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SUNSPOTS IN GLOBAL GAMES: THEORY AND EXPERIMENT*

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Abstract

We solve and test experimentally a global-games model of speculative attacks where agents can choose whether to read, at a cost, a payoff irrelevant (sunspot) announcement. Assuming that subjects exogenously believe some others to follow sunspots, we provide conditions for a unique equilibrium where agents follow a sunspot announcement depending on the realization of an informative private signal. Although most groups converge to classical global-game strategies that neglect sunspots, we find that about one-third of groups are eventually coordinating on sunspots, which is inconsistent with the standard theory. In line with the assumption of subjects expecting others to follow sunspots, subjects overestimate the number of subjects who follow sunspots by about 100% on average. We conclude that in environments with high strategic uncertainty, payoff irrelevant signals can affect behavior even if they are costly to obtain and not expected to be publicly observed.

(JEL codes: C9, D82, F31, G12)

Keywords: Creditor coordination; Global games Speculative attack; Sunspots.

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1. Introduction

Global games are a selection device in coordination games with strategic complementarities that are used for modeling financial intermediation and bank runs, attacks on pegged currency exchange rates, and investments with external returns to scale. Take, for example, a borrower who has financed an investment with multiple short-term credits. If creditors refuse to roll over their claims, the borrowing costs may rise to the extent that the borrower becomes insolvent, in which case withdrawing credit is the optimal decision. However, the same borrower might be able to serve all debt under its old conditions if creditors extend their maturities, which may leave all of them with higher returns than withdrawing.

Creditors facing a coordination problem when a borrower is in distress may be tempted to follow signals that provide no information about fundamentals affecting payoffs ("sunspots"), fearing similar actions by others. For example, at least 90 percent of foreign exchange dealers rely on technical analysis (Lui & Mole, 1998; Oberlechner, 2001; Taylor & Allen, 1992). Technical analyses of financial markets provide forecasts of asset prices and give trading advice based on the history of price movements but without regard to any underlying economic or fundamental analysis.

Creditors may use sunspot signals to coordinate their decisions of whether to roll over or foreclose the loan, expecting similar strategies by other creditors who are getting the same signals. If the underlying game has multiple equilibria and signals are publicly observed, any mapping from signals into the set of equilibrium strategy combinations of the game without sunspot signals is an equilibrium of the game with such signals. If it assigns different actions for different realizations of the signal, it is called a sunspot equilibrium. Here, the expectation that the signal determines the outcome of the game is self-fulfilling. Such self-fulfilling expectations are akin to those faced by the depositors of a bank that is vulnerable to a run (Diamond & Dybvig, 1983) or by traders in foreign exchange markets who secure their positions against a devaluation and, thereby, create the pressure that may lead to a devaluation (Morris & Shin, 1998). All of these are examples of coordination games with strategic complementarities. The existence of sunspot equilibria raises the question of whether real agents would actually coordinate on following sunspots and under which conditions they might do so.

Public announcements play a key role in coordination games. They may coordinate expectations and thereby stabilize a currency or prevent a bank run, but they may also coordinate expectations on the unfavorable equilibrium that are associated with a devaluation or bank run. Applying global games, Morris & Shin (1998, 2003) show that common knowledge about payoffs is responsible for equilibrium multiplicity. If agents possess sufficiently precise private signals about payoffs, the equilibrium of an otherwise identical game is unique. Consequently, Morris and Shin argue that the mere presence of public signals destabilizes an economy by allowing for self-fulfilling beliefs and reducing the predictability of behavior and final outcome.

The literature on coordination games with strategic complementarities has focused on intrinsic signals that provide information about the fundamentals affecting payoffs. Intrinsic public signals may lead to overreactions that are eventually detrimental to welfare (Morris & Shin, 2002), or even to equilibrium multiplicity, while intrinsic *private* signals stabilize markets and may prevent multiplicity as in a global game (Morris & Shin, 1998, 2003). Extrinsic public signals (sunspots) allow for sunspot equilibria if the respective game without these signals has multiple equilibria. In a global game in which intrinsic private signals guarantee equilibrium uniqueness, sunspot equilibria do not exist (Heinemann & Illing, 2002).

The empirical validity of these results has been tested in various experiments: Cabrales, Nagel, & Armenter, (2007) and Heinemann, Nagel, & Ockenfels (2004) test global-game predictions in binary-action coordination games with public and private signals and show that observed behavior is close to the predictions of the theory of global games. Heinemann et al. (2004) find only small differences in behavior between treatments with public and private signals, which indicates that the theory of global games can also be used as a selection device for games with multiple equilibria. They show that subjects coordinate on threshold strategies such that they choose one action if the public signal is below the threshold and the other action if the public signal is above the threshold. Nevertheless, different groups of agents coordinate on different thresholds that are distributed between the thresholds derived from global-game selection and payoff-dominant equilibrium. Arifovic & Jiang (2014) show that the provision of extrinsic public signals may give rise to sunspot equilibria in those games in which different groups of agents are likely to coordinate on different equilibria. The explanation of the impact of sunspots seems to be subjects' perceived strategic uncertainty. Heinemann, Nagel, & Ockenfels (2009) show that those games in which different groups of agents are likely to arrive at different outcomes are also the games in which subjects are most uncertain about the likely strategies of other agents. The results from Arifovic & Jiang (2014) indicate that if strategic uncertainty is high, salient but fundamentally uninformative public signals can be used as focal points to coordinate expectations and behavior in one or the other action.

Fehr, Heinemann, & Llorente-Saguer (2018) show that sunspot signals may affect behavior, even if the sunspots are not publicly observed and sunspot-driven behavior is not an equilibrium. Their underlying coordination game, however, has a continuum of equilibria, which implies large strategic uncertainty. In financial markets, on the other hand, traders usually possess some private information or idiosyncratic opinions about the shadow value of a currency or about the riskiness of a bank. Such private signals accompany a unique equilibrium in which sunspots should not matter. The potential impact of sunspots under public signals and the similarity of behavior under public and private signals in the absence of sunspots raises the question of whether extrinsic signals may also affect behavior if subjects have intrinsic private information and the game, thus, has a unique equilibrium.

In this paper, we test whether extrinsic signals can also affect behavior if these signals are not public and if the underlying game has a unique equilibrium. To achieve this goal, we use an augmented global game, where players have the option to purchase a payoff-irrelevant public signal, called a sunspot, before they decide whether to invest in the project. We introduce a grain of doubt about the rationality assumption defining Nash equilibria by assuming that each agent behaves as if he or she expects that some of the other agents are naïve followers who always choose to buy the sunspot message and follow the action that it indicates. Our model predicts that (1) agents follow sunspots for some range of intrinsic signals, (2) the set of signals for which subjects follow sunspot messages increases as their private signals become noisier, and (3) agents expect more players to follow sunspots than actually do follow sunspots.

To test our predictions against the standard theory, we use an experiment, similar to those mentioned above, where subjects can decide between two options (A or B) and where the payoff from B depends positively on whether the number of other subjects who choose B exceeds an exogenously given hurdle. Subjects receive either public or private signals about the hurdle for success. After receiving their signals, subjects can individually decide whether to read a sunspot message that says either “Choose A” or “Choose B.” This message is the same for all agents who read it, it is randomly drawn with 50% probability for each of the two texts, and subjects are informed about the random nature of these messages. We introduce a small cost for reading this message so that we can identify subjects who condition their actions on this message. The signals that subjects received about fundamentals were either public (common information treatment) or private, for which we distinguished private signals with low and high noise.

In all treatments, the vast majority of subjects used threshold strategies, i.e., invested for low signals, did not invest for high signals, and eventually followed the sunspot message for intermediate signals without any overlap. In about one-third of the groups, following the sunspot message is eventually the most likely strategy for some range of intermediate signals. Since most groups converge to classical global-game strategies that neglect sunspots, the comparative statics of the sunspot global-game solution with respect to the level of signal precision cannot be confirmed. Consistent with the predictions, however, we find that the set of signals for which subjects may follow sunspot messages gets larger if the precision of private signals decreases, while there is no significant difference between treatments with private signals of high precision and fully informative public signals. Thus, in contrast to the classical global-game prediction, it is not the noise per se but the size of the noise that affects the power of sunspots.

Consistent with our motivation of subjects following sunspots because they fear others will follow the sunspot, we find that subjects expect, on average, twice as many players to follow a sunspot than actually do. We conclude that in environments with high strategic uncertainty, payoff-irrelevant signals can affect behavior even if they are costly to obtain and not expected to be publicly observed.

Section 2 explains the coordination game with sunspots. Section 3 lays out the experimental design and results. Section 4 concludes the paper.

2. Coordination game with sunspots

We investigate a coordination game in which players can choose whether to invest in a project or not. Depending on market fundamentals, the investment only pays off if sufficiently many players invest. This is the standard coordination game introduced by Morris & Shin (2004). In our augmented game, players have the option to purchase a payoff-irrelevant public signal, called a sunspot, before they decide whether to invest in the project. We solve this model for two distinct cases: (A) an infinite number of agents; and, (B) a finite number of agents.

First, we solve this model for the case with an infinite number of agents to compare our results to the theoretical literature on global games. In most of the theoretical literature on global games, it is assumed that there are infinitely many agents. Since we test the predictions of the model in a laboratory experiment, we also provide the solution for a finite number of agents. Thus, we can directly compare the predictions with empirical results from the experiment.

2.1. Infinite number of agents

There is a continuum of infinity many agents indexed by i, who have to decide simultaneously whether to invest in a project or not. The project outcome depends on the proportion of agents who invest, denoted by A and on an exogenous state variable denoted by θ. Investment is successful if $A \geq \theta$, that is, if the proportion of agents who invest is larger than the required threshold. The return of a successful investment for each agent who invests is 1. If the investment is not successful, the payoff from investing is 0. The payoff of not investing is $\lambda \in (0,1)$, and can be regarded as the opportunity cost of investment. The payoffs are summarized in Table 1 .

Table 1 Investment game payoff

	$A \geq \theta$ (Project succeed)	$A < \theta$ (Project fails)
Invest	1	0
Not Invest	λ	λ

Let us now extend this game by introducing a payoff-irrelevant message (sunspot). The sunspot message, s, is a random variable with two possible realizations: $s =$ "*invest*" with probability q and $s =$ "*not invest*" with probability $1 - q$. The sunspot message can only be observed by an agent after paying a cost *c*. Agents who do not purchase the sunspot message will not be informed about its realization. The message will be the same for all agents who purchase it.

Each agent makes two decisions: (1) whether to buy the sunspot message and (2) whether to invest or not. When deciding on their investment, agents do not know the proportion of agents who have bought the sunspot message. Thus, a strategy consists of a decision as to whether to buy the sunspot message and whether to invest (conditional on the sunspot message if it is bought or unconditional if it is not bought). As sunspot messages are salient messages mapping into the second-stage action space ("invest" versus "not invest"), we focus on strategies that follow the sunspot message if it is bought. While theoretically, an agent may buy the sunspot message and then choose the action that is opposed to the sunspot message, this is counter-intuitive and violates previous tests of behavior under payoff-irrelevant messages (see Duffy & Fisher, 2005, or Fehr, Heinemann, & Llorente-Saguer, 2012, for examples). As messages are costly, the strategy to buy the sunspot message and then decide for or against investment, irrespective of the sunspot message's content, is dominated by not buying the sunspot message.

This leaves us with three strategies that an agent may choose in the first stage of the game: In addition to "invest" and "not invest," independently of the sunspot realization, the agent may choose "follow," where she follows the recommendation of the sunspot message. If an agent chooses to follow, she pays a cost of c, invests if $s = "invest$," and does not invest if $s = "not\ invest$."

2.1.1. Common information game

If the state of the economy θ is common information, the game has a unique equilibrium or multiple symmetric pure-strategy Nash equilibria, depending on the value of θ:

If $\theta \leq 0$ the equilibrium is unique: nobody buys the sunspot message, everyone invests and investment is successful;

If $\theta > 1$ no one buys the sunspot message and no one invests;

If $\theta \in (0,1]$ there are up to three pure-strategy equilibria characterized by self-fulfilling beliefs:

1. all agents invest without buying the sunspot message,
2. nobody buys the sunspot message and nobody invests, and
3. everyone buys the sunspot message and follows its prescription. This equilibrium exists if the cost of the sunspot message is sufficiently small:

$$c \leq min\{(1-q)\lambda,\ q(1-\lambda)\}. \quad (1)$$

Proof. Payoffs for the unconditional equilibrium strategies are obvious. If all agents condition their investment on the sunspot message, their expected payoffs are $q + (1 - q)\lambda - c$. An agent who deviates to not buying the sunspot message and not investing receives λ, an agent who deviates to not buying and investing has an expected payoff q. Thus, for $c \leq min\{(1-q)\lambda,\ q(1-\lambda)\}$, no agent has an incentive to deviate. QED

The sunspot message may serve as a means to coordinate actions, which may seem valuable to agents of the game if they cannot make up their minds as to how to behave without such a coordinating device or if they believe that other agents will follow the sunspot message.[1]

[1] Arifovic and Jiang (2014) have actually shown that for some values of θ, subjects may coordinate on following salient extrinsic messages, if these messages are provided to all agents at no cost.

The efficient equilibrium is, of course, to invest without buying the sunspot message, whenever $\theta \leq 1$. However, for $\theta > 0$, buying and following the sunspot message yields a higher expected payoff than not buying and not investing. This raises the question of whether real agents would actually coordinate on following the sunspot message and for which states of θ they might do so.

In order to address this question, we compare the predictions of two theories, the theory of global games predicts that agents will not follow the sunspot message. Our own theory assumes that agents exogenously believe some others will follow sunspots, which leads them to follow sunspots themselves for some range of states that are strictly interior to the set of states for which the common-information game has multiple equilibria.

The reason for this comparison is that Heinemann et al. (2004) show that subjects in laboratory experiments treat coordination games with public information about the state of the economy as similar to a global game with private information about the state. Furthermore, Heinemann et al. (2009) show that behavior in a coordination game with common information can be described by the equilibrium of a global game. As we will discuss in the next part, the global-game extension of the common-information game described above has a unique equilibrium in which sunspots are ignored. Thus, we test this prediction against the prediction of a model that embeds the global game as a special case but could explain sunspot-following behavior as well.

2.1.2. Sunspot global game

The state variable θ follows a normal distribution with mean y and precision α (that is, with a variance of $1/\alpha$). Agents do not observe θ. Each agent observes a noisy private signal about it:

$$x_i = \theta + \epsilon_i$$

where ϵ_i is i.i.d. and normally distributed with mean 0 and precision β. After realizing the noisy signal, agents decide whether to invest, follow, or not invest.

Morris & Shin (2004) show that for sufficiently precise signals ($\alpha^2/\beta \leq 2\pi$) the game without sunspots has a unique equilibrium. As Heinemann & Illing (2002) point out, the introduction of sunspot variables does not change this result, because the unique equilibrium can be derived by the iterative elimination of dominated strategies. Thus, in a global game, agents ignore the sunspot messages even when they come at no cost. In equilibrium, agents play a threshold strategy with a threshold signal x^*, such that agents with lower signals invest, agents with higher signals do not invest, and an agent with the marginal signal x^* is indifferent. Thus, there is no equilibrium in which agents buy and follow the sunspot message for any signal.

Experiments on global games have shown that there are little behavioral differences between coordination games with multiple equilibria in which the underlying state is common information and their respective global-game versions with private signals and a unique equilibrium (Heinemann et al., 2004).

Heinemann et al. (2009) argue that a global-game equilibrium can be used as a descriptive theory of behavior under strategic uncertainty in a coordination game with multiple equilibria. This would not be true if actual agents follow sunspots, because in a global-game equilibrium, sunspots are ignored. Thus, if we observe agents following sunspots, we would need another theory, potentially embedding a global-game equilibrium as a special case, to describe such behavior. For this reason, we introduce a simple extension of a global game that may eventually account for sunspot-following behavior in a coordination game.

