefits and side effects of new medicines from the experience of others (Becker, 1970), and farmers learn about qualities of new types of the crop from the performance of their peers (Conley and Udry, 2000). In the presence of full informational externalities, such learning opportunities from the experience of others generates incentives to strategically delay adoption timing. In other words, information on returns to innovation being public goods creates strategic free-riding incentives resulting in either late or no innovation adoptions.

Discovery of new products, services or technologies is not sufficient for technological progress, these innovations yield no benefit until they are employed (Tirole and Fudenberg, 1985). Therefore, policy should consider how to promote early adoption of innovation as well as its discovery. Investigating policy instruments to mitigate the strategic delay in adoption timings helps with addressing the key question for economic growth: “How to close the delay between the generation and the exploitation of new technologies?”. In this paper, we investigate whether and how communication serves as a coordination device for altering free riding and mitigating strategic delay stemming from it.

We model innovation adoption as a risky investment, where an agent adopting a new technology pays a known cost of investment while facing uncertain returns to this investment. For example, when employing a new medicine, the costs are known by the health authorities while the potential returns to the new treatment are unknown. In our model, the return can be high or low. The innovation is of good quality with a commonly known probability of p and is of bad quality with the remaining probability of $1-p$. The returns in case of a good quality innovation are decreasing over time to capture the fact that the longer the delay in adoption the less time the agent can enjoy its fruits. The costs of innovation adoption are also decreasing over time since as newer technologies are introduced, the price of the current ones is becoming cheaper over time. The agent making the first adoption incurs the costs of experimenting with the new technology, while the lessons from this experiment, namely whether the new technology is of good or bad quality become public information. In other words, we assume that there are full informational externalities. A single agent undertaking the investment is sufficient to uncover the uncertainty on returns, i.e., additional experiments bring no added value.

We introduce a communication stage to this baseline game. First, each agent decides whether or not to communicate with the others. Communication takes place among the agents who agree to communicate. Agents opting out of communication do not receive any further information. Following this communication stage, agents play the above-described game. If communicating agents succeed to coordinate on a common adoption time, they share the costs of investment equally. If they fail to do so, then they individually decide on their adoption times.

We characterize the equilibria in our games. We show that there are multiple equilibria, of both symmetric and asymmetric nature. In our baseline game, the asymmetric equilibria correspond to the situation of pioneers and free-riders: immediate investors and those who free ride on the revealed information. There are no symmetric equilibria in pure strategies. In the symmetric mixed strategy equilibrium, the delay in adoption timing depends on and is increasing in the number of agents. In our communication game the asymmetric equilibria correspond to the communicating agents coordinating on immediate adoption timing, and the late individual adopters. A more than two-player communication can emerge in equilibrium if the agents play the symmetric Nash equilibrium of the baseline game, namely the mixed strategy Nash equilibrium. We show that communication reduces the strategic delay in adoption timings independent of the number of agents on the market.

We implement our theoretical setting in a laboratory experiment to test our comparative statics predictions. We run a 2x2 design where we vary (i) the availability of communication and (ii) the number of agents. We are also interested in studying the interaction between the group size and the availability of communication to explore whether the gain from communication changes depending on number of agents. We run the following four treatments: the baseline and the communication games with 2 and 4 players respectively. In order to allow for learning across games, subjects play each game in a repeated fashion 20 times with randomly re-matched partners.

We find that communication significantly reduces strategic delay in adoption timings when there are 2 players, but does so insignificantly when there are 4 players. For groups of 2 players, the average adoption delay decreases from 38.43 to 25.38 with the introduction of communication (with a p-value of 0.0025). We find that communication opportunity mitigates strategic delay in two ways, through coordination at asymmetric equilibrium without communication taking place and coordinating on earlier adoption timings through with communication taking place. Around half of the subjects in the communication treatment opt-out for communication. In such pairs, we observe that the subject opting-out of communication decides on significantly higher adoption times than those who are willing to communicate. These pairs coordinate on the asymmetric equilibrium of pioneers and free-riders. The remaining half of our pairs make use of the communication opportunity and 80% of those pairs coordinate on almost immediate adoptions. The pairs failing to coordinate still decide on earlier adoption times in comparison to no communication treatment.

For groups of 4, we find that the communication reduces the strategic delay in adoption times from 18.15 to 17.60 where the difference is insignificant (with a p-value of 1.00). We show that the interaction of experience and communication availability hidden at the aggregate level is responsible for this result. In the first half of our experiment, when subjects have no or very little experience, communication significantly reduces investment times from 24.54 to 16.58 (with a p-value of 0.09). If we restrict our attention to the second half of the experiment, however, the difference between the two treatments disappears. We attribute this result to the fact that almost half of the groups undertaking communication fail to coordinate on a group adoption time. In this case, subjects choose their adoption times individually where we observe higher levels of free-riding. More interestingly, we find that subjects failing to coordinate on a group adoption time in a communication stage choose significantly later adoption times than those in the no communication treatment. The failure of coordination after a communication takes place sweeps away the potential beneficial effect of communication. The latter finding squares well with the earlier-reported experimental evidence on the effect of group size on coordination (see, for example, Huck et al. (2004)).

The remainder of our paper is organized as follows. In Section 2 we develop our model and present theoretical predictions. In Section 3 we present our experimental design. In Section 4 we report our experimental results. Section 5 offers a concluding discussion.

II. The Model and Theoretical Predictions

We model new technology adoption as a risky investment game, where players are choosing investment times. Consider n risk-neutral players labeled $i = 1, \dots, n$. We first consider our baseline game and then the communication game, which we refer to as the "cartel" game. In the baseline game, each player i decides, independently of the other players, at what time $t_i \in [0, \infty)$ to invest, if she invests at all. The decision not to invest is marked by $t_i = \infty$. In other words, each player's strategy set is $[0, \infty]$. A player's utility only depends on the delay, i.e., on $t_{min} \equiv \min_{i=1,\dots,n} t_i$. The expected utility of player i equals

$$u_i(t_i, t_{min}) = \begin{cases} B(t_{min}) - C(t_{min}) & \text{if } t_i = t_{min} \\ B(t_{min}) & \text{if } t_i > t_{min} \end{cases}$$

where $B(t_{min})$ denotes the expected benefits if investment takes place at a time t_{min} and $C(t_{min})$ is the expected cost of a player who chooses the lowest investment time. Let $\bar{t} \equiv min\{t: B(t) = 0\}$. We assume that B is differentiable over the domain $[0, \bar{t})$ with $B(0) = 1$, $B'(t) < 0$ for all $t \in [0, \infty)$. The costs are assumed to be proportional to the benefits, i.e., $C(t) = \alpha B(t)$ for some $\alpha \in (0,1)$.[1]

[1] Weesie (1993) assumes that costs are time invariant.

