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The Power of Sunspots: An Experimental Analysis

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The Power of Sunspots: An Experimental Analysis*

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Abstract:

We present an experiment in which extrinsic signals may generate sunspot equilibria. The game has a unique symmetric non-sunspot equilibrium, which is also risk dominant. Other equilibria can be ordered according to risk dominance. By comparing treatments with different information structure, we measure the force of extrinsic signals. Results indicate that Sunspot equilibria emerge naturally, if there are salient (but extrinsic) public signals. However, salient private signals of high precision may also cause sunspot-like behavior even though this is no equilibrium. The higher the precision of signals and the easier they can be aggregated, the more powerful they are in dragging behavior away from the risk dominant to risk dominated strategies.

Keywords: coordination games, strategic uncertainty, sunspot equilibria, irrelevant information.

JEL Classification: C72, C92, D84.

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1 Introduction

Ever since Keynes' (1936) beauty contest analogy of investor behavior in stock markets it has been asked, whether extrinsic signals may affect behavior in coordination games. Azariadis (1981) and Cass and Shell (1983) were the first who theoretically explored the influence of extrinsic information on economic activities. They showed that, whenever there are multiple equilibria, there are also sunspot equilibria, in which agents condition their actions on publicly observable but intrinsically uninformative signals.¹ Even though these signals are uninformative they may serve as focal points for agents' beliefs and their public nature allows that beliefs become self fulfilling. Thereby, extrinsic events may determine on which equilibrium agents coordinate.

In his seminal book, Schelling speculates that "Most situations [...] provide some clue for coordinating behavior, some focal point for each person's expectations of what the other expects him to be expected to do" (1960, 57). Such clues might include folk wisdom, collective perception, consensus, stereotypes or (strategy) labels, etc. In other words, a sunspot can be anything, which possibly coordinates the expectations of market participants and breaks the symmetry in coordination problems. For instance, lunar phases are not only known to influence gravity or the obliquity of the ecliptic, they also influence human behavior and mood.² If individuals (mistakenly) attribute certain outcomes to sunspots, this perception can become self-fulfilling and could be used as a coordination device. However, there has to exist a shared understanding about how sunspots affect behavior, because sunspots are essentially social phenomena (Duffy and Fisher, 2005). On the contrary, if agents cannot attach some meaning to a publicly observable event, it will likely have no impact on decisions.

In this paper we use laboratory experiments to explore the impact of sunspots on economic behavior. This approach allows us to (1) control the available extrinsic information and its shared understanding and (2) to investigate how such extrinsic information affects coordination and the occurrence of sunspot equilibria. Empirical evidence for sunspots is hard to obtain with field data. The main reason for the lack of empirical evidence is the difficulty of establishing causality of sunspots and economic outcomes. In the field, it is very hard to detect a particular irrelevant event which is decisive for agent's choices. On the other hand, the hypothesis of sunspot equilibria cannot be falsified either. For instance, non-informative signals might be an explanation for excess asset price volatility, if traders

¹ The term sunspot originated in the work of William Jevons (1884), who proposed a relationship between the number of sunspots and the business cycle. In the theoretical literature the term sunspot is a synonym for extrinsic random variables, i.e. variables which may influence economic behavior but are unrelated to fundamentals such as preferences, technologies or endowment.

² Recent literature in financial economics explores the impact of natural activities such as weather conditions or lunar phases on mood and subsequently on investment decision (see e.g. Yuan et al, 2006; Hirshleifer and Shumway, 2007 and references therein) or on college choice (Simonsohn, 2009). Others have shown that sport events impact stock-market indices (Edmans et al. forthcoming) or expectations about future personal situation and economic situation in general (Dohmen et al. 2006). Mood might be also reflected in confidence indices such as the Michigan Consumer Sentiment Index or the Ifo Business Climate Index, which are reliable early indicators of future GDP.

condition their actions on such signals, but higher volatility may also be caused by news about fundamentals or increasing uncertainty.

We use a 2-person coordination game where agents have to pick a number from the interval zero to hundred. In this simple game players maximize their joint payoff by choosing the same number. If the chosen numbers deviate from each other, players are punished with a quadratic loss function, i.e. the larger the deviation the harsher the loss for the agent. Hence, each coordinated pick of numbers constitutes a Nash equilibrium and payoffs do not depend on the number players coordinate on. Nevertheless, some numbers are presumably more prominent than others. Picking 50, in particular, is the unique symmetric equilibrium and it is also the risk dominant equilibrium strategy and maximin.

The sunspot variables in our experiment are signals about a binary random variable, which is either zero or hundred. We choose semantically salient signals to establish a link between the sunspot variables and the economic outcome, i.e. the meaning of the sunspot variables is as clear as possible. Despite this saliency, it is a priori not clear how the observed signals map into market outcomes. For instance, players could interpret a signal as either low or high and map this into a particular number below or above 50, respectively. Alternatively, they could map a signal (e.g. $s = 100$) directly into the corresponding action ($a = 100$). We systematically vary the information structure of the signals, i.e. the number of signals and their degree of public availability. In the most favorable case, one extrinsic signal is publicly observable. Thus it provides agents with another focal point for solving the coordination problem besides the risk dominant choice. These two focal points – risk dominance and sunspot – differ with respect to their associated risk, i.e. following the sunspot (public signal) is riskier than following any other strategy. In fact, the risk dominance criterion allows us to order the different equilibria by the associated level of strategic risk. By reducing the publicity of the extrinsic signal we can analyze how far actions are distracted away from the risk dominant equilibrium. Thus, we can measure the power of sunspots by the distance between chosen actions and the risk dominant strategy.