2.1.3. Extended global game with exogenous beliefs in sunspots

Based on our motivation that agents may believe that others are following sunspots, we introduce a grain of doubt about the rationality of the assumption defining Nash equilibria. Namely, we assume that each agent behaves as if he or she expects that a proportion $p \in [0,1)$ of agents are naïve followers, who always choose to buy the sunspot message and follow the action that it indicates, while the proportion $1 - p$ of agents are expected to choose rationally between invest, not invest, and follow, depending on their information about fundamentals of the game and given their belief in a proportion p of naïve followers.

Note that it is not necessary that the naïve followers *actually* exist. If agents believe in the existence of some naïve followers, their best response may be to follow the sunspot themselves, provided their signal about fundamentals is critical. For $p = 0$, we are back to the standard global game in which equilibrium strategies ignore sunspots.

The presumed presence of some naïve followers can make a difference in intermediate states of the world: for some signals, the expected share of rational investors is so close to the expected hurdle of success that the sunspot message is expected to determine whether the hurdle is passed or not. For such signals, agents may be prompted to follow the signal themselves. Rational agents best respond to everybody else. Hence, they account for the widespread belief that sunspots may affect the outcome in intermediate states, and may themselves decide to follow the sunspot for some intermediate signals.

If we restrict ourselves to the three strategies "invest," "follow," and "not invest," the extended global game is supermodular and we can focus on the threshold equilibria for which agents switch from one strategy to the next if the private signal surpasses the respective threshold. If there is a unique threshold equilibrium, a supermodular game does not have any other equilibria. We first solve for an equilibrium strategy characterized by two thresholds in posterior beliefs about the fundamental: the investing switching point, ξ^I , and the not-investing switching point, $\xi^N > \xi^I$. These thresholds are such that agents invest without buying the sunspot message if their posterior estimate of the underlying fundamental is below ξ^I, they do not buy the sunspot message and do not invest if their posterior is above ξ^N, and they buy and follow the sunspot message for posterior beliefs between the two switching points. At the switching points, agents are indifferent between the neighboring strategies, which give the equilibrium conditions determining the two thresholds. After solving for an equilibrium, we identify conditions for its uniqueness.

Under Bayes' theorem, agent i's posterior belief about θ follows a normal distribution with mean

$$\xi_i = \frac{\alpha y + \beta x_i}{\alpha + \beta} \tag{2}$$

and precision $\alpha + \beta$. If agents use a switching strategy as described above, they do not buy the sunspot message and invest if the private signal x_i is smaller than

$$x^I(\xi^I, y) = \frac{\alpha + \beta}{\beta}\xi^I - \frac{\alpha}{\beta}y. \quad (3)$$

They do not buy the sunspot message and do not invest if the private signal x is larger than

$$x^N(\xi^N, y) = \frac{\alpha + \beta}{\beta}\xi^N - \frac{\alpha}{\beta}y. \quad (4)$$

They buy and follow the sunspot message if the private signal is between x^N and x^I.

Since we have an infinite number of agents, the probability of a private signal falling in any of these three regions is almost certainly identical to the proportion of agents who receive signals in the respective region. This allows us to denote two critical values of fundamentals at which the project is *expected* to be in the margin between failing and succeeding when the sunspot message is: (a) "invest," by ψ^N ; and, (b) "non invest," by ψ^I.

While these threshold states ψ^N and ψ^I depend on strategies characterized by the critical values for beliefs ξ^N and ξ^I, the optimal strategies depend on the fundamental states for which investment can be expected to succeed. We now solve for the equilibrium, which is a vector of threshold states and threshold signals, such that threshold signals are a best response to threshold states and threshold states are derived from the proportion of investors following the respective threshold strategy plus naïve followers.

In each case, we derive two equations that solve two pairs of unknowns: (ξ^N, ψ^N) when the sunspot message is "invest" and, (ξ^I, ψ^I) when the sunspot message is "not invest."

A. The Sunspot message is "invest"

If the sunspot message is "invest" then all agents whose posterior beliefs are below ξ^N will invest. Hence, an agent who believes in a proportion p of naïve followers, expects a critical state to success, $\psi^N = f + p$, where f is the proportion of agents who are expected to invest resulting from the switching strategy around ξ^N; and p is the proportion of naïve followers. At this state, the probability of receiving a signal below x^N is given by $Prob(x_i < x^N | \psi^N) = \Phi(\sqrt{\beta}(x^N - \psi^N))$, where $\Phi(.)$ is the cumulative distribution function for the standard normal.[2] Thus, the proportion of agents expected to invest because of a signal below x^N is $\Phi(\sqrt{\beta}(x^N - \psi^N))\,(1-p)$. This determines the expected marginal threshold to success as the value ψ^N that solves

$$\begin{aligned} \psi^N &= \Phi(\sqrt{\beta}(x^N - \psi^N))\,(1-p) + p \\ &= \Phi(\sqrt{\beta}(\frac{\alpha+\beta}{\beta}\xi^N - \frac{\alpha}{\beta}y - \psi^N))\,(1-p) + p. \end{aligned} \tag{5}$$

At switching point ξ^N, an agent is indifferent between following and not investing. The expected payoff from following is $qProb(\theta < \psi^N | \xi^N) + (1-q)\lambda - c$, because "following" implies a successful investment whenever $\theta < \psi^N$ (recall that q is the

[2] $Pr(x_i < x|\theta,\psi) = Pr(\theta + \epsilon_i < x|\theta,\psi) = Pr(\sqrt{\beta}\epsilon_i < \sqrt{\beta}(x-\psi)) = \Phi(\sqrt{\beta}(x - \psi))$

probability that the sunpot message is "invest"). Since the conditional density over θ is normal with mean ξ^N and precision $\alpha + \beta$, this indifference condition is given by [3]

$$q\Phi(\sqrt{\alpha+\beta}(\psi^N - \xi^N)) + (1-q)\lambda - c = \lambda, \tag{6}$$

which implies

$$\psi^N = \xi^N + \frac{\Phi^{-1}(\lambda + \frac{c}{q})}{\sqrt{\alpha+\beta}}. \tag{7}$$

This gives us our second equation. Replacing ψ^N in equation (5) by (7) and rearranging the terms gives

$$\xi^N = \Phi\left(\sqrt{\beta}\left(\frac{\alpha}{\beta}(\xi^N - y) - \frac{\Phi^{-1}(\lambda + \frac{c}{q})}{\sqrt{\alpha+\beta}}\right)\right)(1-p) + p - \frac{\Phi^{-1}(\lambda + \frac{c}{q})}{\sqrt{\alpha+\beta}} \tag{8}$$

Figure 1 shows that the switching point ξ^N is obtained as the intersection between the 45° line and a linear transformation of a cumulative normal distribution. Equation (8) has a unique solution if the expression on the right-hand side has a slope that is less than 1 everywhere. The slope of the right-hand side is given by $(1-p)\phi(\alpha/\sqrt{\beta})$ where

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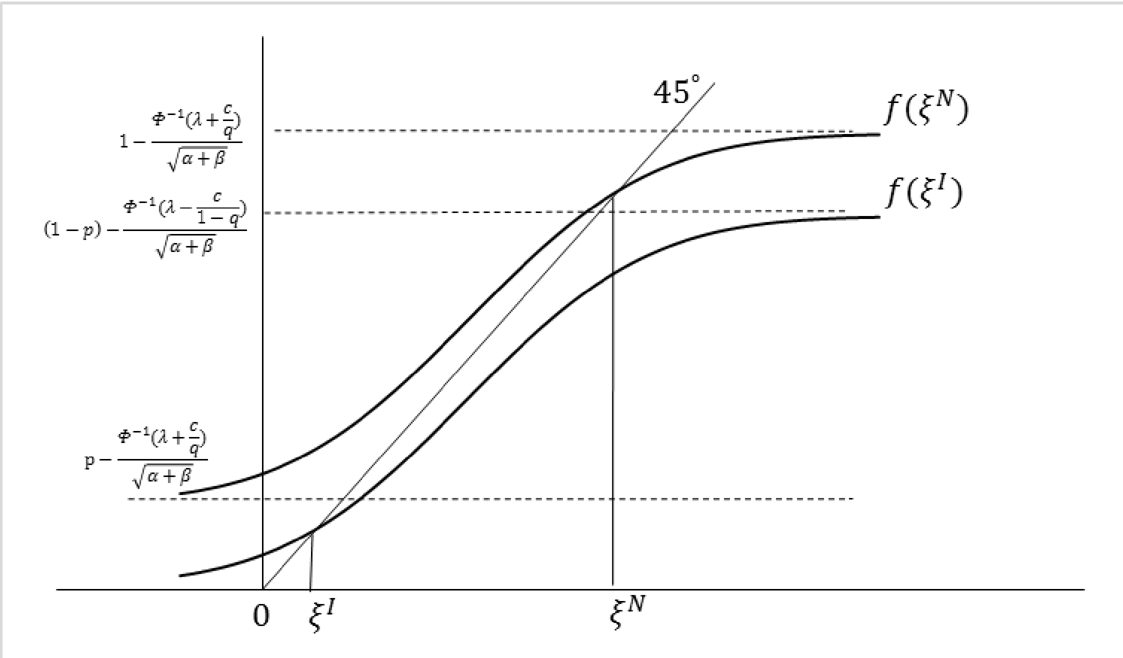
[3] $\theta = \xi + u_i$, where $u_i \sim N(0, \frac{1}{\alpha+\beta})$. Therefore $Pr(\theta < \psi | \xi, \psi) = Pr(\xi + u_i < \psi | \xi, \psi) = Pr((\sqrt{\alpha+\beta} u_i < \sqrt{\alpha+\beta}(\psi - \xi)) = \Phi(\sqrt{\alpha+\beta}(\psi - \xi))$

ϕ is the density of the standard normal evaluated at the appropriate point. Since $\phi \leq 1/\sqrt{2\pi}$, a sufficient condition for a unique solution for ξ^N is given by

$$\frac{\alpha}{\sqrt{\beta}} \leq \frac{\sqrt{2\pi}}{1-p}. \tag{9}$$

Figure 1 Default points $\boldsymbol{\xi^N}$ and $\boldsymbol{\xi^I}$.



Since α is the precision of the ex-ante distribution of θ, while β is the precision of private signals, the condition in equation (9) is satisfied whenever private signals are sufficiently precise relative to the underlying uncertainty of the fundamental.

B. The sunspot message is "not invest"

If the sunspot message is "not invest" the critical value of the fundamentals at which the project is expected to be in the margin between failing and succeeding was denoted as ψ^I. At this state, the proportion of agents expected to invest because of a signal below

x^I is $\Phi(\sqrt{\beta}(x^I - \psi^I))(1-p)$. This determines the expected marginal threshold to success if the sunspot message is "not invest" as the value ψ^I that solves

$$\begin{aligned}\psi^I &= \Phi(\sqrt{\beta}(x^I - \psi^I))(1-p) \\ &= \Phi(\sqrt{\beta}(\frac{\alpha+\beta}{\beta}\xi^I - \frac{\alpha}{\beta}y - \psi^I))\,(1-p).\end{aligned} \tag{10}$$

At the switching point ξ^I, an agent is indifferent between following and investing. The payoff from following is $qProb(\theta < \psi^N|\xi^I) + (1-q)\lambda - c$, because "following" implies a successful investment whenever $\theta < \psi^N$. The payoff from investing is $qProb(\theta < \psi^N|\xi^I) + (1-q)prob(\theta < \psi^I|\xi^I)$, because the investment is also successful for a sunspot saying "not invest," if the state is below ψ^I. The indifference condition between following and investing at a posterior of ξ^I is, thus, given by

$$(1-q)\lambda - c = (1-q)\Phi\left(\sqrt{\alpha+\beta}(\psi^I - \xi^I)\right), \tag{10}$$

which implies

$$\psi^I = \xi^I + \frac{\Phi^{-1}(\lambda - \frac{c}{1-q})}{\sqrt{\alpha+\beta}}. \tag{11}$$

This gives us our second equation. Replacing ψ^I in Equation (10) by (11), and rearranging terms gives

$$\xi^I = \Phi\left(\sqrt{\beta}\left(\frac{\alpha}{\beta}(\xi^I - y) - \frac{\Phi^{-1}\left(\lambda - \frac{c}{1-q}\right)}{\sqrt{\alpha+\beta}}\right)\right)(1-p) - \frac{\Phi^{-1}(\lambda - \frac{c}{1-q})}{\sqrt{\alpha+\beta}}. \qquad (12)$$

The point ξ^I is obtained as the intersection between the 45° line and a linear transformation of a cumulative normal distribution (see Figure 1). Inequality (9) also ensures the uniqueness of ξ^I.

There is a region of signals for which agents follow the sunspot message if and only if

$$\Delta = \xi^N - \xi^I > 0.$$

Theorem 1. If $\frac{\alpha}{\sqrt{\beta}} \leq \frac{\sqrt{2\pi}}{1-p}$ and $p > 0$, there is a $c^{max} > 0$, such that for all $c < c^{max}$, there is an unique equilibrium where agents follow sunspots when their posterior beliefs are contained in an interval (ξ^I, ξ^N), with $\Delta = \xi^N - \xi^I > 0$.

Proof:

We first show the existence of the equilibrium and then its uniqueness. The proof of existence is structured in three steps.

1. For $p = 0$ and $c = 0$, there is no sunspot region. Equations (8) and (12) become identical and since each has a unique solution under condition (9), this implies $\xi^N = \xi^I$.

2. Total differentiation of (8) w.r.t. ξ^N and p gives $\frac{d\xi^N}{dp} = \frac{1-\Phi(\cdot)}{1-(1-p)\frac{\alpha}{\sqrt{\beta}}\phi(\cdot)}$, which is positive for $\frac{\alpha}{\sqrt{\beta}} \leq \frac{\sqrt{2\pi}}{1-p}$. Total differentiation of (8) w.r.t. ξ^N and c gives $\frac{d\xi^N}{dc} =$

$\frac{-[(1-p)\phi(\cdot)\sqrt{\beta}+1]\frac{1}{\sqrt{\alpha+\beta}}\cdot\frac{1}{q\phi(\cdot)}}{1-(1-p)\frac{\alpha}{\sqrt{\beta}}\phi(\cdot)}$, which is negative under the same condition.

Similarly, equation (12) yields $\frac{d\xi^I}{dp}=\frac{-\Phi(\cdot)}{1-(1-p)\frac{\alpha}{\sqrt{\beta}}\phi(\cdot)}<0$ and $\frac{d\xi^I}{dc}=$ $\frac{[(1-p)\phi(\cdot)\sqrt{\beta}+1]\frac{1}{\sqrt{\alpha+\beta}}\cdot\frac{1}{(1-q)\phi(\cdot)}}{1-(1-p)\frac{\alpha}{\sqrt{\beta}}\phi(\cdot)}>0$. This establishes that the sunspot region widens in p and shrinks in c.

3. Thus, for $p>0$ and $c=0$, $\xi^N>\xi^I$. For any given value of $p>0$, if c rises to $(1-q)\lambda$, then Equation (12) implies that ξ^I converges to infinity. If c rises to $(1-\lambda)q$, then Equation (8) implies that ξ^N converges to minus infinity. Hence, for $c\to\min\{(1-q)\lambda,\ q(1-\lambda)\}$, $\xi^I>\xi^N$. As (8) and (13) are continuous in c, there exists a $c^{max}\epsilon(0,\min\{(1-q)\lambda,\ q(1-\lambda)\})$, for which $\xi^I=\xi^N$.

Uniqueness.