All agents benefit equally from the lessons from an experiment run by any of the companies. Additional experiments have zero value-added. Only the agent running the first experiment incurs the costs of the experiment. Benefits are declining over time because the longer it takes for the adoption to take place, the less time the agent can enjoy its fruits. For instance, if the per period expected benefits equal b, the discounted benefits when the experiment is run at time t equals $B(t) = b\int_t^{\infty} e^{-\delta}\ d\tau = \delta b e^{-\delta t}$. Similarly, if the experiment costs c, the discounted costs when the experiment is run at time t is equal to $C(t) = ce^{-\delta t}$. Notice that $C(t)$ is indeed proportional to $B(t)$.

As the game is perfectly symmetric, we focus on symmetric equilibria. It is readily verified that a symmetric Nash equilibrium in pure strategies does not exist. Now, consider a symmetric mixed strategy in which a player invests at or before time t according to atomless probability function $F(t)$. To establish the equilibrium mixed strategy, assume that all players but player 1 play according to F. Let $G(t) \equiv 1 - ((1 - F(t))^{n-1}$ denote distribution of the time that the first among the other players invests, where $g(t) \equiv G'(t)$. Player 1's expected utility when choosing time t equals

$$U(t) = \big(1 - G(t)\big)\big(B(t) - C(t)\big) + \int_0^t B(\tau)dG(\tau)$$

$$= (1-\alpha)\big(1 - G(t)\big)B(t) + \int_0^t B(\tau)dG(\tau).$$

The first [second] term on the RHS refers to the event that player 1 is [not] the first to invest. In equilibrium, $U'(t) = 0$, which implies that

$$(1-\alpha)\big(1 - G(t)\big)B'(t) + \alpha g(t)B(t) = 0.$$

This differential equation has a unique solution:

$$G(t) = 1 - B(t)^{\frac{1-\alpha}{\alpha}}.$$

The resulting mixed strategy equilibrium is defined by

$$F(t) = 1 - \big(1 - G(t)\big)^{\frac{1}{n-1}} = 1 - B(t)^{\frac{1-\alpha}{\alpha(n-1)}}.$$

Notice that $\lim_{t\to\bar{t}} F(t) = 1$, which implies that the probability that none of the players invests equals zero.

Example 1 *If* $n = 2$, $B(t) = max\{0,1-t\}$, *and* $\alpha = 1/2$, *then* $F(t) = t$. *In other words, both players draw the time that they invest from a uniform distribution on the interval [0,1]. The expected delay is 1/3.*

What is the effect of increasing the number of players on the expected investment delay? Note that the distribution of investment time is:

$$H(t) = P\{t_{min} \leq t\} = 1 - \left(1 - F(t)\right)^n = 1 - B(t)^{\frac{1-\alpha}{\alpha}\frac{n}{n-1}},$$

which is decreasing in n. In other words, investment time in the case of n players first-order stochastically dominates investment time in the case of $n + 1$ players. This implies that as the number of players increases, the expected investment delay increases.

Example 2 *If* $B(t) = max\{0,1-t\}$ *and* $\alpha = 1/2$,

$$H(t) = 1 - (1-t)^{\frac{n}{n-1}}.$$

The expected delay equals

$$E\{t_{min}\} = \int_0^1 t dH(t) = \int_0^1 (1 - H(t))dt = \int_0^1 (1-t)^{\frac{n}{n-1}} dt = \frac{n-1}{2n-1}.$$

In the cartel game of our volunteer's timing dilemma, the players can form a cartel before making an investment decision. More precisely, they interact in the following two-stage game:

The players decide independently whether or not they want to be part of a cartel. We write $K_i = 1$ if player i joins the cartel and $K_i = 0$ if she does not join.

Both the cartel and the players outside the cartel independently decide at what time to invest, if investing at all.[2] Let t_K denote the time the cartel invests and let $t_i = t_K$ if $K_i = 1$.

Analogously to the baseline game, the delay is given by $t_{min} \equiv \min\left\{\min_{i:K_i=0} t_i \,, t_K\right\}$. The payoffs are as follows.

$$u_i(t_i, t_{min}) = \begin{cases} B(t_{min}) - C(t_{min}) & \text{if } t_i = t_{min} \text{ and } K_i = 0 \\ B(t_{min}) - C(t_{min})/k & \text{if } t_i = t_{min} \text{ and } K_i = 1 \\ B(t_{min}) & \text{if } t_i > t_{min} \end{cases}$$

[2] We do not model how the cartel members coordinate on when to invest. They might do so by majority voting or randomly assigning a dictator among themselves who decides on their behalf. As long as all cartel members share the investment costs equally, the coordination device is not relevant for the equilibrium analysis.

where k is the number of players in the cartel, i.e., $k \equiv \#\{i: K_i = 1\}$.

It is easy to see that the resulting game has multiple equilibria. Let us focus for the moment on equilibria in which $t_K = 0$ and $t_i = \bar{t}$ for all i for whom $K_i = 0$, i.e., the cartel invests at time zero, and players outside the cartel never invest. The following result establishes that only one-player cartels can emerge in equilibrium.

Proposition 1 *Suppose in stage 2 of the cartel game,* $t_K = 0$ *and* $t_i = \bar{t}$ *for all* $i: K_i = 0$*. Then, there is no pure-strategy equilibrium in which more than one player joins the cartel.*

The proof is simple. If at least one of the other players joins the cartel, the expected payoffs of a player entering a cartel are equal to $B(0) - C(0)/k$ while not entering yields $B(0) > B(0) - C(0)/k$. Clearly, any cartel will collapse because players that do not join the cartel can free ride on the cartel members' decision to invest at time 0.

Notice that a two-player cartel can emerge in equilibrium if the players play the symmetric Nash equilibrium of the baseline game in case only one player enters the cartel. Because of the mixed strategy equilibrium, in the symmetric Nash equilibrium, all players are indifferent about the investment time, including investing at time 0. Therefore, a player's expected payoffs are $B(0) - C(0)$, which is less than $B(0) - C(0)/2$, i.e., a player's expected pay-off in a two-person cartel that invests at time 0.

Example 2 For $n = 2$, the cartel game has a symmetric equilibrium in which both players join the communication group with probability 1 and invest at time 0.