The main finding is that extrinsic public signals that are easy to aggregate lead to almost perfect coordination on the sunspot equilibrium that is implied by the semantics of the signals. This salient sunspot equilibrium reliably shows up whenever agents receive just public signals, although it is associated with higher strategic risk than any other strategy. It seems that the possibility to coordinate on a salient message exerts a force on agents' decisions that dominates the force of risk dominance that should lead them to the risk dominant non-sunspot equilibrium.

If extrinsic signals are not publicly observed, the risk dominant equilibrium predominates, although sunspot-like behavior can be observed for highly correlated private signals. Thus, extrinsic signals may affect behavior, even if it is not an equilibrium to condition actions on these signals. Thereby, we show that in experiments the likelihood of sunspot(-like) actions is a continuous function of the correlation of signals, while theory predicts sunspot equilibria only if signals of different agents are perfectly correlated.

If each agent receives a public and a private signal that are equally salient in their semantics, some subjects condition their actions on the private signal which prevents full coordination. While theory predicts the same set of equilibria as in a game with just one public signal, we find that the power of sunspots is significantly lower if private and public signals are combined.

How do subjects converge to sunspot equilibria? In the first periods, different agents are pursuing different strategies, some take the extrinsic signal into account, some do not. The only non-sunspot strategy that is frequently played is the maximin strategy. Over time, agents meet partners with other strategies and eventually adjust their own strategy in direction of the observed actions of their partners. Thereby, most groups converge to an equilibrium, but not necessarily the same one in different groups. The convergence process leads some groups to coordinate on equilibria that are numerically in between the salient sunspot equilibrium and the maximin strategy.

The paper is organized as follows. In Section 2 we give a brief overview of the related literature. Section 3 introduces the game and theoretical considerations and Section 4 outlines the design and procedures of the experiment. The results are discussed in Section 5, and Section 6 concludes.

2 Related Literature

Although experiments provide a useful tool for investigating sunspot behavior, only a few studies have done so. The first attempt to investigate sunspots in the laboratory was Marimon et al. (1993). They implemented an overlapping generations' economy, where the sunspot was a blinking square on subjects' computer screens that changed its color: red in odd and yellow in even periods. They start with some periods in which a fundamental (size of a generation) varies between odd and even periods leading to a unique equilibrium with alternating high and low prices. After 16 to 20 periods, they switch to an economy, in which fundamentals are kept constant, but two equilibria exist, one stationary and one being a two-cycle. In 4 out of 5 sessions, subjects continue to behave according to alternating prices. It is not clear though, whether alternating predictions are just carried over from the experience in the first phase or whether the blinking square had any effect.

Duffy and Fisher (2005) were the first to provide direct evidence for the occurrence of sunspots. They investigate whether simple announcements like "the forecast is high (low)" can generate sunspots in a market environment with two distinct equilibrium prices. They find that the occurrence of sunspot equilibria depends on the particular information structure of market institutions. Sunspots always affect behavior in less informative call markets while they matter only in 4 out of 9 cases in more informative double auction markets. More interestingly, however, is the importance of the semantic of sunspots. If people do not share a common understanding of the context and hence do not attach the same interpretation to the sunspot, it is highly likely that the sunspot variable does not matter. Indeed,

Duffy and Fisher found that announcements like “the forecast is sunshine (rain)”, without training subjects to associate distinct announcements with distinct equilibria, had no impact on behavior. In order to achieve a common understanding of the sunspot variable Duffy and Fisher trained subjects to believe in sunspots. In an initial training phase subjects were primed to existence of high and low equilibria and the respective announcement. This is different from our approach where the sunspot is semantically salient and sunspot equilibria arise endogenously without any need of training.

Beugnot et al. (2009) test behavior in a three-player-two-action coordination game framed as a workers game with two equilibria: work or strike. Working is payoff dominant, weakly risk dominant, and maximin. “Work” is chosen in 99% of all cases, when subjects do not receive additional information. However, when the game started with a random device announcing either “work” or “strike”, about 23% of all subjects followed the respective signal, while the others decided for “work” independent of the signal. Subjects do not coordinate on a sunspot equilibrium. Instead, there is some convergence in direction of the efficient non-sunspot equilibrium.

Another strand of literature is concerned with recommendations. They can be seen as extrinsic signals, but by phrasing them as advices, they become more salient and may be used to resolve strategic uncertainty. Brandts and MacLeod (1995) analyze, under which conditions, subjects follow such public recommendations as a selection device among multiple equilibria. The results show that advice to follow a weakly dominated strategy is ignored. Subjects only follow the advice if it prescribes a perfect equilibrium. When two equilibria are perfect, subjects choose the efficient one, unless recommendations select a risk dominant (but inefficient) strategy.

There is also some experimental work on the concept of correlated equilibrium which is closely related to sunspot equilibrium (see e.g. Peck and Shell, 1991). For instance, Cason and Sharma (2007) found that subjects follow public third-party recommendations and play according to a correlated equilibrium which led to higher payoffs than in the mixed strategy equilibrium. In a related experiment, Duffy and Feltovich (forthcoming) also find that subjects condition their behavior on third-party recommendations leading to higher than mixed strategy equilibrium payoffs. In this case they speak about good recommendations. If recommendations lead to a lower payoff compared to the mixed Nash payoff (bad recommendation) or if the distribution of recommended outcomes is not a correlated equilibrium, then subjects learn to ignore the recommendations.