Equations (8) and (12) characterize the equilibrium thresholds. Assuming $\frac{\alpha}{\sqrt{\beta}}\leq\frac{\sqrt{2\pi}}{1-p}$, equation (8) has at most one solution, because the derivative of the left-hand side with respect to ψ^N is 1 while the derivative of the right-hand side is smaller than $(1-p)\frac{\alpha}{\sqrt{\beta}\sqrt{2\pi}}$. The same argument guarantees that there is at most one solution ψ^I to equation (12). Thus, if a threshold equilibrium exists, it is unique. Because the game is supermodular, a unique threshold equilibrium implies that there is no other equilibrium. Q.E.D.

2.1.4. Global-game selection

Global-game equilibria are used for two purposes: (1) as a descriptive theory for heterogeneous behavior under strategic uncertainty that arises, in particular, in early rounds of a repeated coordination game before agents learn the strategies of others and coordinate their actions; (2) as a refinement predicting one particular equilibrium in the common information game. This refinement is given by the global-game selection (GGS), the limiting equilibrium for private signals becoming infinitely precise. Having derived the equilibrium conditions for finite signal precision, we can now investigate how the thresholds to the sunspot region are affected by $\beta \to \infty$. We will use the GGS as a benchmark for testing the theory in the laboratory. Very precise signals may prevent subjects from following the sunspot or may reduce the sunspot region to an extent that it disappears in the limit. But, the sunspot equilibrium still exists with a very high level of signals precision and, as we show below, the size of the interval of posteriors for which agents follow the sunspot is bound away from zero.

Let us see what happens in the limit when the private signals become very precise, and noise becomes negligible. This corresponds to the case where $\beta \to \infty$. From (8), threshold ξ^N satisfies[4]

$$\xi^N \to \overline{\xi^N} = p + (1-p)\Phi\left(-\Phi^{-1}\left(\lambda + \frac{c}{q}\right)\right) = p + (1-p)\left(1 - \lambda - \frac{c}{q}\right). \tag{13}$$

By equation (7), we have

$$\psi^N \to \overline{\xi^N} = p + (1-p)\left(1 - \lambda - \frac{c}{q}\right). \tag{14}$$

[4] Note that $\Phi(-\Phi^{-1}(z)) = 1 - z$.

Similarly, from (12), threshold ξ^I converges to

$$\xi^I \to \overline{\xi^I} = (1-p)\Phi\left(-\Phi^{-1}\left(\lambda - \frac{c}{1-q}\right)\right)$$
$$= (1-p)\left(1-\lambda+\frac{c}{1-q}\right). \tag{15}$$

By equation (11), we have

$$\psi^I \to \overline{\xi^I} = (1-p)\left(1-\lambda+\frac{c}{1-q}\right). \tag{16}$$

The difference between equations (14) and (16), gives us the sunspot region at its limit. Thus, the widths of the sunspot region, Δ, converges to

$$\Delta \to \overline{\Delta} = p - c\,\frac{1-p}{q\,(1-q)}. \tag{17}$$

The sunspot region remains positive at its limit as long as the cost of the sunspot is sufficiently small:

$$c^{max} = q\,(1-q)\,\frac{p}{1-p}. \tag{18}$$

The analysis of this limiting case demonstrates that, even when information concerning the underlying fundamental becomes very precise, if the costs of sunspots are sufficiently small, agents will still coordinate on sunspots for some critical values of the fundamental.

2.2. Finite number of agents

In applying the model to our experiment, it is convenient to redefine the state variable θ as the number of agents necessary for the success of the investment, because the experiment will have a finite number of agents N. This alters the equilibrium conditions slightly. In this subsection, we provide the solution of the model for a finite number of agents who simultaneously decide whether to invest, follow, or not invest. In the experiment, the payoffs of the game are 58 experimental currency units (ECU) if an investment is successful, 8 ECU if not, and 33 ECU if a player does not invest. So, the profit from an investment being successful is 50 ECU and the opportunity costs for trying to get this profit are 25 ECU. Normalizing payoffs such that the gain from the success of an investment is 1 as in Table 1, leads to $\lambda = .5$. The costs of reading the sunspot message were 1 ECU, which amounts to $c = .02$.

2.2.1. Common information game

If the number of agents needed for success, θ, is common information, the game can have a unique or multiple symmetric pure-strategy Nash equilibria as in the case with infinitely many agents:

If $\theta \leq 1$, investing is the dominant strategy. Nobody buys the sunspot message, everyone invests and investment is successful;

If $\theta > N$, not investing is the dominant strategy, no one buys the sunspot message and no one invests;

If $\theta \in (1, N]$ there are up to three pure-strategy equilibria characterized by self-fulfilling beliefs: everyone invests, no one invests, and everyone follows the sunspot provided $c \leq min\{(1-q)\lambda,\ q(1-\lambda)\}$.

2.2.2. Global-game with exogenous beliefs in sunspots

As explained in the previous section, we assume that each agent expects that a number $p \in \{0,1,\dots,N\}$ of the other agents are naïve followers, who always choose to buy the sunspot message and follow the action that it indicates, while $1-p$ agents are expected to choose between invest, not invest, and follow, depending on their information about the fundamentals of the game and given their belief in *p* naïve followers.

Applying the global-game approach, assume that state θ follows a normal distribution with mean y and precision α (that is, with a variance of $1/\alpha$). Conditional on state θ, each agent i observes a noisy signal x_i with mean θ and variance β.

They buy and follow the sunspot message if and only if the private signal is between x^N and x^I. A risk-neutral player who receives the marginal signal x^N is indifferent between following and not investing, provided all other agents excluding naïve followers choose to not invest if and only if their signal is above x^N. If the sunspot message is "invest," the probability that the investment is successful is given by the probability that at least $\hat{\theta}-1-p$ out of other $N-1$ non-naïve agents get signals below x^N and choose to follow, where $\hat{\theta}$ is the smallest integer above θ.This can be described by the binomial distribution. The probability that agents get signals below x^N, $Prob(x < x^N|\theta)$, is equal to $\Phi\left((x^N-\theta)\sqrt{\beta}\right)$, where Φ is the standard normal cumulative function. Thus, x^N is the signal x that solves

$$q\int_{-\infty}^{N} f(\theta|x^N)\left(1 - Bin\big(\hat{\theta} - 2 - p, N - 1 - p, \Phi(\sqrt{\beta}(x^N - \theta))\big)\right) d\theta + (1-\mathrm{q})\lambda - c = \lambda, \tag{19}$$

where $f(\theta|x^N)$ is the normal distribution with mean $(\alpha y + \beta x^N)/(\alpha + \beta)$ and precision $\alpha + \beta$ and Bin is the cumulative binominal distribution. Note that $f(\theta|x^N) = \phi\left(\sqrt{\alpha + \beta}(\theta - \xi^N)\right)$ and $x^N(\xi^N, y) = \frac{\alpha+\beta}{\beta}\xi^N - \frac{\alpha}{\beta}y \Leftrightarrow \xi^N = \frac{\beta\, x^N + \alpha\, y}{\alpha+\beta}$.

In equilibrium at signal x^I, agents are indifferent between following and investing. Thus x^I is the signal x that solves

$$\begin{aligned} q\int f(\theta|x^I)\left(1 - Bin\big(\hat{\theta} - 2 - p, N - 1 - p, \Phi(\sqrt{\beta}(x^N - \theta))\big)\right) d\theta + (1-\mathrm{q})\lambda - c \\ = \mathrm{q}\int f(\theta|x^I)\left(1 - Bin\big(\hat{\theta} - 2 - p, N - 1 - p, \Phi(\sqrt{\beta}(x^N - \theta))\big)\right) d\theta \\ +(1-\mathrm{q})\int f(\theta|x^I)\left(1 - Bin\big(\hat{\theta} - 2, N - 1 - p, \Phi(\sqrt{\beta}(x^I - \theta))\big)\right) d\theta. \end{aligned} \tag{20}$$

Equations (19) and (20) characterize the equilibrium threshold signals. We can simplify these equations to:

$$\int_{-\infty}^{N} f(\theta|x^N)\left(1 - Bin\big(\hat{\theta} - 2 - p, N - 1 - p, \Phi(\sqrt{\beta}(x^N - \theta))\big)\right) d\theta = \lambda + \frac{c}{q}, \tag{21}$$

and

$$\int_{-\infty}^{N} f(\theta|x^I) \left(1 - Bin\left(\hat{\theta} - 2, N - 1 - p, \Phi(\sqrt{\beta}(x^I - \theta))\right)\right) \int d\theta = \lambda - \frac{c}{1-q} \,. \tag{22}$$

2.2.3. Global-game selection

For β converging to infinity, the equilibrium conditions (21) and (22) characterize the GGS that we can use as a refinement theory for the common-information game. Hence, we refer to these thresholds as the “sunspot global-game selection” for the game with common information.

From Basteck, Daniëls, & Heinemann (2013), we know that the GGS can be derived by decomposing the game into two smaller games, in which agents simply decide between the neighboring strategies “invest” and “follow” and between “follow” and “not invest.” The GGS of a binary action game is the best response to a uniform distribution of the proportion of other agents taking either action (Morris & Shin, 2003).

So, suppose an agent has a uniform distribution on the number A of the $N - p - 1$ other agents who invest unconditionally, while the others are following sunspots. If the message is “invest” all of the other agents invest and the investment is successful if $\hat{\theta} \leq N$. If the message is “not invest” the investment is successful if $1 + A \geq \hat{\theta}$. Here, the success probability is $\frac{N-p-\hat{\theta}+1}{N-p}$.

In the limit, for $\beta \to \infty$, an agent is indifferent between investing and following if and only if

$$q + (1-q)\frac{N-p-\hat{\theta}+1}{N-p} = q + (1-q)\,\lambda - c.$$

$$\Leftrightarrow \frac{N-p-\hat{\theta}+1}{N-p} - \lambda + \frac{c}{1-q} = 0 \tag{23}$$

As $\hat{\theta}$ is a natural number and the agent has almost perfect information about the state, the critical signal x^I, at which an agent switches from investing to following is the integer $\hat{\theta}$, at which the left-hand side of (23) changes its sign, which is the largest integer x^I with $x^I \leq \left(1 - \lambda + \frac{c}{1-q}\right)(N-p) + 1$.

Similarly, suppose an agent has a uniform distribution on the number A of the $N - p - 1$ other agents who follow sunspots, while the others are not investing. If the message is “invest” the investment is successful if $A + p + 1 \geq \hat{\theta}$. Thus, the probability of an investment being successful given $1 + p \leq \hat{\theta} \leq N$ if the message is “invest” is $\frac{N-\hat{\theta}+1}{N-p}$. If the message is “not invest” nobody invests and the success probability is 0 for $\hat{\theta} \geq 1 + p$.

Hence, in the limit, for $\beta \to \infty$, an agent is indifferent between following and not investing if and only if

$$q\,\frac{N-\hat{\theta}+1}{N-p} - q\,\lambda - c = 0. \tag{24}$$

As $\hat{\theta}$ is a natural number and agents are almost perfectly informed about the state variable θ, the threshold signal x^N is given by the integer $\hat{\theta}$ at which the left-hand side of (24) changes its sign, which is the largest integer x^N with $x^N \leq N - \left(\lambda + \frac{c}{q}\right)(N-p) + 1$.

A positive sunspot region requires $x^I < x^N$, which is equivalent to $c < c^{max}$.

If the costs of reading the sunspot message are higher, e.g., for $p = 0$, agents directly switch from "invest" to "not invest." The respective threshold signal x^*, at which they are indifferent, is given by the best response to a uniform distribution on the number of other non-naïve players investing. For $1 \leq \hat{\theta} \leq N$, the probability of success is $\frac{N-\hat{\theta}+1}{N-p}$ if the sunspot is "invest" and $\frac{N-p-\hat{\theta}+1}{N-p}$ if the sunspot is "not invest." Hence, an agent is indifferent between investing and not investing if and only if

$$q\frac{N-\hat{\theta}+1}{N-p} + (1-q)\frac{N-p-\hat{\theta}+1}{N-p} - \lambda = 0 \qquad (25)$$

As $\hat{\theta}$ is a natural number and agents are almost perfectly informed about the state variable θ, the threshold signal x^* is given by the integer $\hat{\theta}$ at which the left-hand side of (25) changes its sign, which is the largest integer x^* with $x^* \leq N - (1-q)p - (N-p)\lambda + 1$.

In the next section, we calculate the theoretical predictions for the experiment.

2.2.4. Theoretical predictions for the experiment

A set of parameters governs the theoretical model: $\Theta = \{N, q, y, \alpha, \beta, \lambda, c\}$. For the experiment, the parameters chosen are

$$\Theta = \{8, 0.5, 4.5, 0.16, \beta, 0.5, 0.02\}$$

where β varies across treatments: $\beta = 4$ for a private information treatment with low noise (PIL) and $\beta = 0.25$ for a private information treatment with high noise (PIH). In common information (CI) treatment, θ is common knowledge. The state θ is drawn from a normal distribution with mean $y = 4.5$ and a standard deviation of $1/\alpha^2 = 2.5$. The opportunity cost of investing is $\lambda = .5$. The costs of reading the sunspot message are set at $c = 0.02 < min\{(1-q)\lambda, q(1-\lambda)\}$.

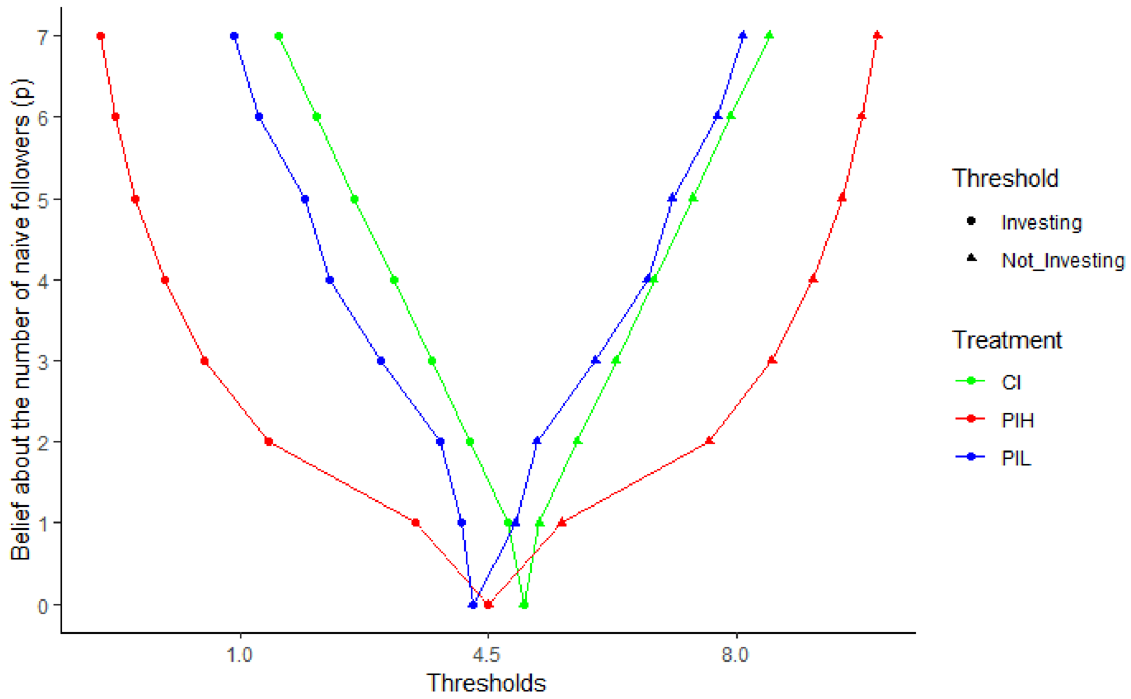
For these parameters, the region of multiple equilibria in the common information game is $\theta \in (1,8]$. If it is common knowledge that all agents believe that a number p of the other agents will buy and follow the sunspot (independent of their signals), the thresholds of the global game with exogenous beliefs in sunspots open an interval of private signals, for which agents follow the sunspot. These thresholds are indicated by the solutions to (25) and (26) and are displayed in Figure 2 for different values of p. The limit case with $p=0$ resembles the standard global-game equilibrium, in which no agent follows the sunspot message. Given these parametric assumptions, we can characterize the predictions of the model in the form of the five main hypotheses to be tested in our experiment.