For $n > 2$, it might be hard for players to coordinate on such equilibria, because of their asymmetric nature. Let us, therefore, focus on symmetric mixed-strategy equilibria in which all players join the cartel with some probability p. Suppose that cartels consisting of at least two players invest at time 0 while players outside the cartel never invest and that players play the symmetric Nash equilibrium of the baseline game if one or zero players join the cartel. Let $p_k \equiv \binom{n-1}{k} p^k (1-p)^{n-1-k}$ represent that the probability that k players other than player 1 join the cartel. The equilibrium condition is:

$$B(0) - \sum_{k=1}^{n-1} p_k \frac{C(0)}{k+1} - p_0 C(0) = B(0) - (p_0 + p_1) C(0)$$

The left-hand [right-hand] side represents player 1's expected payoffs when [not] joining the cartel. This condition can be rewritten as

$$\sum_{k=1}^{n-1} \frac{p_k}{(k+1)} = p_1$$

$$\Leftrightarrow \sum_{k=2}^{n-1} \frac{\binom{n-1}{k} p^k (1-p)^{n-1-k}}{(k+1)} = \frac{p_1}{2}$$

$$\Leftrightarrow \frac{1}{np} \sum_{j=3}^{n} \binom{n}{j} p^j (1-p)^{n-j} = \frac{n-1}{2} p(1-p)^{n-2}$$

$$\Leftrightarrow 1 - \sum_{j=0}^{2} \binom{n}{j} p^j (1-p)^{n-j} = \frac{n(n-1)}{2} p^2 (1-p)^{n-2}$$

We call a cartel effective if at least two players join because then investment takes place at $t = 0$, which is efficient. As the example below shows, this equation may have an interior solution $0 < p < 1$ so that an effective cartel emerges in equilibrium with positive probability.

Example 4 *If* $n = 4$*, the cartel game has a symmetric mixed-strategy equilibrium in which each firm joins the cartel with probability* $\frac{8-\sqrt{10}}{9} \approx 0.538$*. An effective cartel (a cartel with at least two players) emerges in equilibrium with approximately 0.742 probability.*

III. Experimental Design

We run a lab experiment, where we employ a two-by-two design: (i) varying the availability of communication: *COMM* and *NO COMM* treatments, (ii) varying the group size: with $n = 2$ agents and $n = 4$ agents. In the *NO COMM* treatment, subjects play the baseline game while in *COMM* treatment they play the communication stage where subjects can choose to freely chat before the decision stage. This gives us the following four treatments:

- *COMM* with $n = 2$ agents
- *COMM* with $n = 4$ agents
- *NO COMM* with $n = 2$ agents
- *No COMM* with $n = 4$ agents

In the baseline game, players choose their investment times for adopting new technology, a number t_i from the interval $[0,100]$. 0 and 100, where 0 means immediate investment while 100 means no investment. The investment is a risky one and will succeed or fail with 50-50 probability. The benefit of the investment will be 100 minus the earliest time of investment when the project is successful (with probability $p = 0{,}5$), and the benefit will be 0 when the project fails (with probability $1 - p = 0{,}5$). The subject with the smallest delay (i.e. the earliest investment time) among his matched players, makes the irreversible investment. The benefit of the investment only depends on this delay and given by $B(t_{min}) = 100 - t_{min}$. Each subject in the same group enjoys the same benefit irrespective of investing himself, namely the benefit of the information. The subject who invests the earliest bears the cost of investment given by $C(t_{min}) = \frac{1}{2}B(t_{min}) = \frac{1}{2}(100 - t_{min})$.[3]

The payoff function of a subject i choosing time t_i has the following form:

$$u_i(t_i, t_{min}) = \begin{cases} (100 - t_{min}) - \dfrac{100 - t_{min}}{2} & if\ t_i = t_{min}, \\ (100 - t_{min}) & if\ t_i > t_{min}. \end{cases}$$

In the communication treatment, we add a pre-communication stage before the baseline game. In this stage, subjects simultaneously choose whether they want to be engaged in free communication with others before the investment game starts. Those who agree to communicate are forwarded to a chat screen. Those subjects who did not prefer to engage in communication with others are directly forwarded to the investment game, namely the baseline game.

Once subjects agreeing to communicate are forwarded to the communication stage, they first make an initial suggestion for the investment decision. This suggestion is not binding, but suggestive to initiate the discussion in the chat stage. After this screen, they are forwarded to the chat screen, where they have a minute free form of chat. Subjects can leave the chat screen at any point in time, and this information is shared with the remaining subjects in the chat room. After the time finishes, subjects are back on the decision screen, where they are asked to enter

[3] Note that these benefit and cost functions are simple linear approximations to the benefit (i.e., the discounted value of the benefit of the new technology) and cost (i.e., the discounted value of the cost of the irreversible investment) functions we discussed in the model section.

an investment time. If the decision times of subjects who communicated do not match, they receive a message communicating this information and are asked to enter their individual decision times.

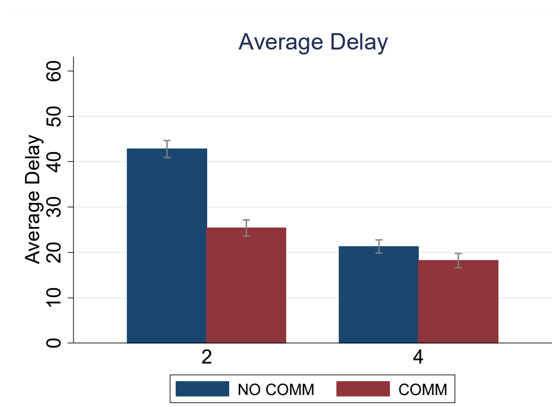
In both treatments, subjects play the corresponding game 20 times, respectively in groups of n = 2 and n = 4. Each repetition is called a round. After each round of play, subjects were informed about the choices of matched participants, the payoffs of their own and matched player, i.e., realized benefits and costs, and whether the investment return was good or bad. In each round, subjects are re-matched randomly with each other to avoid reputation building. Earnings at the end of the experiment is the sum of payoffs earned from each repetition of the stage game and is converted to cash at a rate of 120 points= 1 euros. In total, we have 160 subjects and 10 sessions.

IV. Results

We first present our data in terms of the strategic delay in adoption times. Figure 1 illustrates the average strategic delays for our treatments. Our main result is that communication helps to strategic delay in all of our treatments. Communication reduces delays on average around 40% for $n = 2$ with a p-value of 0.0015, and around 15% for $n = 4$ with a p-value of 0.50. The aggregate data support our prediction that communication facilitates earlier adoption times.