3 The Game

The game we will analyze is a pure coordination game. Two agents independently and simultaneously pick an action $a_i \in [b, c]$. Agent i 's payoff is given by

$$\pi_i(a_i, a_j) = f(|a_i - a_j|) \quad (1)$$

where $f: R \rightarrow R$ is a twice continuous differentiable function with, $f'(x) < 0 \forall x > 0$, $f'(0) = 0$, and $f''(x) < 0 \forall x$. Therefore, agent i maximizes her payoff when she matches agent j 's action. Clearly, any coordinated pick of numbers constitutes a Nash equilibrium and agents do not care which specific number they coordinate on, since their payoff is independent of the specific action. In equilibrium both agents receive the same payoff and moreover the payoff is exactly the same in all equilibria. Agents are penalized for a deviation from their partner's pick by the concave payoff function; the loss grows more than proportionally in the distance between chosen actions.

3.1 Equilibria with signals

Let us now extend this game by introducing payoff irrelevant information which can be either public or private or both. Let Φ be the set of possible realizations of public signals that agents might receive and Ψ^i be the finite set of possible realizations of private signals for agent i , which has at least two elements. For easiness of presentation, let us assume that $\Psi^i = \Psi$ for both i , although this is not a necessary condition for proving the next Lemma. Let $P: (\Phi, \Psi, \Psi) \rightarrow [0, 1]$ be the joint probability distribution on the signals, where P assigns strictly positive probabilities on each element in (Φ, Ψ, Ψ) . The following lemma shows that equilibrium actions do not depend on private signals.

Lemma 1. *Let $\{a_{\varphi, \psi}^{i*} \mid \varphi \in \Phi, \psi \in \Psi\}$ be a Bayesian Nash equilibrium strategy profile, where $a_{\varphi, \psi}^{i*}$ is a Bayesian Nash equilibrium action played by agent i with public signal φ and private signal ψ . Then, equilibrium actions are the same for both agents and do not depend on the private signal, that is, $a_{\varphi, \psi}^{i*} = a_{\varphi}^* \forall \psi \in \Psi$ for any given $\varphi \in \Phi$.*

The assumptions of continuity and differentiability of the payoff function are not necessary and are just assumed for easiness of presentation. The assumption that P assigns a strictly positive probability to each element of (Φ, Ψ, Ψ) can also be relaxed. In general, the result holds as long as one's private signals does not reveal perfect information about the others' signal, in which case the private signal would be public information. Concavity, on the other hand, is an important assumption as the following counter-example shows.

Suppose that the payoff function for both players is linear in differences, i.e. $\pi^i(a_1, a_2) = -|a_1 - a_2|$. There is no public signal, $\Phi = \{\emptyset\}$, and there are two possible private signals that can be 0 or 100, i.e., $\Psi = \{0, 100\}$. Moreover, assume that $P(0, 100) = P(100, 0) = 1/8$ and $P(0, 0) = P(100, 100) = 3/8$, where the numbers are the private signals for players 1 and 2 respectively. It is easy to check that in this case, playing the private signal ($a_{\varphi, \psi}^{i*} = \psi$) is one of the many equilibria of the game. If player j is playing this equilibrium and $\psi^i = 0$, then player i 's expected utility of choosing a^i is equal to $E(\pi^i(a) | \psi^i = 0) = -25 - a^i/2$, which is maximized at $a^i = 0$. The same reasoning applies for $\psi^i = 100$. Hence, although conditioning the actions on the private signal always incurs expected costs of mismatch, and thus a welfare loss, it can constitute an equilibrium if payoff functions are not strictly concave.

The implication of Lemma 1 is that the set of Nash equilibria in a setup without signals and a setup with imperfect private signals is exactly the same. Similarly, the set of Nash equilibria in a setup with a public signal and with both a public and a private signal is exactly the same. A strategy is a mapping from the signal space to the interval $[b, c]$. Equilibria in these games are given by mappings from public signals to the interval $[b, c]$. When there is a public signal, there exist sunspot equilibria in which both agents condition their actions on the public signal. Any function $f: \Phi \rightarrow [b, c]$ is an equilibrium, provided that both agents follow the same function and, thus, always are perfectly coordinated.

3.2 Riskiness of Equilibria

Due to the large set of equilibria, it is natural to use some selection criteria. One of the most widely used criteria to assess the risk of different equilibria is given by risk dominance (Harsanyi & Selten, 1988). In its original notion, risk dominance is a binary relation that does not provide any strict order on the equilibria of our game.³ There is, however, an alternative notion of risk dominance in which, according to Harsanyi and Selten's heuristic justification, selection of an equilibrium results from postulating an initial state of uncertainty where the players have uniformly distributed second order beliefs on all equilibria. Here, each player believes that the other players' beliefs are uniformly distributed on the set of equilibrium strategies, which in our case is the whole action space. Among

³ From any two equilibria, risk dominance selects the equilibrium that maximizes expected payoffs, if an agent believes that her partner chooses between these equilibria with equal probability. In our game, an agent who believes that her partner chooses between two distinct numbers with the same probability is indifferent between these numbers. If, instead, an agent considers her partner to choose between at least three different numbers with equal probability, the lowest and highest numbers provide a lower expected payoff than the numbers in between.

others, this alternative notion has been used at Stahl and Haruvy (2004). From now on, we will refer to this alternative notion simply as risk dominance.