Hypothesis 1: Choices are consistent with threshold strategies.

Hypothesis 1 establishes that subjects will use threshold strategies either switching directly from "invest" to "not invest" or with two thresholds, a smaller one, x^I, where they switch from "invest" to "follow" and a larger one, x^N, where they switch from "follow" to "not invest." Such threshold strategies are predicted by the theory of global games with and without exogenous beliefs in sunspots.

Hypothesis 2: Sunspot messages will be ignored for all signals.

Figure 2 Equilibrium predictions for threshold signals



The standard theory of global games predicts a direct switch from "invest" to "not invest," while our extended global game predicts the existence of an intermediate region, in which subjects follow the sunspot for any $p \geq 1$. Thus, given that H1 is not rejected, Hypothesis 2 discriminates between the two models.

Hypothesis 3: The set of signals for which subjects follow sunspot messages in the PIH treatment is greater than in the CI and PIL treatments.

Hypothesis 4: The set of signals for which subjects follow sunspot messages in the CI treatment is about the same as in the PIL treatment.

If H2 is rejected, we can test for the comparative statics properties of the equilibrium of the global game with exogenous beliefs in sunspots. Figure 2 shows the threshold signals at which agents switch between not investing and following the sunspot and between following and investing without looking at the sunspot. The sunspot region in the middle widens as the expected number of naïve followers increases. Between treatments, the sunspot region is wider under the high noise of the private signal (PIH) than in the other two. Thresholds of the PIL treatment are always a bit higher than under common information (CI), but the difference is numerically small. Figure 2 depicts the thresholds in PIH and PIL and also in the limit case, the GGS, as a refinement of the CI treatment. For the selected parameters the sunspot region is larger in PIH than in CI and PIL, which implies hypotheses 3 and 4.

Hypothesis 5: On average, subjects expect more players to follow sunspots than actually do follow sunspots.

Finally, the extended global game assumes that all agents behave as if they exogenously believe in some others following sunspots, while in fact all agents best respond to this belief and follow sunspots only for intermediate signals. Thus, the extended game implies that agents (on average) believe that more players follow sunspots than actually do. In the experiment, we elicit beliefs about the total number of players following sunspots. Thus, we can directly test whether this assumption holds.

3. The Experiment

We present the results of a series of laboratory experiments designed to test the implications of the sunspot model described in section 2 in comparison to the standard global-game equilibrium. The experiment was conducted at the Experimental Laboratory at Berlin University of Technology from February to May 2016. Subjects were recruited using ORSEE (Greiner, 2004). Most of the subjects were undergraduate students from the university. Sessions were computerized using a z-Tree program (Fischbacher, 2007).

The main experimental studies that relate to our paper are Cabrales et al. (2007) and Heinemann et al. (2004). In particular, our experimental design is closely related to the work of Heinemann et al. (2004) who test the predictions of the model by Morris & Shin (1998) in the laboratory and find that, on average, 92% of observed strategies are consistent with the use of undominated threshold strategies.

The analysis of the results will first address the hypotheses stated in the previous section. This will be followed by a convergence analysis and some additional results that enrich the predictions of our model.

3.1. Experimental design

We implemented a between-subjects design that allowed us to directly compare the behavior of subjects across treatments. There were three main treatments: Common Information (CI), Private Information with Low noise signal (PIL), and Private Information with High noise signal (PIH).

Overall, we ran eight sessions with 16 or 24 subjects each, leading to a total of 176 subjects. Subjects were randomly assigned to groups of eight who played the respective game for 12 or 15 periods. Subjects of different groups never interacted with each other, so that the groups give us independent observations. The first two sessions (one with CI and one PIH) had only 12 periods and were completed faster than we expected. We decided to run the remaining sessions with 15 rounds to collect more observations. Table 2 summarizes our experimental design.

In each session, there were two or three groups of eight subjects who were randomly matched and remained for all periods. The game was explained using neutral terms. Subjects were told to choose between two actions, A or B, avoiding terminology such as "investment." Before starting the first period, subjects had a chance to complete a quiz with the answers provided to make sure they understood the instructions. Each session lasted from 90 to 120 minutes and subjects earned, on average, 25€ including a 5€ show-up fee.

each guess, we paid subjects 12 ECU minus the absolute distance between their guess and the actual number of readers.

Table 2 Experimental design

Treatment	Signal	Sessions	Total Groups (12 periods, 15 periods)	Subjects
CI	Common information	3	8 (3, 5)	64
PIL	Private information with precision of β=4	2	6 (0, 6)	48
PIH	Private information with precision of β=0.25	3	8 (2, 6)	64
Total		8	22 (5, 17)	176

In each period, all subjects had to make decisions for 10 independent situations. In each situation each subject had to make three decisions:

- Whether to look at the message which contained either "choose A" ("not invest") or "choose B" ("invest") with equal probabilities. Subjects were informed that the message is random with 50% probability for both versions and that it is the same for all who look at it.

- Choose between A (not invest) or B (invest).

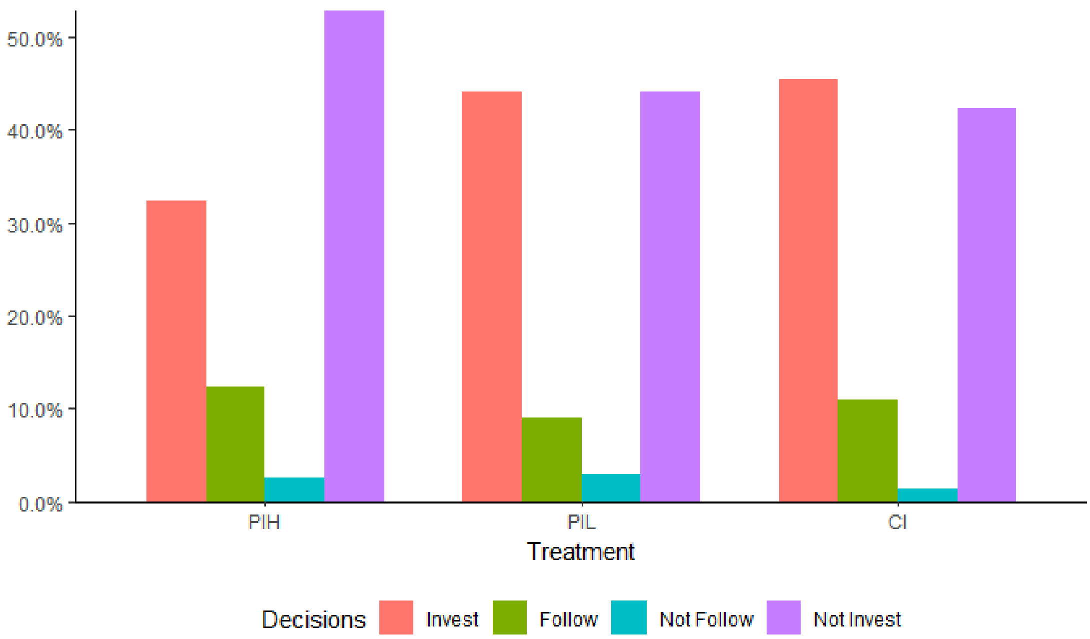
- Guess how many members of the subject's own group (including her- or himself) would look at the message.

For each situation, a state θ (called X in the experiment), the same for all group members, was randomly drawn from a normal distribution with mean 4.5 with a standard deviation of 2.5 (that is, $\alpha = 0.16$). In groups with CI, subjects were informed about θ. In sessions with PIL and PIH, this information was withheld; instead, each subject received a private signal from a normal distribution with a mean of θ and a standard deviation of 0.5 and 2 (that is, a precision of 4 and 0.25) accordingly. The state θ and private signals were displayed with three decimal digits. Looking at the message costed 1 experimental currency unit (ECU). The payoff for alternative A was 33 ECU. The payoff for alternative B was 58 if at least θ group members chose B and eight otherwise. The payoff for guessing the number of readers was also incentivized. For

After all subjects in a session completed their decisions in one period, they were informed for each of the 10 situations about the true value of θ (along with their previous signal in treatments PIL and PIH), the text of the message, the number of group members that chose B, whether B was successful, their own payoff for each situation, and also the sum of their payoffs for the 10 situations of this round. They were not informed about how many subjects looked at the sunspot message, nor about their payoff from guessing this number. This information was only provided at the end of the experiment for the one period that was selected for payoffs. Information about previous periods could not be revisited. Subjects were allowed to take notes and many of them did. At the end of each session participants had to fill out a questionnaire.

The final payoff was based on the 10 situations in two randomly selected distinct periods: one period for the payoffs of the games and one period for payoffs from guessing the number of players who looked at the sunspot message. Subjects were paid in private, using the exchange rate of 22 ECU per 1 euro. All of these rules, including the distributions of state variable and signals (called "hint numbers" in the experiment), were described in the instructions (see Appendix) that were read aloud before the start of the experiment.

Figure 3 The relative frequencies of decisions.



3.1. Results

Figure 3 depicts summary statistics for the relative frequencies by which subjects invested without looking at the sunspot message ("Invest"), neither looked at the message nor invested ("Not Invest"), followed the sunspot message ("Follow"), or looked at the sunspot message but took the opposite decision ("Not Follow"). While the theory section assumes that nobody would pay for a sunspot message and then choose the opposite action ("Not Follow"), we found that 2% of decisions actually did so. The reasons may be confusion or curiosity.[5]

In all three treatments, about 10% of all decisions followed the sunspots. Under the high noise of the private signal (PIH), subjects decided more often to "not invest" and less often to "invest" than in the other two treatments. This is in line with previous results on threshold games that subjects are less inclined to take the risky action if there is larger uncertainty about the threshold.

Table 3 Blocks of three rounds

Block	Rounds	Groups
1st	1 to 3	All groups
2nd	4 to 6	All groups
Mid	7 to 9	Only 15-period groups
2nd-last	Second last three rounds	All groups
Last	Last three rounds	All groups

To analyze time trends and learning or coordination effects, we categorize the data in blocks of three rounds. This way of categorizing the rounds serves two purposes. First, it enables us to analyze the data consistently for all groups without differentiating between groups with 12 or 15 rounds. Second, compiling three rounds of data brings a larger number of observations for tests and regression analyses than analyzing each period separately. This makes the regression analysis meaningful while still keeping a sense of time for convergence analysis. To compare subjects' early and late strategies

[5] Since we have a repeated game, subjects might also be interested in learning the sunspot message in order to detect whether the success of the investment was related to the message. Such knowledge might help them to improve their strategies in subsequent rounds. For this reason, we informed them all about the sunspot message during the information phase of each round (after decisions had been taken). It could, thus, not justify paying for the message.

between treatments, we categorize the data as described in Table 3. We refer to the first three rounds as the "1st block," the second three rounds as "2nd," the last three rounds as "Last," the second last three rounds as "2nd-Last," and the remaining rounds (in treatments with 15 rounds) as "Mid."

Figure 4 The relative frequencies of decisions in blocks of three rounds

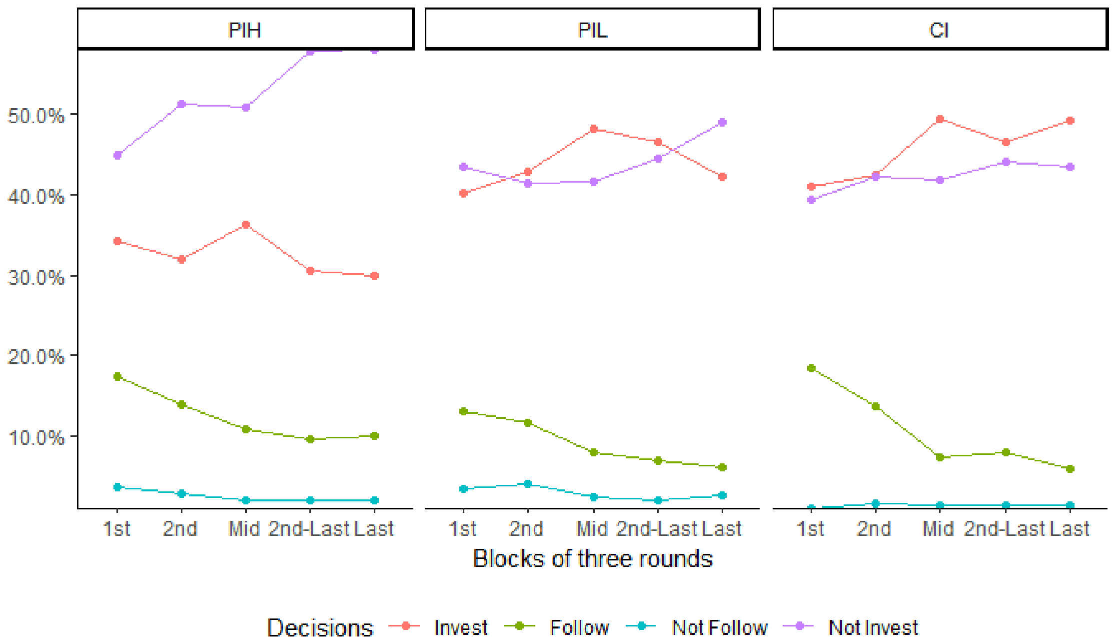
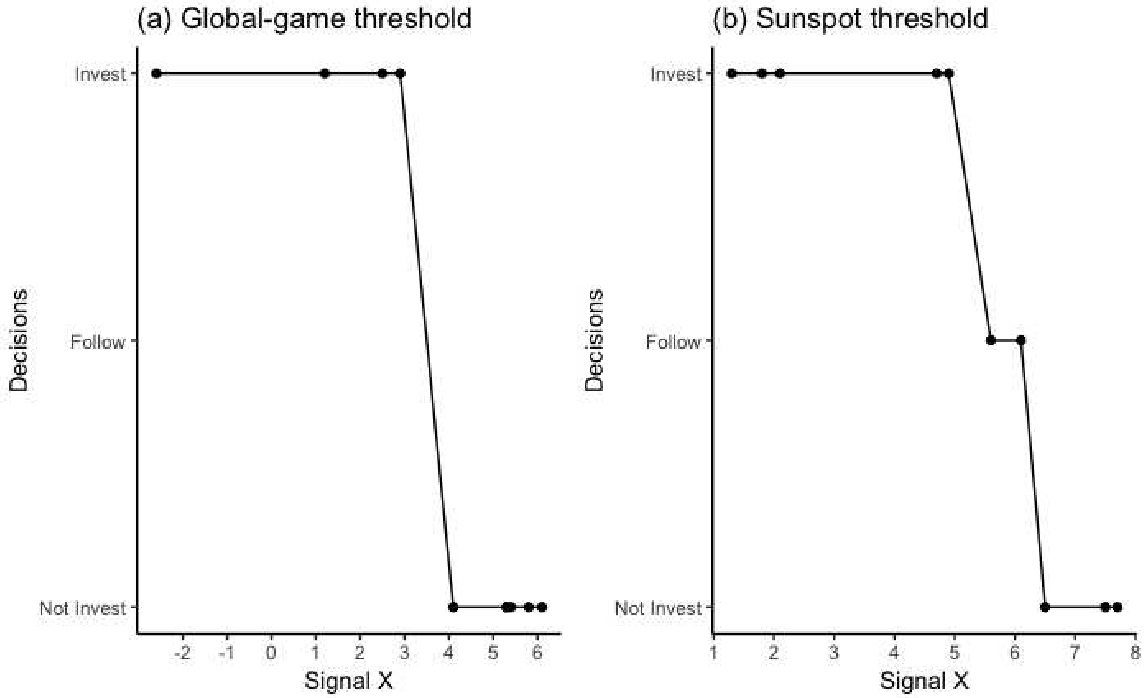


Figure 4 shows how the relative frequencies of the four possible combinations of decisions changed over time. In all treatments, the proportion of decisions that followed the sunspots started to decrease from about 15% in the first block of periods to about 7.5% in the last block. The only other strong trend is the share of "Not Invest" in the PIH treatment, which increased from 45% in the first block to 58% in the last block.