Table 1 provides statistical details for all periods combined, and separately for the first half, the second half, the first quarter, the last quarter, and the first and final periods of the experiment. The p-values reported in the table correspond to Mann-Whitney U test statistics of

Figure 1: Average Delay Across Treatments



Notes: *Error bars represent one-tailed confidence intervals at 95% level.*

the null hypothesis that the average delay is the same in COMM and NO COMM. The null hypothesis is overall rejected in favor of the alternative hypothesis that the delay in investments is significantly lower in the presence of communication when $n = 2$ and only for the first periods when it comes to groups with $n = 4$ subjects.

Table 1: The Effect of Communication on Average Delay

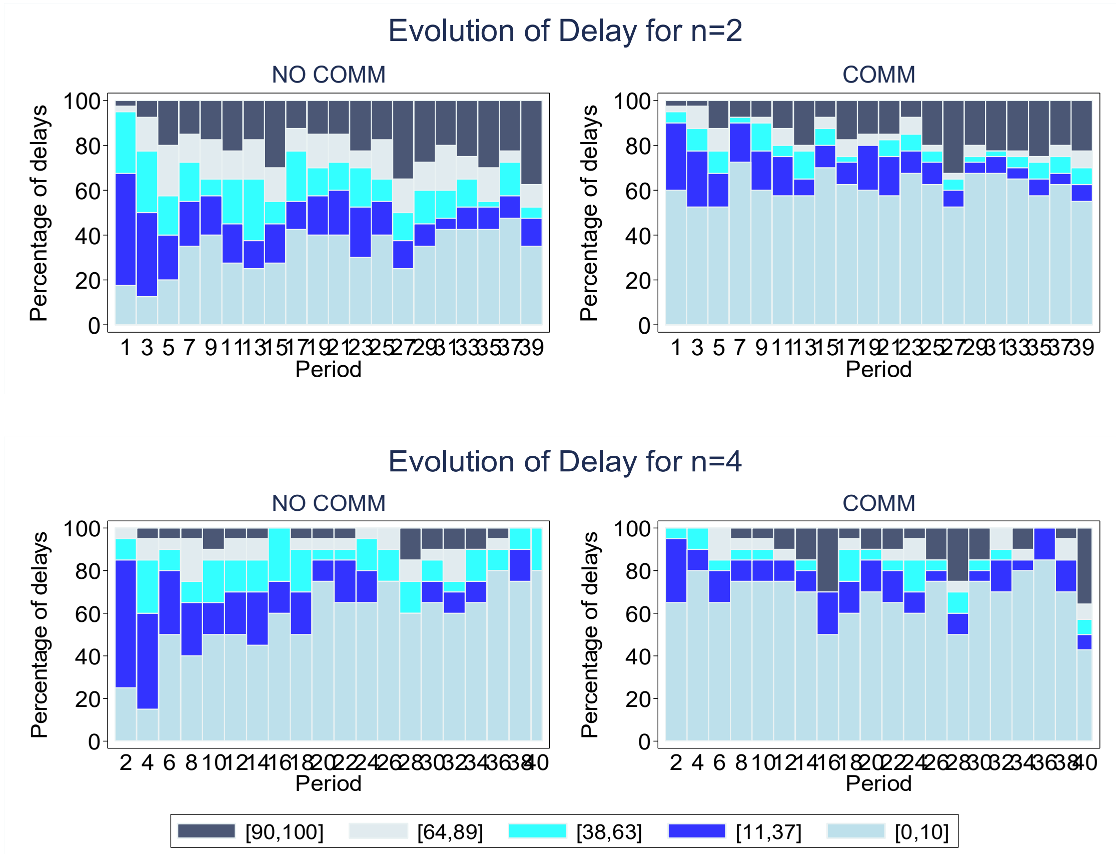
	Group Size 2			Group Size 4		
Periods	COMM	NO COMM	p-values	COMM	NO COMM	p-values
All	25.38	42.80	0.0015	18.15	21.23	0.4963
1st period	14.13	29.85	0.0025	9.5	22.35	0.0441
1st half	22.18	41.92	0.0032	16.58	24.54	0.0963
2nd half	28.58	43.68	0.0041	19.76	17.84	0.7055
Last period	34.32	50.58	0.0587	16.65	9.5	0.7545
N	10	10		10	10	

Notes*: This table shows the average delays for each treatment, where p-values correspond to Mann Whitney U Test statistics of the null hypothesis that the average delay is the same across COMM and NO COMM treatments.*

To unfold the effects of experience on behavior, we present the distribution of average delays for our treatments over time in Figure 2. In doing so, we present the distribution of average delays in five categories: (i) when the delay is smaller than 10 (including immediate investment) (ii) when the delay is larger than 90 (including no investment) (iii) when the delay is relatively large, between 64 and 80, (iv) when the delay is relatively small between 11 nand 37 and (v) for the intermediate values from 38 to 63. The upper panel shows the evolution of the distribution respectively for NO COMM and COMM treatments for n=2, while the lower panel shows the comparison of NO COMM and COMM for n=4.

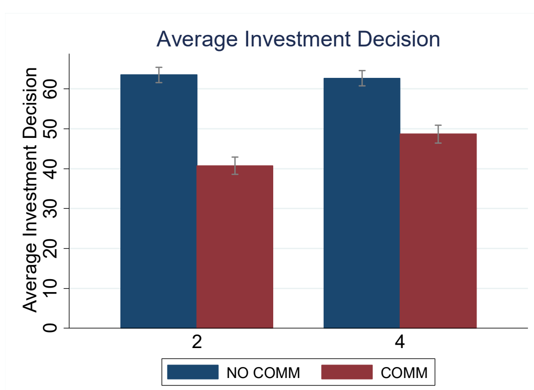
Figure 2 shows that the behavior becomes bimodal during the course of our experiment, namely the average strategic delay either becomes very small or very large towards the end of our experiment. It also suggests that in the COMM treatment behavior changes more in the first half while in NO COMM it changes more in the second half of our experiment. To illustrate this better, Figure 3 depicts the average strategic delay for the first and the second half of our experiment. We see that the efficacy of communication decreases from the first half to the second for both $n = 2$ and $n = 4$ groups, while the decrease is quite dramatic for the

Figure 2: Evolution of Delays



***Notes**: This figure shows the evolution of the average delays categorized in five groups for* $n = 2$ *in the upper panel and* $n = 4$ *in the lower panel.*

Figure 3: Average Adoption Timings Across Treatments



Notes: Error bars represent one-tailed confidence intervals at 95% level.