An alternative notion of riskiness that one could use is the one of a secure action (see Van Huyck et al., 1990). Based on the maxmin criterion of Von Neumann and Morgenstern's (1947), a secure action is one that maximizes the minimum possible payoff. The secure action does not need to belong to the support of Nash equilibria. In our game, though, it trivially does, because the support of Nash equilibria coincides with the whole set of actions.⁴

The following lemma characterizes the risk dominant equilibrium and the secure action of our game. Note that this is irrelevant of the generated signals.

Lemma 2. $a_{\psi,\varphi}^{i*} = \frac{b+c}{2} \forall \psi, \varphi$ is both the secure action and the risk dominant equilibrium.

Proof. See Appendix. ■

Lemma 2 shows that choosing the midpoint of the interval is both the secure action and the risk dominant equilibrium. By choosing the midpoint of the interval an agent minimizes the maximum possible distance to his partner's choice and can assure himself a minimum payoff of $f((c-b)/2)$. In addition, the midpoint is also risk dominant and the best response to the belief that the actions of others are uniformly distributed on $[b,c]$ or, alternatively, to the belief that the strategies of others are uniformly distributed on the whole set of all possible strategies. Unlike for Lemma 1, concavity is not a necessary condition for Lemma 2 to hold.

Both criteria can order the different equilibria. According to the notion of secure action, a strategy is riskier than another one if it can lead to a worse payoff. According to the notion of risk dominance, an equilibrium is riskier than another one if the expected payoff against a uniform distribution over all possible strategies is lower. In the absence of public signals or in the case of two public signals in which the equilibrium is symmetric⁵, both measures of riskiness can be expressed as a function of the absolute distance to $(b+c)/2$. Therefore, in the rest of the paper we will interpret the absolute distance to $(b+c)/2$ as a measure of riskiness. We will say that an information structure (treatment) exerts a stronger effect on behavior than another information structure, if (after some convergence) the average distance of chosen actions from 50 is higher. Alternatively we can say that an information structure is more likely to produce sunspot-like behavior than another information structure if the fraction of groups converging to a sunspot equilibrium or to a sunspot-like non-equilibrium strategy is larger than in the respective other treatment.

⁴ The security criterion has also been applied to the game after the deletion of non-equilibrium actions (see, i.e., Stahl & Haruvy, 2004).

⁵ Suppose there are two public signals: s and t . An equilibrium with two public signals is symmetric if the equilibrium action with s is symmetric with respect to the interval to the equilibrium action with t .

4 Experimental Design, Procedures and Hypotheses

4.1 Game setup

In all experimental treatments, subjects repeatedly played the coordination game explained above. Subjects were randomly assigned to matching groups of six that were fixed throughout a session. Within each group, subjects were matched in pairs in each period, where the partner of the previous period was excluded. Subjects from different matching groups never interacted, so that observations from different groups can be treated as independent. Subjects were aware that they were randomly matched with another subject from their matching group and that they never face the same subject twice in a row.

Subjects had to independently and simultaneously choose an integer between 0 and 100 (both included). Their payoffs depended on the distance between their own and their partner's choice. In particular, the payoff function was the following:

$$\pi_i(a_i, a_j) = 200 - \frac{1}{50}(a_i - a_j)^2 \quad (2)$$

Subjects could earn at most 200 points if their actions perfectly matched and they were penalized for a deviation between their choices by the quadratic loss term.⁶ It is easy to check that this payoff function fulfills the properties of the function characterized in the previous section and that both Lemma 1 and 2 hold for (2).⁷

4.2 Treatments

The treatments differ by payoff irrelevant information given to the subjects. In the benchmark (Treatment N), subjects received no additional information. In all other treatments subjects received some extrinsic information (signals). This information was generated as follows. In each period the computer drew a random number $Z \in \{0,100\}$ both numbers being equally likely. This number was not disclosed to subjects, but they received one or two signals. Each signal was a random number

⁶ Note also that the minimum payoff is zero since the maximum distance between two actions is 100.

⁷ Note that in contrast to the outlined game, subjects only choose integers between 0 and 100 instead of choosing from an interval. Technically Lemma 1 holds except for differences in actions of ± 1 .

$s \in \{0,100\}$ with $prob(s=100 | Z=0) = prob(s=100 | Z=100) = p$, where $p \in [0.5,1]$ is the probability of the signal being the same as the number Z . Hence, p is a measure of the signals' precision.⁸

In Treatment P75 and P95, both subjects received independently drawn private signals X_i . The only difference between these two treatments was the probability with which signal X_i coincides with the number Z . In P75 this probability was $p = 0.75$ while in P95 it was $p = 0.95$.⁹ According to theory, sunspot equilibria do not exist for private signals with a value of p that is strictly smaller than one (see Lemma 2). With $p = 1$, the private signal in fact becomes a common (public) signal and sunspot equilibria exist. Hence, the set of equilibria is discontinuous in p and by changing the precision of signals we can test for continuity in p .

Table 1. Treatments summary.