The first hypothesis that we derived from the theories states that subjects use threshold strategies. Recall that in every round, subjects chose whether to purchase the message and also chose A or B for 10 randomly chosen unordered situations. We say that a subject's strategy in a particular period is consistent with the threshold strategies if for low signals the subject invests without looking at the sunspot message, follows the sunspot message for medium signals, and neither looks at the sunspot messages nor invests for high signals without any overlap.

Figure 5 Examples of global-game and sunspot strategies.



If a subject directly switches from "Invest" to "Not Invest" and does not look at sunspot messages for any signal, we call it "global-game" threshold strategy or, in short, "global-game strategy" as illustrated in panel (a) of Figure 5. If a subject follows a threshold strategy looking at sunspots for some intermediate signals, we call it a "sunspot" threshold strategy or in short "sunspot strategy" as illustrated in panel (b) of Figure 5.

Our first hypothesis claims that subjects use threshold strategies. We find strong support for this hypothesis in the data. We find that 78% of choices are consistent with threshold strategies. In particular, 58% of subjects use global-game thresholds, and 20% use sunspot thresholds.

Result 1 (threshold strategies) On average, 78% of strategies are consistent with threshold strategies, increasing to 85% in the last three periods.

The ratio of threshold strategies is clearly smaller than in the experiment by Heinemann et al. (2004), where it was 92% on average. We attribute this to the more complicated set-up of our experiment with four possible combinations of choices instead of only two in their experiment. In fact, we find that 94% of strategies that ignored sunspots are threshold strategies, but only 60% of strategies did not ignore sunspots. The difference can be explained by the fact that following sunspot thresholds with two switching points is a less obvious strategy than following one threshold for a player who ignores sunspots. In addition, subjects who do not use the threshold strategies might have thoughts that are unexplained by our theories and that may also lead them to pay for sunspot messages more often than subjects who behave consistently.

Figure 6 Percentage of threshold strategies.

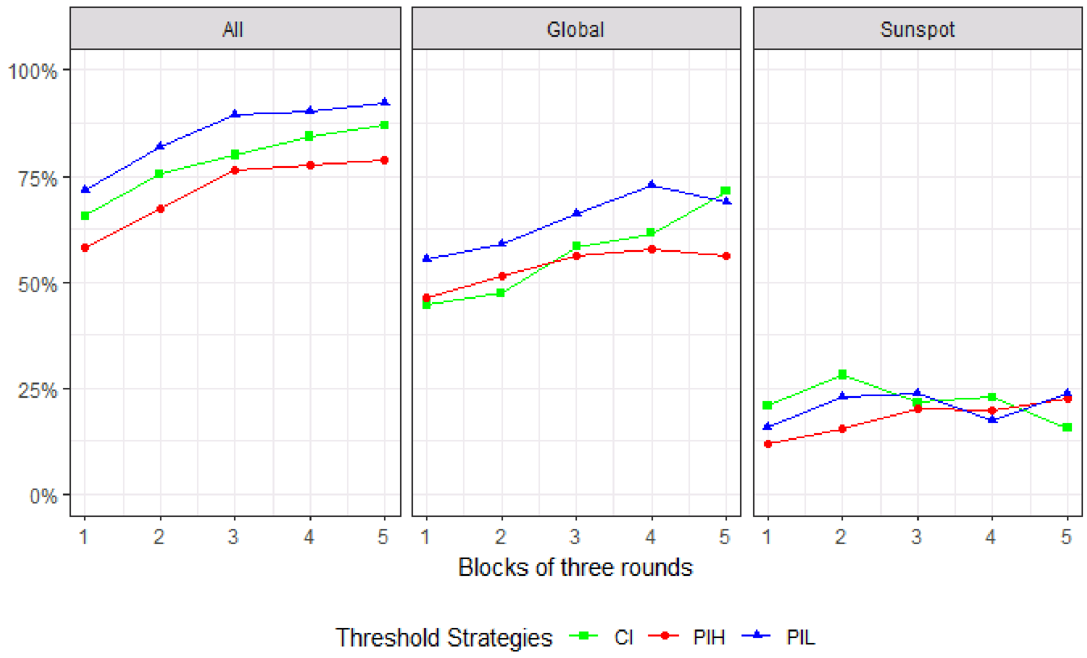


Figure 6 shows that the rate of threshold strategies increases over time from approximately 65% in the first three rounds to 85% in the last three rounds. This increase comes mainly from global-game strategies. Global-game strategies increase from approximately 50% in the first three rounds to 65% in the last three rounds. To determine the statistical significance of these findings we look into the regression analysis.

Table 4 Threshold strategies and rounds.

	Choosing a sunspot or global-game threshold strategy					
	Sunspot PIH	Sunspot PIL	Sunspot CI	Global PIH	Global PIL	Global CI
	(1)	(2)	(3)	(4)	(5)	(6)
Round	0.011***	0.003	-0.009**	0.008	0.013***	0.028***
	(0.004)	(0.003)	(0.003)	(0.005)	(0.003)	(0.006)
Constant	0.093***	0.186***	0.284***	0.477***	0.538***	0.355***
	(0.027)	(0.030)	(0.065)	(0.088)	(0.066)	(0.069)
Observations	912	720	888	912	720	888
R^2	0.015	0.001	0.007	0.004	0.014	0.054
F Statistic	13.833***	0.586	6.666***	3.737*	10.409***	50.783***

*Note: The dependent variable is the proportion of sunspot threshold strategies in the first three panels, and the proportion of global-game threshold strategies in the last three panels. The independent variable is the number of the round. The standard errors are clustered at both group level and subject level. OLS estimates with robust standard errors in parentheses. Logit and probit regressions yield similar results. Stars indicate significance levels: *p<0.1; **p<0.05; ***p<0.01.*

Table 4 shows OLS regressions of the impact of rounds on the likelihood of choosing threshold strategies in the different treatments. The dependent variable for the first three panels is the dummy variable of choosing a sunspot threshold strategy. In the last three panels, the dependent variable is the dummy variable of choosing a global-game threshold strategy.

Since the observations within each group and also by every subject are not i.i.d, the standard errors are clustered at both the group level and the subject level. Logit and probit regressions yield the same qualitative results. The first panel compares the likelihood of choosing a sunspot strategy between CI (treatment dummy = 1) and PIH (treatment dummy = 0), second panel between PIH (treatment dummy = 1) and PIL (treatment dummy = 0), and the third panel between PIL (treatment dummy = 1) and CI (treatment dummy = 0).

Result 2 (Sunspot strategies) On average, 20% of strategies are sunspot threshold strategies.

Our second hypothesis claims that sunspot messages are ignored for all signals as predicted by the standard theory of global games. The first three panels in Table 4 show how the share of sunspot threshold strategies in the different treatments depends on time, here, the period number.

The constant plus the coefficient for "round" gives the estimated share in Round 1. The share of subjects who use sunspot threshold strategies in the first period is 10% in Treatment PIH, 19% in Treatment PIL, and 27% in Treatment CI. The constants are significant in all three treatments. The differences between the constants (and thereby the share of sunspot strategies in a hypothetical Period 0) are significant at p=.005 between PIH and CI and at p=.018 between PIH and PIL.

Result 3 (Sunspot convergence) The rate of sunspot threshold strategies in PIH increases over time, while it does not significantly change in PIL and it decreases in CI.

The rate of sunspot strategies shows different convergence trends in each treatment. The rate of sunspot strategies in the PIH treatment significantly rises by 1.1% (p = 0.006) for every round. This is surprising as one may expect that subjects eventually converge to the global-game equilibrium of not using sunspot strategies. While PIL does not show any significant trend, the rate of sunspot strategies in the CI treatment significantly falls by .9% (p = 0.01) for every round. Given that we have 12 to 15 rounds in each session, the share of sunspot strategies rises to more than 20% in PIH and falls below 20% in CI.

Our result suggests that the convergence analysis depends on the level of signal precision. Although the rate of sunspot strategies decreases over time when the state is common information, this may not be the case if there is private information. In fact, with a high level of noise, the rate of sunspot strategies may increase.

Result 4 (Global-game strategies) On average, 58% of strategies are global-game threshold strategies.

Panels 4 to 6 in Table 4 show OLS regressions where the dependent variable is the likelihood of choosing a global-game threshold strategy. The initial rates of global-game strategy in PIH, PIL, and CI treatments are 49%, 55%, and 38%. This rate is significantly larger in PIL than in CI ($p = 0.046$).

Result 5 (Global-game convergence) The rate of global-game threshold strategies in PIL and CI rises over time, while in PIH it does not significantly change over time.

Over time, the share of subjects who choose global-game strategies rises significantly by about 1.3% per round in PIL and by 2.8% per round in CI. Both trends are significant at ($p < 0.01$). This trend is significantly stronger in the CI treatment compared to both PIL ($p=.074$) and PIH ($p=.009$).

Thus, in treatments PIL and CI, the share of global-game strategies increases over time, while the share of sunspot strategies is constant or decreasing. In treatment PIH, the rate of sunspot strategies rises over time, while the rate of global-game strategies has no significant trend.

Our second hypothesis claims that sunspot messages are ignored as predicted by the standard theory of global games. Indeed, we find that 30% of subjects never buy any sunspot messages. However, the other 70% eventually pay for these messages and then follow them in 83% of these cases. We view this as sufficient evidence to reject Hypothesis 2. Hence, we now turn to an analysis of the values of the switching points and how they depend on treatments. As subjects have an incentive to coordinate their actions, individual thresholds of distinct subjects from the same group are not independent (except for the first period). Thus, we estimate the average switching points of all subjects in a matching group and treat this estimate as one independent observation. We will use these estimates to test whether groups converge to a global-game threshold or to sunspot thresholds. They will also allow us to test comparative statics predictions between treatments and the numerical prediction of the respective global-game equilibrium.

By fitting multinomial logistic functions to the pooled data from three periods of a whole group, we can estimate the probabilities with which subjects in this group and in these periods "invest," "not invest," "follow," or "not follow" conditional on the subjects' signals. In this way, the probability of each action varies between zero and 1 while the sum of all probabilities is equal to 1. The odds ratio for each strategy depends on the values of the explanatory variables through:

$$\ln\left(\frac{prob(Invest)}{prob(Not\ Invest)}\right) = a_I + b_I X$$

$$\ln\left(\frac{prob(Follow)}{prob(Not\ Invest)}\right) = a_F + b_F X$$

$$\ln\left(\frac{prob(Not\ Follow)}{prob(Not\ Invest)}\right) = a_{NF} + b_{NF} X$$

where X is the subjects' signal about the state. By fitting the pooled data of a whole group to a multinomial logistic function, we can compute the fitted probabilities as

$$prob(Invest) = \frac{e^{a_I + b_I X}}{1 + e^{(a_I + b_I X)} + e^{(a_F + b_F X)} + e^{(a_{NF} + b_{NF} X)}}$$

$$prob(Follow) = \frac{e^{a_F + b_F X}}{1 + e^{(a_I + b_I X)} + e^{(a_F + b_F X)} + e^{(a_{NF} + b_{NF} X)}}$$

$$prob(Not\ Follow) = \frac{e^{a_{NF} + b_{NF} X}}{1 + e^{(a_I + b_I X)} + e^{(a_F + b_F X)} + e^{(a_{NF} + b_{NF} X)}}$$

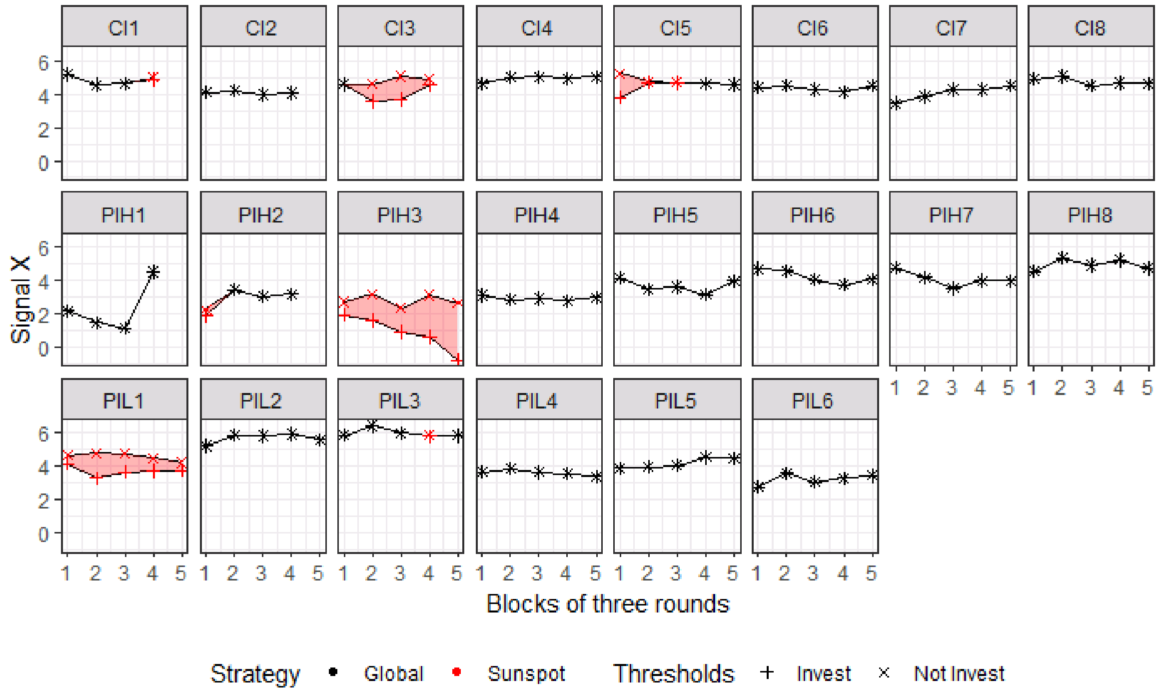
$$prob(Not\ Invest) = \frac{1}{1 + e^{(a_I + b_I X)} + e^{(a_F + b_F X)} + e^{(a_N + b_N X)}}$$

Extending the method employed by Heinemann, Nagel, and Ockenfels (2004) to four potential strategies, we estimate the switching points by the signals at which the most likely action changes from one to another. For low signals, $prob(Invest|X)$ is close to 1 but decreases in X. The probability not to invest rises from 0 to 1 and the probability to follow can eventually exceed both of them for some intermediate signals. If there is a range of signals for which $prob(follow|X) > \max\{prob(Invest|X), prob(Not - invest|X), prob(Not - follow|X)\}$, this range describes the sunspot region. The estimated threshold for switching from "invest" to "follow," X^I, is then given by the smallest value for which $prob(follow|X^I) = prob(Invest|X^I)$. The estimated threshold for switching from to "follow" to "not invest," X^N, is given by the largest value for which $prob(follow|X^N) = prob(Not - Invest|X^N)$.

If both $prob(Follow|X)$ and $prob(Not - follow|X)$ are smaller than $\max\{prob(Invest|X), prob(Not - invest|X)\}$ for all X, the group is said to follow a global-game threshold.

Figure 7 displays for each matching group the range of signals (vertical axis), for which the respective strategy is estimated to be most likely. Black curves indicate the evolution of switching points over the four (respectively 5) blocks of periods (horizontal axis). If there is only one switching point then subjects tend to switch from "invest" to "not invest" directly, that is, they coordinate on a global-game threshold strategy. If there are two switching points, the red region between them indicates the range of signals for which subjects are most likely to follow sunspot messages. All the estimated parameters are provided in Table 8 in the appendix.