Table 2: The Effect Group size on Adoption Timings in NOCOMM

Variables	(1)	(2)	(3)	(4)
dummyGS	-0. 7789 (1.4789)	3.3267** (1.6590)	3.6691** (1.8023)	1.502 (1.3506)
Round		0.5333* (0.3672)	0. 2846 (0. 2607)	
dummyGS xRound		-0. 4105 *** (0.1505)	-0. 2071 (0. 1398)	
Delayy_{t-1}			0.1331*** (0.0181)	0. 1335*** (0.0181)
Constant	63.2618 *** (2.6400)	54.6050*** (5.3073)	55.4627 *** (4.5018)	58.4343*** (2.5202)
Observations	3,040	3,040	2,880	2,880

Notes: *This table report results from mixed-effect regression with standard errors (in parenthesis) clustered at both individual and matching group level. *** (**) [*] indicate that the estimated coefficient is significant at the 1% (5%) [10%] level. The dependent variable is adoption timings in all specifications.*

latter group. To be able to unfold the behavior further, we turn our attention to individual adoption timings. Figure 3 below depicts the average adoption timings for the four treatments we have. First, to further explore the differences between NOCOMM2 and NOCOMM4, we estimate the effect of groupsize on adoption timings in Table 2. The econometric analysis is based on mixed-effect model regressions that capture the dependency among data points via random-effects parameters. Standard errors are corrected for clustering at the matching group level. The regression results confirm what is visualized in Figure 3. As shown in column (1) of Table 2, the groupsize difference in the NO COMM treatment is very small in size (-0.7789) and not statistically significant. Controlling for the round and the interaction between the groupsize and round changes this result: the average adoption timings in groupsize of 4 is 3.3267 points higher and the difference is statistically significant at 5% level (column (2)). This tells us that mask the difference between NO COMM 2 and NO COMM 4. Controlling for the strategic delay in the previous round does not change this result (column (3) and (4)).

Table 3: The Effect Communication on Adoption Timings

	Groupsize 2		Groupsize 4	
Variables	(1)	(2)	(3)	(4)
COMM	-23.0138*** (3.6285)	-25.2975*** (6.0627)	-14.5052** (5.8290)	-21.2644*** (7.0122)
Round		0. 5330** (0. 2706)		0.1224 (0.2482)
COMM xRound		0.2283 (0.4377)		0.6759 (0. 4266)
Constant	63.2618*** (2.5687)	57.9897*** (4.3971)	62.4828*** (3.2975)	61.2585*** (4.3352)
Observations	3,040	3,040	3,040	3,040

Notes: *This table report results from mixed-effect regression with standard errors (in parenthesis) clustered at both individual and matching group level. *** (**) [*] indicate that the estimated coefficient is significant at the 1% (5%) [10%] level. The dependent variable is adoption timings in all specifications.*

Now we elaborate on how communication affects adoption timings separately for $n = 2$ and $n = 4$. To formally quantify treatment differences, and to test their statistical significance, we estimate the effect of communication availability on adoption timings by regressing the individual timings on a treatment dummy. The econometric analysis is based on mixed-effect model regressions that capture the dependency among data points via random-effects parameters. Standard errors are corrected for clustering at the matching group level. Results are based on the number of players in the group, $n = 2$ for columns (1) and (2) and $n = 4$ for columns (3) and (4). The regression results confirm what is visualized in Figure 3. When $n = 2$, the adoption timings with COMM is estimated to be 23.01 points lower than with NO COMM, and the treatment effect is significant at the 1% level. The effect gets larger when we control for the time trend. When $n = 4$, the adoption timings with COMM is estimated to be 14.50 points lower than with COMM, where the treatment effect is significant at 5% level. The average adoption timing in COMM is estimated to be 21.26 points lower than in NO COMM when we control for round and the interaction between round and treatment, and the treatment effect becomes significant at the 1% level. This suggests that the behavior is changing over time in $COMM$ 4 treatment in a way different than in $COMM$ 2 treatment. To unpack these results further, we investigate how communication groups are formed and whether and how they affected individual adoption timings in the next section.

Behavior in the COMMUNICATION Treatment

In this section, we unpack the behavior in the COMM treatments further. In the COMM treatments, three possible scenarios are happening: (i) groups in which no communication happened (at most one group member agreed to chat), (ii) groups in which communication happened (at least two group members agreed to chat) and an agreement about a common investment time is reached and (iii) groups in which communication happened but an agreement about a common investment time is not reached. Table 2 provides a summary of how often these groups emerge when n=2 and n=4 respectively. For the ease of representation, we call the members who agreed to communicate as cartels. Note that, the only possible cartel size is 2 in the n=2 treatment, while cartel sizes of 2, 3, and 4 are possible in the n=4 treatment.

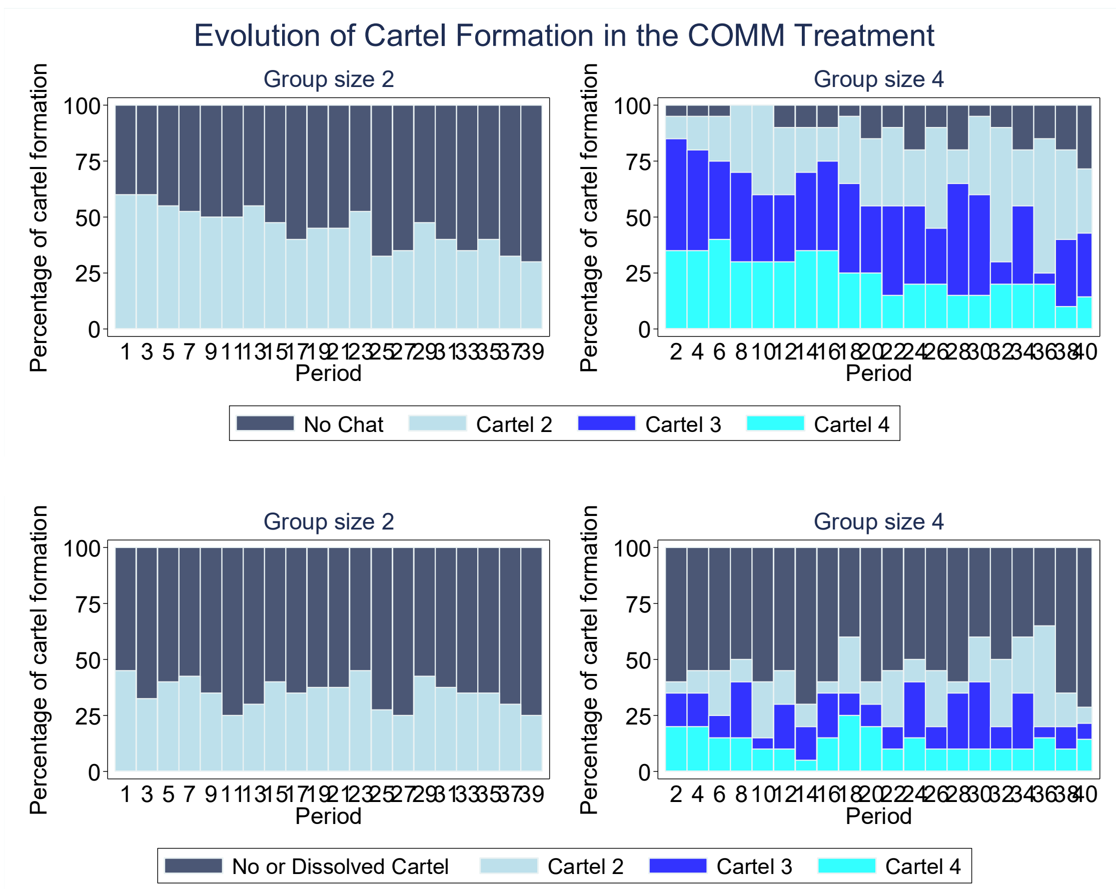
Table 3: Ratios of Cartel Occurrences in the COMM Treatment