Treatment	Common Signals (Y)	Private Signal (Xi)	Precision p	Existence of sunspot equilibria	Number of sessions / number of groups
N	-	-	-	No	1 / 2
P75	-	1	75%	No	1 / 3
P95	-	1	95%	No	2 / 6
AC	-	1*	100%	No	2 / 6

C	1	-	75%	Yes	2 / 6
CP	1	1	75%	Yes	4 / 12
CC	2	-	75%	Yes	2 / 6

Notes: *revealed with 90% probability

In Treatment AC the true number Z was revealed to each subject with probability $p = 0.9$. We call this “almost common information,” as it generates common p -beliefs (with $p = 0.9$) in the sense of Monderer and Samet (1989). This treatment allows an alternative test whether behavior is discontinuous in p as predicted by theory. In AC there exists no sunspot equilibrium since the information is not disseminated to all subjects with probability 1.

In Treatment C, both subjects received a common (=public) signal Y with $p = 0.75$. Since it was common information that both subjects receive the same signal, sunspot equilibria exist. Any function $f : Y \mapsto [0,100]$ is an equilibrium. In Treatment CC, subjects received two independently drawn public signals X and Y , both with $p = 0.75$. Here, any function f mapping the tuple (X,Y) to the interval $[0,100]$ is an equilibrium. In Treatment CP, subjects received both, a common and a private signal. The common signal Y and both subjects' private signals X_1 and X_2 were drawn independently. The probability of a signal coinciding with Z was $p = 0.75$ for each signal. Subjects were always informed,

⁸ This setting allows for comparing different information structures and for introducing the correlation of signals in a way that can be easily understood by subjects who are not trained in statistics.

⁹ Note that in P75 subjects get the same signal in 62.5% of the cases, while in P95 this probability is 90.5%.

which signal was common and which one was private information. Again, subjects could ignore the private signal and condition their behavior on the common signal which allows sunspot equilibria, i.e. any function $f: Y \mapsto [0,100]$ is an equilibrium. Table 1 gives an overview over sessions and treatments.

4.3 Procedure

Subjects played the game for 80 periods. After each decision period, they learned their partner's choice, the distance between own choice and partner's choice and the resulting payoff. They also learned the realization of the random variable Z , except for Treatment N. In treatments with private signals (P75, P95, CP), they never learned their partners' private signal.

The general procedure was the same in each session and treatment. At the beginning of a session subjects were seated in a random order at PCs. Instructions were distributed and read out aloud, questions were answered in private. Throughout the sessions, students were not allowed to communicate with one another and could not see each others' screens. They were not informed about the identity of their partner or the other members of their matching group. In the instructions, the payoff function (2) was explained in detail and was also displayed as a mathematical function and as a non-exhaustive payoff table. Additionally, subjects could use a calculator during the experiment which allowed them to enter hypothetical numbers for their own and their partner's decision and receive the resulting payoff. Before starting the experiment, subjects had to answer questions about the game procedures and in particular how the payoffs were determined. We did this mainly for three reasons. First, we wanted to make sure that subjects understood how their payoff is determined. Second, we wanted to prompt subjects to the fact that neither the number Z nor the signals affect their payoff, and third, the quiz also ensured that subjects could clarify last questions and could be ascertained that others understood the game as well.¹⁰ Once all subjects had answered the questions correctly, the experiment started. Instructions and questionnaires are given in the Appendix.

We run a total of 14 sessions with 18 subjects in each session.¹¹ Participants were only allowed to participate once. In total 246 subjects participated. Students were recruited through the online recruitment system ORSEE (Greiner, 2004) and the experiments took place at the experimental economics laboratory at the Berlin Institute of Technology from July 2008 to June 2009. The experiments were conducted using the software toolkit z-tree (Fischbacher, 2007). At the end of a session we determined the earnings of the subjects by randomly selecting 10 out of the 80 periods.

¹⁰ For instance, in treatment P75 the statement was: "Your payoff in a period depends on a) the number Z , b) the distance between your chosen number and the number chosen by your partner or c) your private hint X ." Subjects had to indicate the right statement and in case of a wrong indication they received the following message: "Your answer is wrong. Your payoff in a round depends on the distance between your chosen number and the number chosen by your partner."

¹¹ In one session we had only 12 subjects.

Subjects were then paid in private the sum of Euro cents (1 point = 1 Euro cent) earned in the selected periods plus a show up fee of 3 Euros. A session lasted about one hour and subjects earned on average 21 Euros.

5 Results

We start analyzing data with a quick overview of the aggregate behavioral patterns in the different treatments. In order to organize our analysis we introduce two convergence criteria. In theory, convergence implies that all players play an equilibrium strategy and no deviation is observed. This rigorous criterion is not likely to be observed in an experimental setting. Therefore, in order to compare strategies across treatments we introduce two criteria – strong and weak convergence. The *strong convergence* criterion requires that all six subjects in a matching group play according to the same strategy at least in the last 15 periods, allowing a deviation of ± 1 . The *weak convergence* criterion requires that at least four subjects in a matching group follow the same strategy at least in the last 15 periods, again with a deviation of ± 1 .

These measures will allow us to assess the ability of groups to coordinate and the strategies they coordinate on.¹² For converging groups we identify five types of strategies that were the most salient: 1) “50”: the risk dominant strategy, 2) “25/75”: playing 25 (75) when the signal is 0 (100), 3) “10/90”: playing 10 (90) when the signal is 0 (100), 4) “0/100”: following the signal. In Treatment CP, these strategies refer to the public signal only, 5) “Mean”: play the average of both signals. Table 2 summarizes how many groups converged to these equilibria.