Figure 7 Most likely strategies for every group.



Note: The most likely strategy, according to the multinomial logistic regression, is "invest" for signals below the invest threshold, "not invest" for signals above the not-invest threshold, and "follow the sunspot message" for signals in the red area between invest threshold and not-invest threshold.

Result 6 (Estimated thresholds) In approximately one-third of groups, there is a range of signals for which following sunspot messages is eventually the most likely action.

The results show strong differences between the groups in all three treatments. In approximately, one-third of groups, there is a region of signals for which following the sunspot is the most likely action in at least some periods. While groups PIL1 and PIH3 coordinate on sunspots for some range of signals in all blocks of three periods, other groups such PIL3, PIH2, CI1, CI3, and CI5 coordinate on sunspots for at least one block of three periods. The remaining groups (68%) always tend to switch directly from "invest" to "not invest."

Table 5 The coordination within the group and the time.

	The standard deviation within groups		
	PIH	PIL	CI
	(1)	(2)	(3)
Time	-2.327***	-1.882	-1.755**
	(0.723)	(1.625)	(0.715)
Constant	16.341***	11.839	9.811***
	(3.381)	(7.368)	(2.795)
Observations	38	30	37
R^2	0.194	0.095	0.246
F Statistic	8.662***	2.929*	11.394***
Note:	*p<0.1; **p<0.05; ***p<0.01		

*Note: The dependent variable is the overall standard deviation within a group. The independent variable is time as blocks of three rounds. The standard errors are clustered at the group level. OLS estimates with robust standard errors in parentheses.*p<0.1; **p<0.05; ***p<0.01*

The standard deviations of the fitted logistic functions, $\frac{\pi}{b_I\sqrt{3}}$, $\frac{\pi}{b_F\sqrt{3}}$, and $\frac{\pi}{b_{NF}\sqrt{3}}$ are measures of coordination within the group. The higher the parameters b_I, b_F, and b_{NF} are, the smaller the variation of thresholds is between different members of the same group. The overall standard deviation of the fitted logistic functions, $\sqrt{(\frac{\pi}{b_I\sqrt{3}})^2 + (\frac{\pi}{b_F\sqrt{3}})^2 + (\frac{\pi}{b_{NF}\sqrt{3}})^2}$ is an inverse measure of coodination within a group[6].

Result 7 (Coordination convergence) Overall, the coordination within groups increases over time in PIH and CI.

[6] Note that if nobody buys a sunspot message then $prob(Follow) = 0$ and $\frac{\pi}{b_F\sqrt{3}}$=0.

Comparing these estimates between blocks of the same group indicates that the overall standard deviation is decreasing over time in PIH and PIL (Table 5). In PIH and CI treatments, the overall standard deviations within groups are significantly different from zero. Thus, there is room to improve the coordination. And the coordination does get to improve over time. However, in the PIL treatment, the overall standard deviation is never significantly different from zero. This suggests that in some groups there is a high level of coordination from the start.

Result. 8 (Relative frequency I) The set of signals for which subjects might follow sunspot messages in Treatment PIH is approximately three times larger than in treatments PIL and CI

Table 6 estimates the impact of signals and rounds on the likelihood of following the sunspot message. Here, we pool the data from all the groups to get an overall estimate of the likelihood subjects will follow the sunspots. The quadratic form of OLS is used because the extended global game predicts that subjects follow the sunspots at intermediate signals around the prior mean of 4.5 (see Figure 2). "Signal^2" is the squared deviation of signals from their mean, which is 4.5. In this regression, the linear term "Signal" is accordingly defined as the actual signal minus the prior mean. The OLS estimates show that the linear term is insignificant in all treatments. Thus, there is no bias in looking at sunspots for higher or lower signals.

Table 6 The likelihood of following the sunspot message, signal, and rounds.

	Probability to follow the sunspot		
	PIH	PIL	CI
	(1)	(2)	(3)
Signal2	-0.00043	-0.00306**	-0.00281***
	(0.00057)	(0.00125)	(0.00084)
Signal	-0.00658	-0.00203	-0.00156
	(0.00421)	(0.00461)	(0.00193)
Round	-0.00627**	-0.00665***	-0.01256***
	(0.00244)	(0.00075)	(0.00242)
Constant	0.17638***	0.16256***	0.22030***
	(0.03712)	(0.04163)	(0.04152)
Observations	9,120	7,200	8,880
R2	0.01088	0.01726	0.03232
F Statistic	33.43718***	42.12666***	98.82627***

Note: The dependent variable is the following sunspot dummy variable. The independent variables centered signal, centered signal squared, and rounds. OLS estimates with robust standard errors in parentheses. The standard errors are clustered at both the group level and the subject level. Same interpretation holds for logit and probit regressions.

The quadratic term is significant for treatments PIL and CI with negative coefficients, which supports the predictions of the extended global game: the probability of following sunspots is hump-shaped around the prior mean. In Treatment PIH the coefficient of the quadratic term is also negative but insignificant. Here, subjects eventually look at sunspot messages irrespective of their signals. The round number has a significant and negative impact on the likelihood of following sunspots in all three treatments. This indicates that subjects tend to look at sunspots less frequently in the later periods, a finding that we have already seen in Figure 4.

Using the estimated coefficients, we can calculate the range of signals for which the probability of following sunspots is positive. For Treatment CI, this range shrinks from [-3, 11] in the first round to [0, 8] in Round 15. For Treatment PIL, the range is [-4, 13] in the first round and [1, 7] in Round 15. This range is largest in treatment PIH: due to the low coefficient on the quadratic term it is given by [-26, 19] in the first round and by [-20, 13] in Round 15. This range for the average rounds are depicted in Summarizing, we see that independent of the treatment only a minority of groups coordinates on a sunspot-threshold strategy. Nevertheless, about 20% of all subjects follow sunspot-threshold strategies and in treatments with CI or private information with low noise (PIL) the probability of subjects following sunspots is positive for a range of signals that is centered around the prior mean of signals. These are the situations with the highest strategic uncertainty. As we argued in the theory section of this paper, the reason why subjects follow sunspots might be that they put an exogenous probability on other subjects following these sunspots. This reasoning implies that the expected number of subjects following sunspots is higher than the actual number of subjects who follow sunspots (Hypothesis 5).

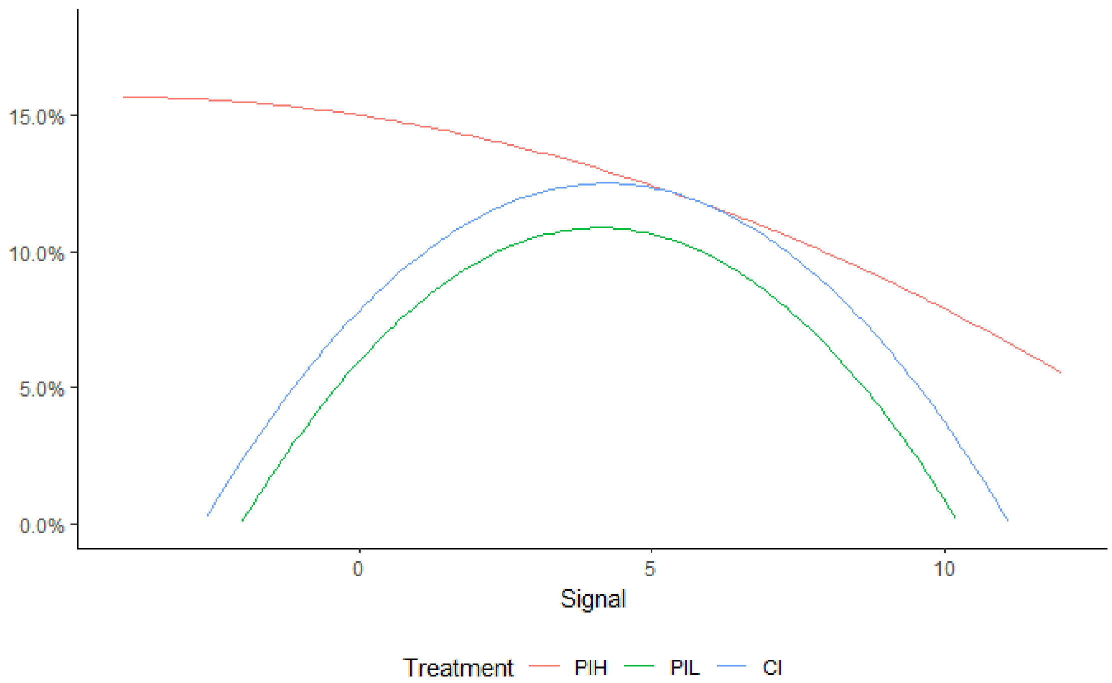
Figure 8. Thus, the qualitative comparative statics are consistent with Hypothesis 3.

There is no significant difference in the impact of the signal on the probability of following the sunspot between PIL and CI. Coefficients do not change significantly between CI and PIL treatments. This is consistent with Hypothesis 4.

Summarizing, we see that independent of the treatment only a minority of groups coordinates on a sunspot-threshold strategy. Nevertheless, about 20% of all subjects follow sunspot-threshold strategies and in treatments with CI or private information

with low noise (PIL) the probability of subjects following sunspots is positive for a range of signals that is centered around the prior mean of signals. These are the situations with the highest strategic uncertainty. As we argued in the theory section of this paper, the reason why subjects follow sunspots might be that they put an exogenous probability on other subjects following these sunspots. This reasoning implies that the expected number of subjects following sunspots is higher than the actual number of subjects who follow sunspots (Hypothesis 5).

Figure 8 Probability of following sunspot messages.



Note: The probability of following sunspot messages are based on estimated values for an OLS regression similar with averaged rounds.

Result. 9 (Belief overestimation) Subjects expect, on average, 1.79 players to follow sunspots while, on average, 0.87 players follow sunspots.

This general finding is consistent with Hypothesis 5. Of course, the degree to which subjects overestimate the number of followers differs between subjects and depends on the signals. While in 30% of all decisions subjects expect the right number of players to follow sunspots, in 53% of all decisions subjects overestimate the number of followers. In the remaining 17% of all decisions, subjects underestimate the number of followers. “Belief overestimation” is the difference between subjects’ stated beliefs about the number of followers and the actual number of followers.

Table 7 Beliefs overestimation

	Beliefs overestimation		
	PIH	PIL	CI
	(1)	(2)	(3)
Signal	0.01851**	0.00313	0.03688**
	(0.00920)	(0.02265)	(0.01540)
$Signal^2$	-0.00831***	-0.01539*	-0.01742**
	(0.00134)	(0.00927)	(0.00707)
Round	-0.02615*	-0.03020	-0.00651
	(0.01490)	(0.01920)	(0.02354)
Constant	1.28140***	1.11674***	1.08606***
	(0.21285)	(0.23877)	(0.25475)
Observations	9,120	7,200	8,880
R^2	0.00964	0.01106	0.00951
F Statistic	29.58781***	26.82091***	28.40256***

Note: The dependent variable is the rate of belief overestimation. The independent variables centered signal, centered signal squared, and round. OLS estimates with robust standard errors in parentheses. The standard errors are clustered at both group level and subject level.

This general finding is consistent with Hypothesis 5. Of course, the degree to which subjects overestimate the number of followers differs between subjects and depends on the signals. While in 30% of all decisions subjects expect the right number of players

to follow sunspots, in 53% of all decisions subjects overestimate the number of followers. In the remaining 17% of all decisions, subjects underestimate the number of followers. "Belief overestimation" is the difference between subjects' stated beliefs about the number of followers and the actual number of followers.

Table 7 shows the impact of signals and rounds on this difference for all treatments. As in the regressions in Table 1, "signal" stands for the actual signal minus its prior mean of 4.5. In all treatments, the rate of belief overestimation is hump-shaped, as indicated by the significant negative coefficients on "$signal^2$". In treatments PIH and CI, subjects tend to overestimate the number of followers more for larger signals than for smaller signals. Although the coefficients for the round number are negative in all three treatments, they are insignificant in CI and PIL and only marginally significant in PIH. This indicates that belief overestimation is not strongly declining over time. Note that subjects did not get an immediate feedback about the number of followers. They could only infer this from their feedback about the total number of subjects who chose A or B in situations with different realizations of the sunspot message.

4. Conclusions

The theory of global games delivers a key solution to coordination games with strategic complementarities by assuming common knowledge of rationality. This paper makes three contributions in that regard. The first two are theoretical. By assuming that agents believe that some fraction of other agents naïvely follows sunspots, we provide a condition for a unique equilibrium in which agents follow costly sunspot messages even with private signals about fundamentals, while the standard theory of global games predicts that behavior is unaffected by sunspots when agents receive private information about fundamentals. Our second theoretical contribution is to address the role of transparency on the thresholds for sunspot-following behavior: under the assumption of an exogenously given belief in naïve sunspot followers, the range of signals for which otherwise rational agents choose to follow sunspots does not disappear if the precision of private signals converges to infinity. As long as the costs for obtaining sunspot messages are sufficiently small, there exists a positive range of fundamentals for which agents follow sunspots even with rather precise private information about these fundamentals. By means of simulation, we have shown that the range of signals for which subjects follow sunspots in equilibrium may widen if private signals get very imprecise. In this respect, transparency about fundamentals may reduce the impact of extrinsic signals on behavior and, thus, central banks or bank supervisors may want to provide sufficient information about economic fundamentals in order to avoid rumors or uninformative signals triggering currency or banking crises.

Our third contribution tests the predictive power of the extended global game in a laboratory experiment. In all information conditions, some subjects use global-game threshold strategies and may eventually coordinate on a common threshold strategy where they follow sunspot messages in situations with high strategic uncertainty. However, most groups converge to classical global-game strategies that neglect sunspots. The comparative statics of the sunspot global-game solution with respect to the level of signal precision cannot be confirmed. This is in line with other experiments on global games like Heinemann et al., (2004) or Szkup & Trevino (2017), who also find that the empirical evidence on responses to the precision of private information does not follow the comparative statics of global-game thresholds. In those papers, more precise information leads to a better coordination on the efficient action, which is “invest” in our game.

Elicited beliefs reveal that subjects overestimate the number of subjects who follow sunspots by about 100% on average. This is in line with the assumptions of our extended global game and presumably drives subjects to follow sunspots. Fearing that others follow sunspots eventually drives the coordination toward a sunspot threshold strategy, even though such a strategy is not a Nash equilibrium. From our theoretical analysis and the experiment we conclude that in environments with high strategic uncertainty, payoff-irrelevant signals can affect behavior even if they are costly to obtain and not expected to be publicly observed.

The overestimation of sunspot-following behavior and the actual proportion of subjects who follow sunspots are independent of the level of noise. Thus, no amount of transparency can prevent agents from following sunspots if they are fearful of others doing so. In this regard, the interaction between the fear that others might follow sunspots and the historic relation between sunspot messages and the final outcome as an indicator of the message’s credibility becomes crucial, and how public announcements can influence this interaction is a key question for future research.

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Appendix

Multinomial logistic estimation

Table 8 displays the results of multinomial logistic regressions to estimate parameters and standard deviation of individual thresholds in each group for every block of three rounds.