	n=2	n=4	n=4 Cartel size 2	Cartel size 3	Cartel size 4
Cartels Formed	45%	89%			
Cartels Dissolved	10%	43%	39%	49%	40%
# Observation	800	394	120	134	97

Notes: *This table summarizes the ratio of formed and dissolved cartels (i.e. communication groups).*

We find that when n=2, only 45% of the time subjects agreed to established communication, while 55% of the time subjects opt-out of communication opportunity. When communication takes place, 90% of the time an agreement on common investment time is reached, while 10% of the time such an agreement failed. Communication is established more often with n=4, namely 89% of the times at least two subjects agreed to communicate, while 11% of the times no more than one subject agreed to communicate. Only 47% of those groups where communication took place reached an agreement on common investment times.

Figure 4: Successful and Unsuccessful Cartels



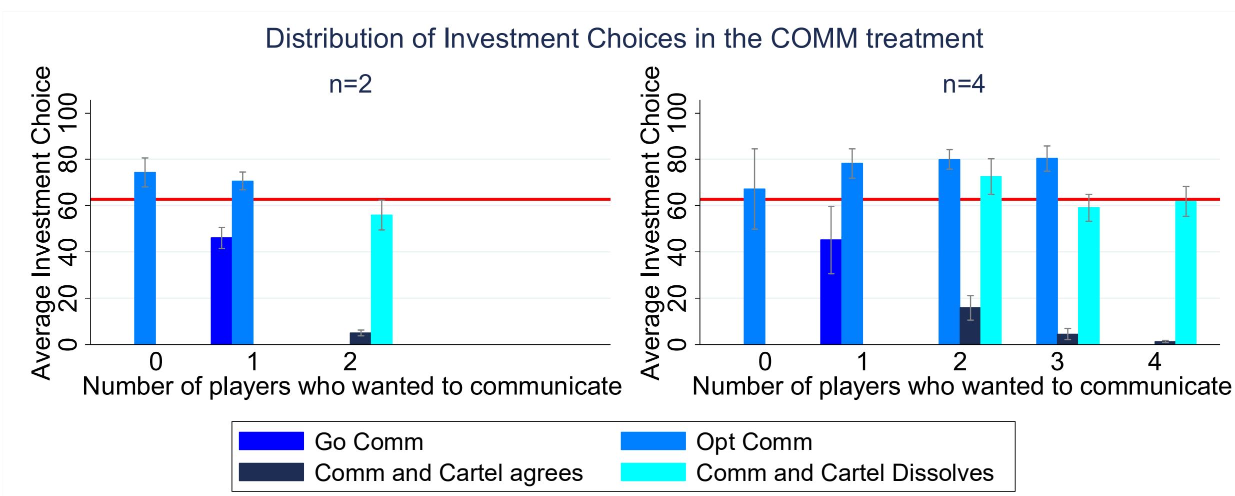
Notes*: This figure shows the evolution of the cartel formation for* $n = 2$ *on the left- and for* $n = 4$ *on the right-hand side panel.*

Figure 4 illustrates the distribution of cartels of different sizes across periods for both n=2 on the left-hand panel and n=4 on the right-hand panel. The left-upper panel of Figure 6 shows that, when n=2, the ratio of groups where communication took place is around 60% in the first period, while it drops over periods and reaches 30% in the last period. Comparing the upper- and lower-left panels, when n=2, more cartels dissolve in the first half of the experiment in comparison to the second half. For n=4, comparing the upper- and lower right panels, around half of the cartels dissolve both in the first and the second half of the experiment.

Next, we focus on (i) how the choice to opt for or go for communication affects the choices for investment times and (ii) how does an agreement or a disagreement after the communication stage takes place affects the choices for investment times.

Figure 5 depicts the average investment times of groups with n=2 on the left and with n=4 on the right-hand side. In this figure, we categorized groups according to the number of subjects who had chosen to communicate, on the left-hand side from 0 to 2, and on the right-hand side from 0 to 4. In each category, we depict the average investment time choice for those who had chosen to communicate and those who opt from communication. Further, if communication took place, we divide the subjects who had chosen to communicate according to whether they agreed on a common investment time following the communication stage. In both figures, the red line corresponds to the average investment time choice in the NO COMM treatment.

Figure 5: Average Investment Times depending on Choosing to Chat or Not



Notes*: This figure shows the average adoption timings depending on the number of players who wanted to communicate and whether the cartel agrees or dissolves.*

We observe that the average investment times with NO COMM treatment very similar for n=2 and n=4 treatments, it is 62.65 when n=2 and 63.50 when n=4. Subjects choosing not to communicate submit significantly higher investment times than the ones choosing to communicate. In the markets where only one player had chosen to communicate and the one(s) not, the average investment times for the subjects who wanted to communicate is 46.02 when n=2 and 45.13 when n=4, while the same average for those who opt for communication is 74.37 when n=2 and 78.23 when n=4. The average choice of subjects who opt for communication is always higher than the average in NO COMM treatment for both n=2 and n=4.