Table 2. Coordination summary.

Treatment	Non-Sunspots Treatments				Sunspots Treatments		
	N	P75	P95	AC	C	CP	CC
Total number of groups	2	3	6	6	6	12	6
Coordinated groups	2	2 (3)	3 (5)	4 (5)	5 (6)	6 (9)	5 (6)
“50”	2	2 (3)	3	4	-	1	-
“25/75”	n.a.	-	-	-	-	1 (3)	n.a.
“10/90”	n.a.	-	- (2)	-	-	-	n.a.
“0/100”	n.a.	-	-	- (1)	5 (6)	4 (5)	n.a.
“Mean”	n.a.	n.a.	n.a.	n.a.	n.a.	-	5 (6)

Note: numbers in parentheses indicate the number of groups who converge according to the weak criterion.

¹² An additional interesting feature of coordination is its speed. Tables A2 and A3 provide the periods in which groups converge to the different strategies.

Table 2 points out that the different treatments (and their different information structures) not only have an impact on whether groups converge or not, but also to which strategies they converge. Another interesting observation is that strategies are symmetric: subjects who choose m when they receive signal 0, play $100-m$ when the signal is 100.¹³ In the appendix A2 we show that symmetry does not only apply to the strategies a subject converges to, but it applies to actions played during the entire experiment. In our further analyses, we can, therefore, pool the data for symmetric sets of signals. For tests, we take averages from each group as independent observations. We first analyze differences in strategies and convergence across different treatments. Then, we turn to welfare implications.

[Figure 1 about here]

5.1 Sunspots

Result 1 *Sunspots emerge naturally and reliably in the presence of salient (but extrinsic) public signals.*

Figure 1 gives a first impression of the impact of extrinsic information on behavior. In Figure 1 we depict the average distance to 50 over all matching groups for treatments N, P75 and C.¹⁴ Note that only in Treatment C sunspot equilibria exist. Without additional information (N) subjects quickly converge to playing “50”. With imprecise (P75) extrinsic information subjects learn to ignore the information quickly and converge to “50”. In these treatments the average distance to “50” is close to zero. As explained above, “50” is not just the secure action, but is also risk dominant, results from level- k reasoning, and is the unique symmetric equilibrium according to the theory of focal points by Alós-Ferrer and Kuzmics (2008).¹⁵ Thus, in the absence of signals, it seems very natural for subjects to converge to this strategy.

If, however, the extrinsic information is publicly available, there is a clear convergence process toward the received signal. The observation of sunspot equilibria naturally implies that the average absolute distance to 50 is large. In Treatment C, the average distance of action from “50” is 46.7, which is close to the maximum possible value of 50 and larger than in all non-sunspot treatments. It is significantly higher than in non-sunspot treatments N and P75, where the average distance is 2.04 (Mann-Whitney, $z = 2.739, p < 0.01$).

¹³ In treatment CP and CC, symmetry refers to playing m when both signals are 0, $100-m$ when both signals are 100, n when the public signal is 0 and the private signal is 100, and $100-n$ when the public signal is 100 and the private signal is 0. For two distinct public signals in Treatment CC, symmetry prescribes playing 50 as in Treatment N.

¹⁴ See the Appendix for more detailed Figure for each group separately.

¹⁵ Van Huyck et al (1990) provide evidence that risk dominance is a selection criterion in a similar game.

A closer look at Table 2, which summarizes for each treatment the strategies to which different groups converge, provides a more detailed picture.¹⁶ First we can note that in N, P75 and C all groups achieve coordination and converge to either the risk-dominant strategy (N and P75) or to “0/100” (C). Second we see that not all groups converge according to strong convergence criterion. In P75 as well as in C there is one group who needs a considerable time to converge. For instance in P75, convergence seems harder for group 5. This is caused by a single subject who seemed to condition his actions on the private signal until the end of the game.¹⁷ In C all but two group converge quickly to playing the public signal ($a_i = Y$), although this constitutes the most risky action ex ante. The other two groups eventually converge under the non-strict measure in periods 68 and 57, respectively. They do not converge in a strict sense, because two subjects condition their actions on the public signal and choose actions in the ranges [0,10] and [90,100] for the signal being 0 or 100, respectively.

5.2 Behavior with almost public information

Despite the different information structure in P95 and AC, the theory prescribes that the behavior in both treatments should be the same as in N: subjects should ignore their signals. Note that for a subject who receives a signal, the conditional probability that the other subject gets the same signal is 90.5% in P95, while it is 90% in AC.¹⁸ We observe similar behavior in both treatments. The average absolute distance to 50 is about 17.26 in P95 and 13.86 in AC and the difference is not statistically significant (Mann-Whitney test, $z=0.48$, $p=0.63$). In AC, the average distance of actions conditional on receiving a signal is 14.83. In P 95, the average distance to 50 is significantly higher than in N and P75 (Mann-Whitney test, $z = 1.643$, $p = 0.05$, one-sided).

[Figure 3 about here]

Figure 3 plots the average distance to 50 in blocks of 10 periods conditional on receiving a private signal for all groups in P95 and AC. Note that if both groups played according to the risk dominant equilibrium the average distance to 50 in treatment P95 and the average distance to 50 with and without signals in treatment AC should coincide at zero. Both treatments show some heterogeneity among groups. Some groups quickly converge to the risk dominant equilibrium: in P95, half of the groups (groups 8, 9 and 10) convergence in a strict sense in periods 7 to 13; in AC, four groups converge from periods is 3, 4, 1 and 13).