Table 8 Multinomial logistic regression

Group	Time	aI	bI	aF	bF	aNF	bNF	Overall sd
CI1	1	2.569	-0.497	0.666	-0.154	NA	NA	0.943
CI1	2	4.050	-0.891	2.349	-0.626	-4.203	0.322	2.059
CI1	3	6.807	-1.473	5.052	-1.214	1.691	-0.832	3.776
CI1	4	12.007	-2.424	7.906	-1.580	-5.132	0.371	5.291
CI2	1	3.166	-0.773	-2.400	-0.064	NA	NA	1.408
CI2	2	3.607	-0.863	-2.088	-0.251	NA	NA	1.629
CI2	3	5.264	-1.332	-1.889	-0.339	NA	NA	2.493
CI2	4	5.331	-1.316	-1.856	-0.580	NA	NA	2.608
CI3	1	6.650	-1.453	4.058	-0.890	2.649	-1.314	3.903
CI3	2	9.281	-2.334	4.219	-0.914	2.077	-1.033	4.917
CI3	3	8.011	-1.871	4.240	-0.838	4.310	-1.352	4.455
CI3	4	16.327	-3.434	10.128	-2.075	11.233	-2.586	8.657
CI4	1	2.525	-0.546	0.824	-0.342	-1.829	-0.170	1.209
CI4	2	7.853	-1.568	3.060	-0.667	3.618	-1.307	3.895

Group	Time	aI	bI	aF	bF	aNF	bNF	Overall sd
CI4	3	38.492	-7.663	30.624	-6.109	32.777	-7.426	22.303
CI4	4	39.369	-7.995	29.800	-6.160	8.592	-1.995	18.661
CI4	5	44.350	-8.820	3.310	-1.103	1.357	-0.955	16.214
CI5	1	4.168	-0.927	2.349	-0.448	1.971	-1.513	3.319
CI5	2	6.226	-1.316	3.677	-0.774	1.687	-0.648	3.008
CI5	3	11.953	-2.557	7.268	-1.552	6.790	-1.994	6.521
CI5	4	25.093	-5.413	11.450	-2.511	9.472	-2.657	11.848
CI5	5	29.423	-6.462	16.068	-3.629	21.232	-5.046	16.263
CI6	1	3.591	-0.818	0.553	-0.462	-1.265	-0.551	1.976
CI6	2	4.758	-1.069	NA	NA	NA	NA	NA
CI6	3	9.368	-2.196	0.323	-0.987	0.013	-0.916	4.672
CI6	4	4.329	-1.046	-2.082	-0.536	NA	NA	2.132
CI6	5	4.451	-1.121	NA	NA	NA	NA	NA
CI7	1	1.914	-0.555	0.720	-0.328	-1.826	-0.399	1.374
CI7	2	3.152	-0.817	0.803	-0.495	NA	NA	1.733
CI7	3	3.416	-0.803	1.205	-0.758	NA	NA	2.002
CI7	4	3.941	-0.923	2.400	-0.922	-1.915	-0.333	2.442
CI7	5	4.386	-0.975	2.452	-1.020	-1.213	-0.716	2.871
CI8	1	4.205	-0.858	2.268	-0.525	-1.226	-0.358	1.936
CI8	2	3.807	-0.754	1.551	-0.380	NA	NA	1.531
CI8	3	3.815	-0.846	1.463	-0.479	0.720	-0.566	2.041
CI8	4	6.542	-1.401	1.078	-0.490	0.448	-0.640	2.932
CI8	5	6.592	-1.422	2.536	-0.847	0.162	-0.955	3.466
PIH1	1	0.848	-0.394	-1.869	-0.114	NA	NA	0.744

Group	Time	aI	bI	aF	bF	aNF	bNF	Overall sd
PIH1	2	1.425	-0.983	-4.780	0.044	-9.460	0.541	2.037
PIH1	3	1.452	-1.302	-2.977	-0.695	-5.282	0.130	2.687
PIH1	4	1.107	-1.573	NA	NA	NA	NA	NA
PIH2	1	0.600	-0.282	0.392	-0.171	-1.188	-0.376	0.907
PIH2	2	1.882	-0.547	1.258	-0.385	-1.130	-0.480	1.494
PIH2	3	1.292	-0.424	0.100	-0.215	-0.464	-0.534	1.297
PIH2	4	1.991	-0.631	0.934	-0.417	-0.834	-0.247	1.444
PIH3	1	1.213	-0.526	0.708	-0.262	-4.346	-0.079	1.075
PIH3	2	2.088	-1.061	0.835	-0.265	-2.634	-0.105	1.993
PIH3	3	1.466	-1.065	0.844	-0.363	-2.689	-0.239	2.086
PIH3	4	2.593	-1.249	2.290	-0.737	-1.205	-0.469	2.764
PIH3	5	1.446	-1.053	1.753	-0.664	-2.678	-0.124	2.270
PIH4	1	1.950	-0.629	-0.184	-0.187	-0.134	-0.487	1.482
PIH4	2	1.898	-0.669	-0.431	-0.245	-1.835	-0.447	1.526
PIH4	3	2.623	-0.903	0.131	-0.503	-1.073	-0.563	2.134
PIH4	4	1.860	-0.669	-1.117	-0.268	-2.969	-0.253	1.386
PIH4	5	2.261	-0.762	-0.230	-0.353	-1.995	-0.317	1.628
PIH5	1	1.857	-0.449	0.280	-0.333	0.067	-0.596	1.482
PIH5	2	1.231	-0.355	0.110	-0.415	-1.200	-0.277	1.111
PIH5	3	1.961	-0.544	0.388	-0.368	0.100	-0.537	1.539
PIH5	4	2.065	-0.658	1.013	-0.451	-0.441	-0.513	1.720
PIH5	5	4.962	-1.254	2.918	-0.921	2.210	-1.032	3.386
PIH6	1	3.033	-0.648	0.643	-0.498	0.229	-0.686	1.935
PIH6	2	3.818	-0.835	-0.239	-0.414	-0.019	-0.554	1.967

Group	Time	aI	bI	aF	bF	aNF	bNF	Overall sd
PIH6	3	5.180	-1.288	1.735	-0.811	0.167	-1.132	3.440
PIH6	4	5.404	-1.444	0.733	-0.610	-0.054	-0.879	3.260
PIH6	5	5.279	-1.296	0.518	-0.545	-0.676	-0.823	2.955
PIH7	1	1.534	-0.325	0.664	-0.142	-0.424	-0.169	0.712
PIH7	2	3.033	-0.728	1.093	-0.297	-0.389	-0.211	1.476
PIH7	3	2.982	-0.850	-0.137	-0.232	-1.481	-0.288	1.681
PIH7	4	6.498	-1.629	0.695	-0.402	1.194	-0.629	3.251
PIH7	5	4.376	-1.104	0.754	-0.417	-0.566	-0.448	2.290
PIH8	1	2.119	-0.469	-0.143	-0.151	-0.620	-0.427	1.182
PIH8	2	5.638	-1.055	0.326	-0.280	1.967	-0.809	2.464
PIH8	3	6.946	-1.417	-1.316	-0.332	NA	NA	2.640
PIH8	4	8.632	-1.655	1.706	-0.685	NA	NA	3.249
PIH8	5	11.169	-2.369	1.636	-0.725	NA	NA	4.494
PIL1	1	5.926	-1.364	2.134	-0.457	-1.850	-0.045	2.610
PIL1	2	5.962	-1.570	2.463	-0.509	-3.120	-0.054	2.995
PIL1	3	8.842	-2.004	6.471	-1.356	-0.071	-0.320	4.427
PIL1	4	11.451	-2.673	8.267	-1.822	-5.325	0.370	5.906
PIL1	5	9.967	-2.427	7.208	-1.696	-0.291	-0.289	5.395
PIL2	1	7.507	-1.433	4.717	-0.976	-1.403	-0.298	3.190
PIL2	2	13.146	-2.235	6.556	-1.194	2.319	-0.715	4.776
PIL2	3	15.172	-2.599	2.251	-0.585	4.692	-1.068	5.205
PIL2	4	16.997	-2.855	-0.104	-0.315	NA	NA	5.210
PIL2	5	40.521	-7.238	2.569	-0.483	19.816	-3.828	14.876
PIL3	1	7.876	-1.339	4.427	-0.817	3.914	-0.869	3.251

Group	Time	aI	bI	aF	bF	aNF	bNF	Overall sd
PIL3	2	26.362	-4.085	19.929	-3.145	22.906	-3.776	11.591
PIL3	3	19.992	-3.320	13.219	-2.378	14.321	-2.788	8.968
PIL3	4	55.190	-9.431	29.610	-5.033	-0.947	-0.320	19.398
PIL3	5	13.376	-2.286	4.459	-1.025	2.236	-0.826	4.784
PIL4	1	3.905	-1.061	1.230	-0.566	0.826	-0.754	2.575
PIL4	2	7.651	-1.978	1.694	-0.674	3.696	-1.298	4.462
PIL4	3	8.173	-2.235	3.040	-0.987	-1.423	-0.194	4.446
PIL4	4	4.405	-1.228	0.969	-0.665	1.310	-0.773	2.895
PIL4	5	7.322	-2.149	-0.692	-0.383	2.360	-0.964	4.328
PIL5	1	4.433	-1.138	1.065	-0.781	-0.542	-1.024	3.116
PIL5	2	12.001	-3.019	4.056	-1.612	2.546	-1.326	6.657
PIL5	3	16.371	-4.018	6.741	-2.336	NA	NA	8.429
PIL5	4	17.993	-3.953	9.128	-2.816	NA	NA	8.804
PIL5	5	26.235	-5.958	NA	NA	NA	NA	NA
PIL6	1	1.408	-0.505	-0.016	-0.403	-1.090	-0.384	1.364
PIL6	2	3.168	-0.881	1.169	-0.550	0.802	-0.520	2.107
PIL6	3	3.977	-1.293	-0.089	-0.504	-1.249	-0.539	2.701
PIL6	4	5.502	-1.659	1.991	-1.020	0.425	-0.797	3.817
PIL6	5	8.579	-2.484	1.497	-0.788	3.719	-1.621	5.567

Instructions

[All Treatments]

General information

This is an experiment in economic decision-making that gives you a chance to earn money. This will be paid to you privately at the end of the experiment. We ask that you do not communicate with each other from now on. If you have a question, please raise your hand.

You are randomly divided into three groups of 8 participants, which will persist for the duration of the experiment. The rules are the same for all participants. The experiment is divided into 15 independent rounds. Each round consists of a decision-making and an information phase. In the decision phase of each round you will be presented with 10 games in which you have to make three decisions each:

- whether to view a message,
- whether to choose A or B
- What is your guess about the number of participants in your group that read the message?

At the end of the 15 rounds, 2 rounds will be randomly chosen to determine your payouts.

Rules of the games:

The rules are the same in all games.

Random processes

In each game, a number X is randomly selected. This number X is the same for all participants in your group. The probability distribution of X looks like this:

Figure 1: Probability density function of X

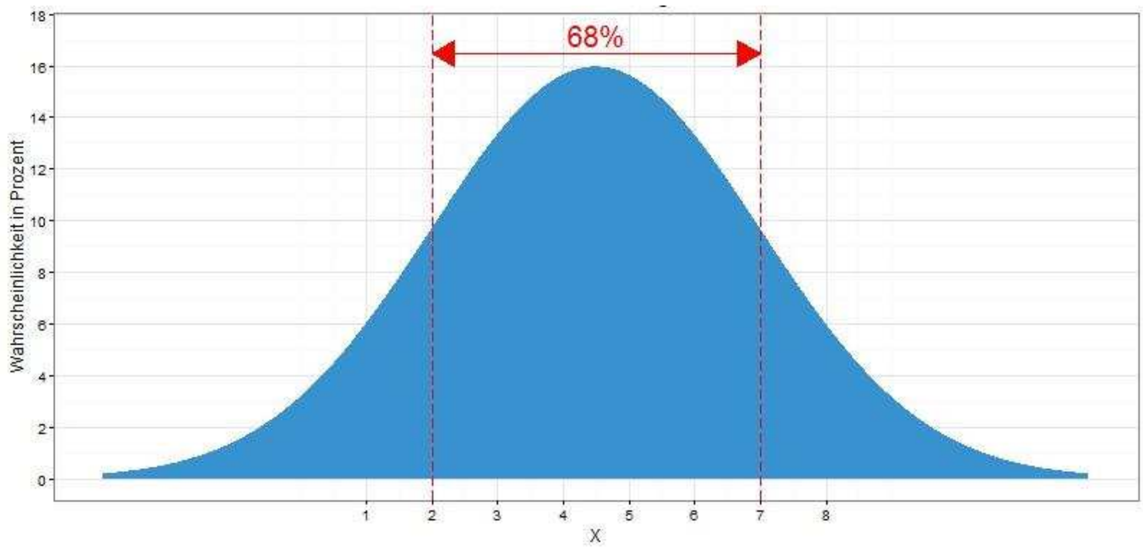
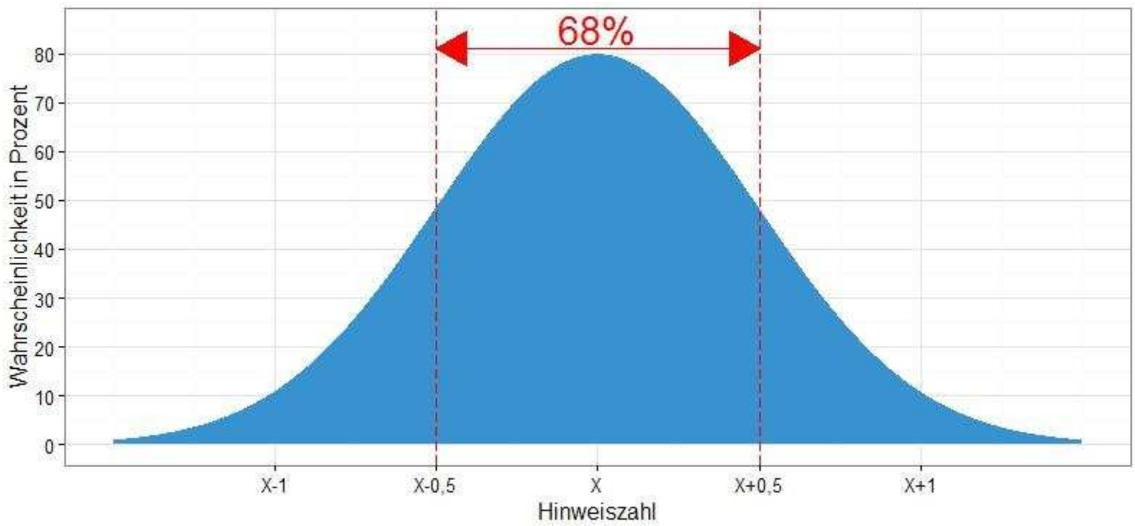


Figure 1 shows the density function of the number X. This density function is a normal distribution with expectation 4.5 and a standard deviation of 2.5. Figure 1 shows that in 68% of all cases, the number X is between 2 and 7. Numbers closer to 4.5 are more likely than numbers farther from 4.5.

[Only in private treatments]

At the moment of your decision, you do not know what number X is drawn. However, each participant receives a hint about the unknown number X. A hint is a hint number that is normally distributed around the true number X.

Figure 2 shows the distribution of hints for any number X.



The distribution of the hint numbers is a normal distribution with a mean value X and a standard deviation of [PIL: 0.5 /PIH: 2]. In 68% of cases, the hint number falls between [PIL: X-0.5 /PIH: X-2], and [PIL: X+0.5 /PIH:X+ 2].

This means that the hint number can take any value. However, the hint numbers closer to the unknown number X are more likely than the hints further away from X. If the unknown number is X=4.32 then your hint number is taken from a distribution with mean 4.32 and standard deviation [PIL: 0.5 /PIH: 2]. So, with a probability of 68%, your hint number will be between [PIL: 3.82 and 4.82 /PIH: 2.32 and 6.32].

Conversely, the number X can take any value, but the numbers that are closer to your hint number are more likely than the numbers farther from the hint number.

The hint numbers are drawn independently from the same distribution for each participant. Therefore, different participants will usually receive different hint numbers.

[In all treatments]

In addition, the computer generates a message in each game. With a 50% probability, the message is “Choose A,” with a 50% chance the message is “Choose B.” You can view the message for a fee. The text of the message is the same for all participants who look at it.