Table 4: Regression Results on Earnings for COMM Treatment

Variables	(0)	(1)	(2)	(3)	(4)	(5)
ChatDecision	0 .3266	-10.8155***	-7.5406***	-18.3558***	-5.3808***	-5.9222***
	(1.959)	(1.2476)	(1.4117)	(3.3189)	(0.9591)	(0.7381)
Dummy4			22.3882***		17.2760***	
			(5.5643)		(4.5724)	
Constant	34.0579***	27.3038***	22.019***	46.3160***	29.0399***	56.8447***
	(0.0000)	(2.1747)	(1.9422)	(4.0462)	(2.4436)	(4.3994)
Observations	3,176	890	890	1,204	1,204	536

Notes: *This table report results from linear regression with standard errors (in parenthesis) clustered at the individual level. *** (**) [*] indicate that the estimated coefficient is significant at the 1% (5%) [10%] level. The dependent variable is a subject's earnings in all specifications. Specifications (1) and (2) are based on data when only one player wants to chat while the others do not, while (3) and (4) are based on data when two players chat, (5) is based on when three players chat. Specification (0) is based on all data from the COMM treatment. The Variable ChatDecision is a dummy variable that is defined to be 1 when the subject chooses to chat and 0 otherwise.*

Looking into the cases where communication took place, an important determinant of decision is whether an agreement is reached or not. When an agreement is reached among subjects who communicated, the average investment time is significantly dropping, to 4.94 in n=2 and 15.78, 4.48, and 1.22 when n=4 respectively for communication group sizes of 2, 3, and 4. Those subjects who could not manage to agree in the communication stage choose much higher investment times, mainly around 70 on average in both n=2 and n=4 treatments.

Next, we look into how behavior changes when subjects fail to coordinate on a common investment time after the communication stage. Note that, after the communication stage subjects who had been chatting submit their decisions, call this initial decision. If all the submitted initial decisions are the same game ends. If not, namely when one or more subjects do not agree with the rest of the communication group, all subjects are informed that they failed to enter the same investment time. In this case, subjects are asked to submit their individual investment times, call this final decision, as if there were no communication stage.

To study the behavior after an agreement failure, we look at the difference between the initial decision and the final decision of subjects who failed to agree after the communication stage. It turns out that initial and final decisions are the same for 52% of those subjects, while 44% of the subjects submitted a higher final decision than their initial decisions. Out of this 52%, 35% has investment time choices less than 10, while 49 has more than 90.

Lastly, we investigate whether the choices to communicate or not serve as strategic signaling and affect the earnings of subjects. To so do we estimate the effect of chat decision on earnings in the communication treatment. We control for the group size, by adding a dummy variable called Dummy 4, which is 1 for a group size of 4 and 0 for a group size of 2. We find that the earnings of players committing to chat while other group members opting-out are 10 points less than their group members, which is significant at the 1% level. This result is in line with our argument that subjects used opting out of chat as a signaling mechanism to signal "hard to play with". These subjects also submitted significantly higher investment times than those who committed to chat.

V. Conclusion

Innovation is at the core of growth and welfare, however, empirical literature documents that consumers and firms have been slow in adopting new technologies. The take-up speed is at a slower pace than the technological progress justifies, affecting growth negatively. One of the critical determinants of adoption decisions is the uncertainty about the returns to the adoption investment. Agents can resolve this uncertainty at no cost by strategically delaying their investments and observing the experience of early adopters. These informational externalities create free-riding incentives, one of the drivers of late adoption times. In this paper, we investigate a potential remedy for the slow take-up of innovation: communication as a coordination device among agents to facilitate the early adoption of new technologies.

We model innovation adoption as a risky investment game. Agents undertaking the innovation adoption face uncertain returns to this investment. The innovation is of good quality with a commonly known probability of p and is of bad quality with probability $1-p$. If the technology is of good quality, an agent investing in this technology receives a positive return, however, if it is of bad quality he will make a loss, with a positive expected payoff in total. Agents decide on the timing of their adoption investments. The agent making the first adoption incurs the costs of experimenting with the new technology, while the lessons from this experiment become public information (i.e. all agents learn whether the new technology is of good or bad quality). A single agent undertaking the investment is sufficient to uncover the uncertainty on returns, i.e., additional experiments bring no added value.

To this baseline game, we introduce a pre-communication stage. In this pre-communication stage, each agent decides whether or not they prefer to communicate with the others. Following this communication stage, agents choose their adoption timings as in the baseline game. If agents succeed to coordinate on a group adoption time, they adopt the technology at the same time and share the costs equally.

We theoretically characterize the equilibria in our game. We show that there are multiple equilibria in both the baseline and the communication games, of both symmetric and asymmetric nature. The asymmetric equilibria correspond to the situation of pioneers and free-riders. There are no symmetric equilibria in pure strategies. We show that in the symmetric mixed strategy equilibrium, the delay in adoption timing depends on and is increasing in the number of agents. We show that communication opportunity reduces the strategic delay in adoption timings.

Our main experimental result is that the availability of communication reduces the strategic delay in adoption times. We find that around half of the subjects in our $n=2$ treatment opt-out for communication, coordinating on the asymmetric equilibrium of pioneers and free-riders. The remaining half of our pairs make use of the communication opportunity, around 80% of which coordinate on almost immediate adoptions.

Communication reduces the strategic delay in adoption times when there are 4 players but does so insignificantly at the aggregate. We show that the interaction of experience and communication availability hidden at the aggregate level is responsible for this result. In the first half of our experiment, communication significantly reduces strategic delay in adoption times, however, the difference between the two treatments disappears if we restrict our attention to the second half of the experiment. We attribute this result to the fact that almost half of the groups undertaking communication fail to coordinate on a group adoption time. More interestingly, we find that subjects failing to coordinate on a group adoption time in a communication stage choose significantly later adoption times than those in the no communication treatment. The failure of coordination after a communication stage sweeps away the potential beneficial effect of communication.

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VI. APPENDIX

A. INSTRUCTIONS

COMMUNICATION TREATMENT

You are participating in an experiment on decision making. You are not allowed to talk or try to communicate with other participants during the experiment. If you have a question, please raise your hand.

Description of the Experiment

In this experiment you will be asked to make decisions in 40 periods. In each period, you will be randomly matched with (an)other participant(s): in odd periods you will be matched with 1 other participant so that you are in a group of 2. In even periods you will be matched with 3 other participant so that you are in a group of 4. The identity of the other participants you will be matched with will be unknown to you.