¹⁶ For a more comprehensive overview on each independent group, including the periods of convergence see Table A1 and A2 in the Appendix

¹⁷ In this group, 5 subjects consistently chose 50 in 90% of the cases while the remaining subject only did so in 25% of the cases.

¹⁸ Getting these numbers as close as possible was the reason, why we chose $p = 0.9$ in Treatment AC.

The most interesting finding in treatments P95 and AC is the behavior of groups who did not converge to an equilibrium: the emergence of what we call *sunspot non-equilibrium* behavior. Unlike predicted by theory, highly precise private signals cannot only make it more difficult to coordinate but may also lead to coordination on non-equilibrium strategies. In treatment P95, the private signal affected behavior in three groups throughout the game and dragged behavior away from the risk dominant equilibrium. Group 11 did not converge at all: four subjects chose 50 most of the time although one of them eventually adopted a sunspot non-equilibrium strategy (25/75); the other two subjects consistently conditioned their choices on the private signal until the end. Groups 6 and 7 converge in a weak sense to a sunspot non-equilibrium strategy. In both groups, subjects condition their behavior on the private signal resulting in a bi-modal choice of 10 and 90. In two groups of treatment AC, subjects condition their behavior on the signal when it is available and otherwise choose 50. Both groups converge to a sunspot non-equilibrium. Hence, when the precision of the private signal or in other words, the correlation between private signals, is high, sunspot behavior can potentially emerge. This is in contradiction to the theoretical prediction which describes a discontinuous behavior, i.e. as long as private signals are imprecise, sunspot equilibria are not possible.

Result 2 *Salient extrinsic private signals of high-precision may cause sunspot behavior even though this is no equilibrium and drag behavior away from a stable focal point.*

To capture the dynamics of the convergence process in treatments without sunspot equilibria – N, P75, P95 and AC – we estimate the following regression model (Noussair et al 1995):

$$|a_{it} - 50| = \beta_{11}D_1 * (1/t) + \dots + \beta_{1k}D_k * (1/t) + \beta_{21}D_1 * (t-1)/t + \dots + \beta_{2k}D_k * (t-1)/t + u_{it} \quad (3)$$

where i is the index for individuals and t the time period. The dependent variable is the absolute distance of the decision to 50 and D_k is a dummy variable for each group k and u is a random variable which is normally distributed with zero mean. Note that $1/t$ converges to zero as t goes to infinity, whereas $(t-1)/t$ converges to one. Hence, the coefficients β_{1j} measure the origin of the convergence process of group j and the coefficients β_{2j} are the asymptotes to which group j converges. The model allows to test whether groups converge to the various theoretical predictions by testing whether the estimates for β_{2j} significantly different from the theoretical prediction. Further we can compare the β_{1j} to the theoretical prediction and assess the speed of convergence. For treatment AC we estimated model (3) separately, because subjects did not receive a signal in all 80 periods.

The results are displayed in Table 3. The β_{2j} coefficients for N and P75 are all below 1, which means that these groups converge to theoretical prediction of 0, i.e. they converge to the risk-dominant equilibrium. However, the coefficients for group 4 and 5 are significant at the 95% level. Note that group 5 only weakly converges, see Table A1. In treatment P95 the non-significant β_{2j} coefficients (groups 8,9 and 10) are also well below 1. These are the groups who neglect the available information and converge to the risk dominant equilibrium of 50. While the β_{2j} coefficients for the other three groups in P95 are well above 15, only group 6 and 7 converge to a sunspot-like non-equilibrium (a_i

=10). In treatment AC all groups except group 15 and 17 converge to the risk-dominant equilibrium. The β_{2j} coefficients for group 15 and 17 indicate that these groups converge to a sunspot equilibrium, however, the latter group only converges in the very last periods.

Table 3: Regression - No Sunspots – N, P75, P95, AC

Dep. variable: $ a_{it} - 50 $		β_{1j}		β_{2j}	
Group	Treat	<i>coefficient</i>	<i>standard errors</i>	<i>coefficient</i>	<i>standard errors</i>
1	N	5.010***	(0.956)	-0.019	(0.199)
2	N	0.017	(0.240)	0.003	(0.050)
3	P75	17.395***	(1.536)	-0.266	(0.320)
4	P75	18.983***	(1.318)	-0.659**	(0.275)
5	P75	8.703***	(2.043)	0.938**	(0.426)
6	P95	24.323***	(1.921)	39.936***	(0.400)
7	P95	42.727***	(2.332)	40.720***	(0.486)
8	P95	22.013***	(2.240)	0.170	(0.467)
9	P95	9.115***	(1.180)	-0.242	(0.246)
10	P95	14.870***	(2.025)	0.185	(0.422)
11	P95	41.712***	(6.781)	17.266***	(1.414)
<i>N</i>	<i>5280</i>				
12	AC	3.882***	(1.347)	-0.108	(0.310)
13	AC	33.908***	(1.991)	-1.398***	(0.459)
14	AC	0.319	(0.375)	-0.015	(0.071)
15	AC	49.424***	(0.432)	50.013***	(0.101)
16	AC	24.933***	(3.284)	0.426	(0.671)
17	AC	37.173***	(5.486)	41.759***	(1.270)
<i>N</i>	<i>2662</i>				

Notes: GLS regression with AR(1) errors, * p<0.10, ** p<0.05, *** p<0.01, Treatment AC is estimated separately.