The message is generated purely by chance and is independent of the number X [PIL and PIH: and the hint numbers].

Decisions:

Each participant has the opportunity to read the message by clicking on “Read message.” This will cost 1 Experimental Currency Unit (ECU). The text is the same for all participants, but only those participants who pay 1 ECU can see it.

Each participant must choose between A and B.

Each participant makes a guess about how many of the 8 participants (including yourself) have selected “Read Message.”

<u>If you choose A</u>, you will be credited ECU 33. The amount will be reduced to 32 ECU if you read the message. This payout is the same in all games, overall rounds, and for all participants.

<u>If you choose B</u>, your payout will depend on how many of the other participants have chosen B in the same game and how big the unknown number X is. If at least X members of your group opt for B then Action B is successful and you get 58 ECU. If less than X group members choose B, then B is unsuccessful and you receive 8 ECU. The payouts are reduced to 57 or 7 ECU if you have read the message.

Note:

If the unknown number X is less than or equal to 1, then action B succeeds regardless of the decisions of the other participants.

If the unknown number X is greater than 8, then action B is unsuccessful even if all 8 participants choose B.

[Only in CI: The number X is given with 2 decimal places. Since at least X participants must choose B to be successful, you must round X to the next highest whole number to get the required number of B decisions.]

In each game, you will also be asked how many of the 8 participants (including yourself) have chosen "Read message." Here, you can enter numbers from 0 to 8. You will get ECUs for your guess. The closer you are to the true number of people who have chosen "Read message" the more points you get. Your payout is:

12 ECU minus the absolute amount of the difference between your guess and the true number of participants who read the message

12 ECU -| *the true number of those who choose "Read message" - your guess* |.

For example, if you do not read the message, but suspect that 4 of the other participants have selected "Read message," while in fact, only 2 participants have read the message, the absolute difference is 2 and you will therefore receive 10 ECU for your guess.

If you have made your decisions for A or B and have entered your guesses, please click on the red OK button to submit your decision.

After all participants have made their decisions for the 10 games and clicked on the red OK button, the round is over and the next round follows.

At the end of the 15 rounds, one round is randomly selected. You will receive the payout of your decisions between A and B for this round. From the remaining 14 rounds, one more round is randomly selected in which you receive your payout for the guesses about the number of participants who have read the message.

The rounds to be paid out will be communicated to you after the 15 rounds have expired. The selection of the rounds to be paid out is purely random and does not depend on your decisions. That means any decision you make may be relevant to your fee.

Information after each round:

Each participant receives information about the 10 different games after each round:

[In PIL and PIH: your hint]

[In PIL and PIH: the previously unknown] number X,

the text of the message,

how many participants (including you) opted for B

whether action B was successful,

your own payout, which results from your decision between A and B,

You will not receive information about how many participants read the message. You will receive this information only after the last round and only for the round that will be paid out.

Example:

The number of participants is eight. The unknown number X that was drawn is 4.28.

The hint numbers of the participants are: 3 .12, 4.35, 3.96, 4.60, 3.88, 5.96, etc.

The message is “Select B.”

Three participants read the message. This will cost them 1 ECU each.

Two of the participants choose A, the other six take B.

In order to receive a positive payout, at least 4.28, i.e., 5 participants have to choose B. Since 6 participants have chosen B, each of the B-decision-makers receives 58 ECU. The participants who have chosen A receive 33 ECU. For those who read the message, the payouts are reduced by 1.

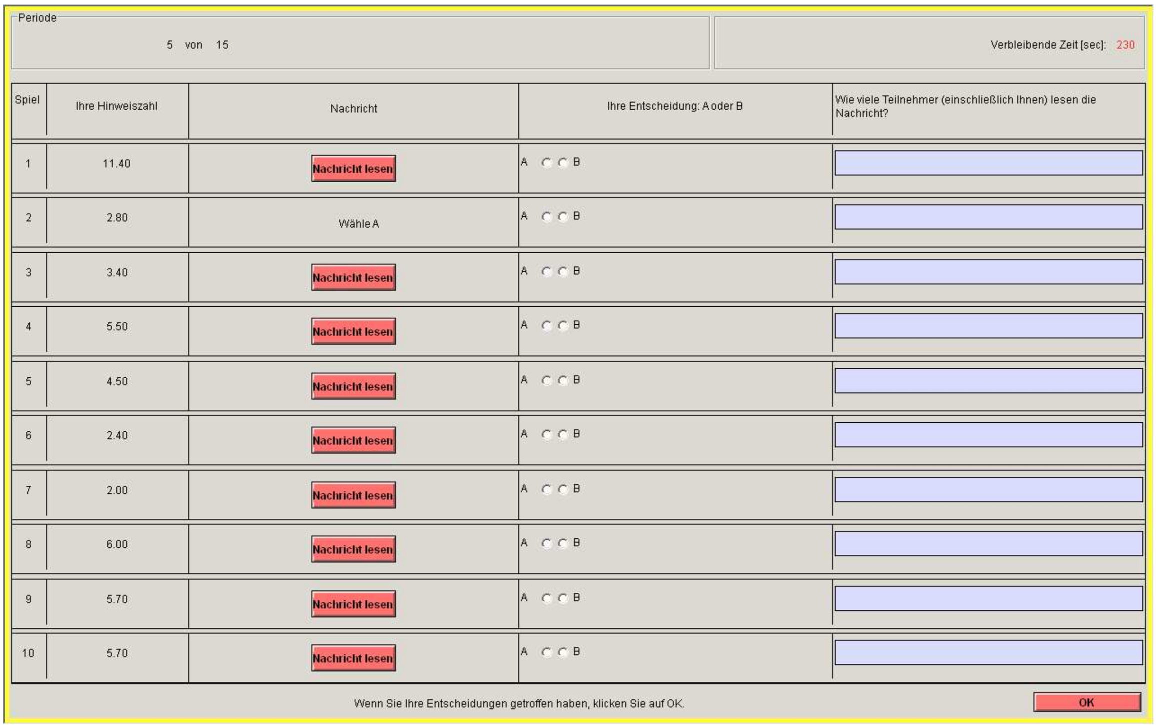
[In PIH and PIL: Keep in mind that you do not know the true value of X, but you will only get a hint number that approximates X. You should also note that the text of the message is neither related to the true value of X nor to the hint number. Therefore, you can never predict exactly how many of the other participants choose B.]

[In CI: Note that the text of the message is not related to the value of X.]

Instructions for the PC:

Each round is divided into a decision phase and an information phase. In the decision phase, the current number of rounds will be displayed on the screen in the header. Below is a table with 10 games. For each game you will be given the value of the [PIH and PIL: hint /CI: X] number. In the next column you have the possibility to read the message by clicking on the corresponding button. As soon as you click on the “Read message” button, you will see the text “Choose A” or “Choose B.” You cannot undo this decision. In the fourth column you have to choose between A and B. In the last column, enter your guess about the number of participants (including yourself) who have read the message. If you have made your decisions for all 10 games, please click the red OK button. You can change your decisions until you have clicked the OK button. If you have exceeded the time limit, you will be advised to make your decisions.

Fig. 3: Screenshot of the decision phase



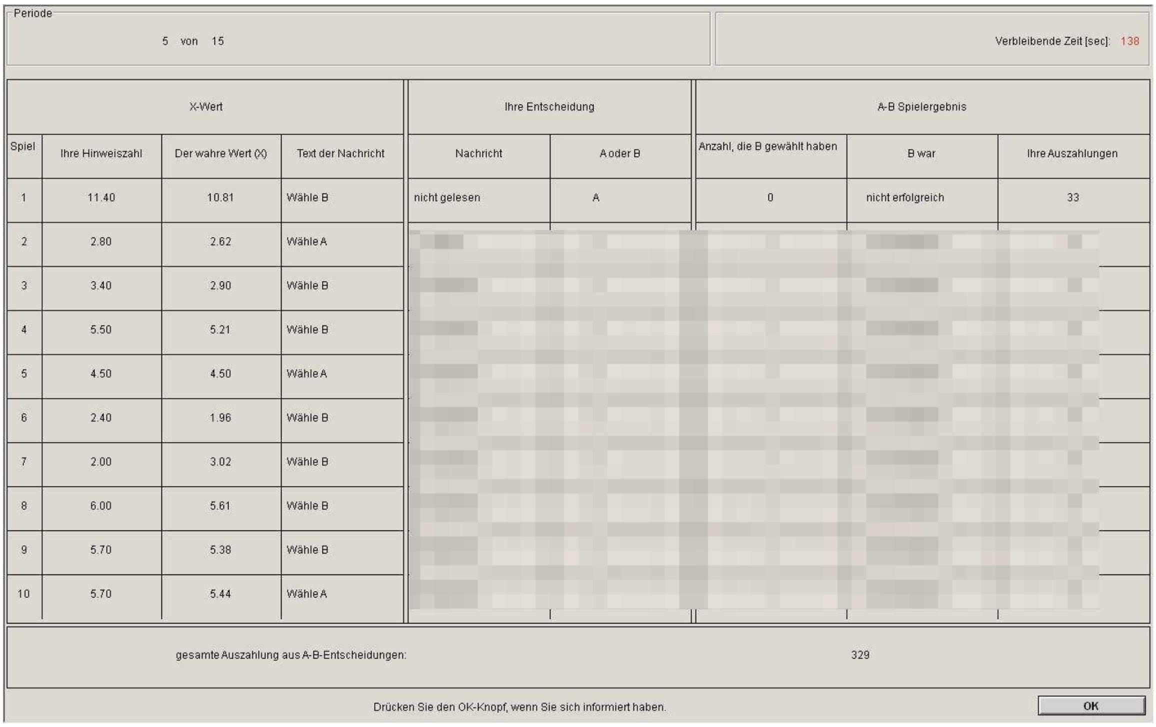
Once all participants have clicked the OK button, the decision phase of a round is completed and the information phase begins. A new table consisting of 3 parts will be displayed on your screen. The first part, titled “X value,” gives [PIH and PIL: your personal hint number,] the unknown value X and the text of the message for each game.

The next part, consisting of 3 columns, with the heading “your decision,” indicates whether you have read the message and whether you have chosen A or B.

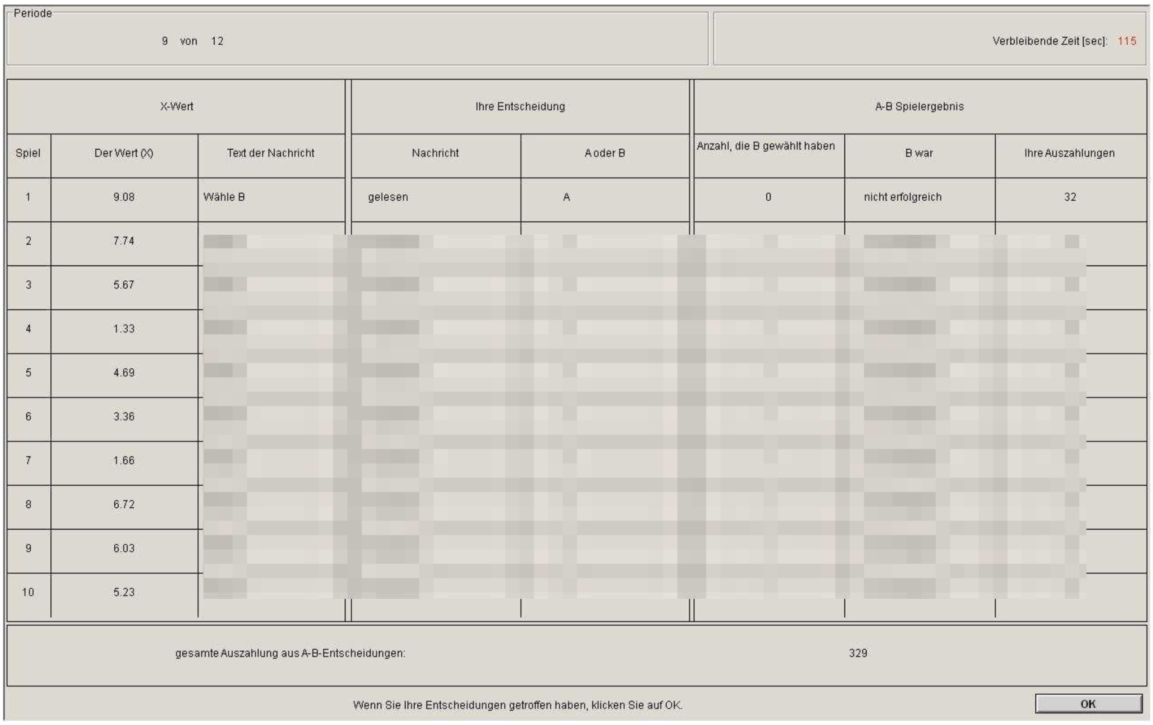
The last part titled “A-B game outcome” indicates the number of participants who have chosen B, whether B was successful, and your payoff for your decision between A and B (in ECU) in case this round will be selected to be paid out.

In the header of the screen, you will see a clock running backward. You have 120 seconds to look at the information. When the time is up, the next round starts. You can also finish the information phase in advance by clicking the gray Ok button. However, you can then no longer inform yourself about the result of the previous round.

[In PIH and PIL: Figure 4: Screenshot of the information phase]



[In CI: Figure 4: Screenshot of the information phase]



Questionnaire:

At the end of the experiment we kindly ask you to complete a questionnaire. Your personal information will be kept strictly confidential and will only be used for research purposes.

Payout:

At the end of the 15 rounds, one round is randomly selected for which you will receive the payout for your decisions between A and B. The cost of reading the message will be charged here. From the remaining 14 rounds, one more round is randomly selected for which you receive your payout for the guesses about the number of participants who have read the message.

The selection of the rounds to be paid out is purely random and does not depend on your decisions.

Your final payment is the sum of the payouts from the selected rounds. You will receive one euro for every 22 ECU.

Exercises:

To understand the game better, you should first answer the following questions. The correct answers will be provided below. If you have questions, please raise your hand and one of the instructors will help you.

1 The unknown number X is 5.48. Of the other 7 participants, 3 opt for A and 4 for B. You do not read the message.

   a) What is your payout if you choose A? ____

   b) What is your payout if you choose B? ____

2 The unknown number X is 2.69. You choose B. How many participants need to choose B for B to succeed? ____

3 [In PIH and PIL:] Your clue number is 7.14, you read the message and choose A. What is your payout? ____

4 You click on "read message" and assume that 2 other participants read the message as well. What is the expected number of participants (including you) who read the message?

5 You suspected that a total of 3 participants read the message. 5 participants (including you) read the message. What is your payout on the assumption? ____

Indicate whether the following statements are true or false:

6 All players reading the message see the same text.

7 The text of the message depends on the unknown number X

8 [In PIH and PIL:] The text of the message depends on your clue number.

9 The unknown number X is the same for all participants in your group.

10 [In PIH and PIL:] All participants receive the same clue number.

11 When I have made my 10 decisions between A and B and entered the 10 guesses, the decision phase is complete.

Solutions and explanations:

1 a) 33. The payout for A is always 33 (minus 1 if you read the message).

b) 8 . Since (with you) fewer than X participants have opted for B, B is not successful.

2 at least 3.

3 [In PIH and PIL:] 32. The payout for A is equal to 33 (minus 1 because you have read the message).

4 3. That is two others and you.

5 10. Five participants have read the message with you. You suspected 3. The Difference is 2. Your payout is therefore 12 - 2 = 10.

6 True. The text is the same for all participants.

7 Wrong. The text of the message is independent of X.

8 [In PIH and PIL:] Wrong. The text of the message is independent of your clue number.

9 True.

10 [In PIH and PIL:] Wrong. The numbers of the participants are drawn independently.

11 Wrong. To complete the decision phase, you still need to click on the red OK button click.