In each period, you and the other member(s) in your group (referred to as the "others") will be asked to decide at what time to make a costly investment. The time of investment can be any integer number between 0 and 100, where 0 means an immediate investment and 100 means no investment. You will take your decisions without seeing the decisions of others in your group.

The return to the costly investment will depend on the time of the earliest investment in your group and whether the investment succeeds or fails. The investment will succeed with probability 50% and fail with probability 50%. The computer will randomly determine whether the investment succeeds or fails. If the investment succeeds, the return to it will be

100 minus the *earliest investment time* in your group. If the investment fails, the return to it will be 0. All members of the group will *equally* benefit from the return of this investment. No additional return is accrued if two or more group members make the costly investment.

The group member with the *earliest* investment time will pay the cost of investment, which is 25 minus a quarter of his/her investment time, while all others will not bear any cost of investment. If there are more than one group member with the earliest time, they will share the cost equally. The cost of investment is the same whether the investment succeeds or fails.

For example, suppose that in a group of 4, the group members choose the following investment times: 20, 16, 53 and 98. The earliest investment time, chosen by the second group member, is equal to 16. As a result, the return to each group member will be $100 - 16 = 84$ if the investment succeeds or 0 if it fails. The cost of the investment will be $25 - \frac{16}{4} = 21$ and will only be paid by the second group member, irrespective of whether the investment succeeds or fails. In this scenario, the earnings of the group members with the investment times 20, 12, 53, 98 will respectively be 84, 63, 84, 84 if the investment succeeds and 0, -21, 0, 0 if the investment fails.

You can calculate your earnings in more detail for any group investment time choice of yours and your group members by using the EARNINGS CALCULATOR on your screen.

In each period, prior to the described decision situation, you will be asked whether you want to chat with your group members to try to coordinate your investment times. If at least two group members *choose to chat*, then chat will realize among you and the group members who had chosen to chat (referred to as the “chat group”). In this case, everyone in the chat group will first be asked to enter a suggestion for the common investment time. These suggestions will be shown to everyone in the chat group. Then the chat group members can chat with each other for a limited amount of time (3 minutes in rounds 1-5, and 1 minute in rounds 6-40). You may choose to leave the chat screen any time you wish, in which case you will not be able to see the rest of the conversation.

The group members who choose *not to chat* will directly be forwarded to the decision screen and make an individual decision. They will not be shown the suggestions made by the chat group members not any conversation between chat group members.

Once the time for chat is up, everyone in the chat group will automatically be forwarded to the decision screen. In this case, you will be asked to enter an investment time. If you and others in the chat group submits the same investment time and this turns out to be the earliest investment time in your group, then the cost of investment will automatically be shared by the members of your chat group. If at least one person from the chat group submits a different investment time than the rest, an agreement will not be reached among the chat group and all chat group members will be asked to submit their final investment time decisions.

For example, suppose that in a group of 4, three members of the group chooses to chat. The chat group members all submit the same investment time of 16. The fourth player submits investment time 20. Then the return will be 100-16=84 for all the four members if the investment succeeds, and 0 if it fails. The cost of investment will be $25-\frac{16}{4}=21$ and be shared by the three chat-subgroup members. Namely, all the three members who had the chat will pay 7 irrespective of whether the investment succeeds or fails. In this scenario, the earnings of the group members with the investment times 16, 16, 16, 20 will respectively be 77, 77, 77, 84 if the investment succeeds and -7, -7, -7, 0 if the investment fails.

Once everyone in your group submits their decisions, you will be directed to the results page and be provided with the following information on your screen: whether the investment succeeded or no, investment times, and earnings of everyone in your group.

After the 40 rounds, we will ask you to complete a number of additional tasks.

At the end of the experiment, your earnings will be paid in cash by the experimenter. Your total earnings are the sum of your earnings in points over all periods of the experiment (including your earnings from the additional tasks). Your earnings in points will be converted into euros. The exchange rate is €15 for 1000 points.

N0-COMMUNICATION TREATMENT

You are participating in an experiment on decision making. You are not allowed to talk or try to communicate with other participants during the experiment. If you have a question, please raise your hand.

Description of the Experiment

In this experiment you will be asked to make decisions in 40 periods. In each period, you will be randomly matched with (an)other participant(s): in odd periods you will be matched with 1 other participant so that you are in a group of 2. In even periods you will be matched with 3 other participant so that you are in a group of 4. The identity of the other participants you will be matched with will be unknown to you.

In each period, you and the other member(s) in your group (referred to as the "others") will be asked to decide at what time to make a costly investment. The time of investment can be any integer number between 0 and 100, where 0 means an immediate investment and 100 means no investment. You will take your decisions without seeing the decisions of others in your group.

The return to the costly investment will depend on the time of the earliest investment in your group and whether the investment succeeds or fails. The investment will succeed with probability 50% and fail with probability 50%. The computer will randomly determine whether the investment succeeds or fails. If the investment succeeds, the return to it will be 100 minus the *earliest investment time* in your group. If the investment fails, the return to it will be 0. All members of the group will *equally* benefit from the return of this investment. No additional return is accrued if two group members make the costly investment.

The group member with the *earliest* investment time will pay the cost of investment, which is 25 minus a quarter of his/her investment time, while all others will not bear any cost of investment. If there are more than one group member with the earliest time, they will share the cost equally. The cost of investment is the same whether the investment succeeds or fails.

For example, suppose that in a group of 4, the group members choose the following investment times: 20, 16, 53 and 98. The earliest investment time, chosen by the second group member, is equal to 16. As a result, the return to each group member will be $100 - 16 = 84$ if the investment succeeds or 0 if it fails. The cost of the investment will be $25 - \frac{16}{4} = 21$ and will only be paid by the second group member, irrespective of whether the investment succeeds or fails. In this scenario, the earnings of the group members with the investment times 20, 12, 53, 98 will respectively be 84, 63, 84, 84 if the investment succeeds and 0, -21, 0, 0 if the investment fails.

You can calculate your earnings in more detail for any group investment time choice of yours and your group members by using the EARNINGS CALCULATOR on your screen.

Once everyone in your group submits their decisions, you will be directed to the results page and be provided with the following information on your screen: whether the investment succeeded or no, investment times, and earnings of everyone in your group.

After the 40 rounds, we will ask you to complete a number of additional tasks.

At the end of the experiment, your earnings will be paid in cash by the experimenter. Your total earnings are the sum of your earnings in points over all periods of the experiment (including your earnings from the additional tasks). Your earnings in points will be converted into euros. The exchange rate is €15 for 1000 points.