5.3 Sunspots with more than one signal

In this section we focus on the treatments with two signals, i.e. CP and CC. In both treatments the available signals can generate sunspot equilibria. The last two columns in Table 2 provide a summary of the converging strategies in these treatments.¹⁹ The most immediate observation is that in CP and CC, all groups but one (group 26) depart from playing the risk dominant equilibrium and condition their choices on public signals. If they converge, they converge to a sunspot equilibrium.

[Figure 4 & 5 about here]

Again Figure 4 and 5 show the average distance to 50 by ten-periods blocks for CC and CP, respectively. Treatment CC is the treatment with the largest set of equilibria, since any function mapping a combination of public signals to an action constitutes an equilibrium. Out of six independent groups, we observe coordination in five of them according to the strict criterion, while group 37 converges only according to the weak criterion. This is mainly due to a single subject, whose choices cannot be distinguished from random behavior. In all cases, as can be taken from Figure 3 (or Table A2 in the Appendix), groups converge to playing the average of both signals. Averaging over signals seems the most natural focal strategy. Hence, it seems that if public signals can be aggregated in a simple way, then subjects quickly learn how to do it and respond to them as easily as to a single public signal. Since the two signals coincide in only 62.5% of all cases, the average distance between actions and 50 is 30.5, which is significantly smaller than in Treatment C (Mann-Whitney, $z = 2.882$, $p < 0.01$). Conditional on both signals being equal, the average distance is 48.97, which is about the same as in C.

Treatment CP provides the most versatile results, because here different types of sunspot equilibria emerge. Five groups coordinate on following the public signal as in Treatment C and the average distance to 50 is about 45.9 in these groups. Interestingly, three groups converge to an intermediate sunspot equilibrium in which subjects choose 25 whenever $Y = 0$ and 75 whenever $Y = 100$. The average distance in these three groups is 23.6. Another three groups do not achieve coordination even according to the weak criterion, but the average distance is 25.0 and close to the converging groups. It seems that subjects in these six groups are torn between neglecting and following the signal, which potentially lead to the observed intermediate sunspot equilibrium in three groups. One group manages to resort to risk-dominant equilibrium from the outset.

One of the features that CP shows is that the effect of signals is not additive. The private signal or public signal by themselves did not prevent coordination. However, if the two signals are displayed simultaneously the difficulty of coordination increases considerably (see Figure 4 and Table A2 in the Appendix). Despite some variance, convergence to equilibrium takes a surprisingly long time, if it

¹⁹ For a more comprehensive overview on each independent group, including the periods of convergence see Table A1 and A2 in the Appendix

takes place. This fact is exemplified by groups 25, 28 and 34 that never manage to coordinate their actions at all. Depending on whether a subject starts with behavior conditional or independent of signals, she needs to learn that (i) private signal should be ignored, even if public signals matter, and (ii) it may be good to condition ones action on the public signal, even though it is as irrelevant as the private signal. It is not surprising that this takes longer than in any other treatment. However, it is still surprising how difficult it was for these groups to coordinate during 80 periods.

Result 3 *The presence of multiple signals has no impact on coordination as long as it is public. However, an additional private signal can considerably impede the convergence process.*

Again, we can use the regression model (3) to investigate the convergence process in CP. The results are displayed in Table 4. Looking at the β_{2j} coefficients clearly reveal that 5 out of the 12 groups converge to the sunspot equilibrium ($a_i = Y$). The 95-% confidence interval of the β_{2j} coefficient includes 50 only for 4 groups (Groups 27, 30, 31, 35), while the upper bound of the confidence interval for group 33 is slightly below 50. Also interesting is that the β_{1j} coefficients for most groups are between 20 and 38. This comes mainly from the situation with different public and private signals. It seems that in that case subject did not ignore the private signal. Only groups where the initial fraction of people following the public signal was high enough eventually converge to a sunspot equilibrium. This is also highlighted by the fraction of the risk-dominant strategy in these groups in the beginning. In groups who converge to a sunspot equilibrium the fraction of the risk-dominant strategy is only about 5% in the first 20 periods compared to 24% in those groups who did not converge to a sunspot equilibrium.²⁰ Those groups in which the fraction of subjects following the public signal was not high enough or in which some subject did not adapt their behavior seem to converge to an intermediate case. As Figure 5 and Table 2 indicate, at least 3 groups (24, 29 and 32) converge to a 25/75 equilibrium. This is a best response to the presence of some subjects in the group who constantly play 50 and do not adapt their behavior. For all 3 groups the 95-% confidence interval for the asymptote β_{2j} includes 25.

5.4 Welfare

The previous results clearly show that different information structures induce very different behavior. We have seen that public information reliably generates sunspots, whereas, for instance, no information or low-precision private information leads to the risk-dominant equilibrium. For welfare considerations it does not matter which equilibrium is eventually played. Hence, following or neglecting sunspots need not affect welfare. What matters, however, is the convergence path to the

²⁰ This comparison does not include the group who converged to risk dominant equilibrium.

equilibrium. If a certain information structure results in a slower convergence process, we will observe mis-coordination in the beginning and thus welfare losses.

[Figure 6 about here]

Table 4 Regression - Sunspots – CP

Dependent variable: $ a_{it} - 50 $						
Group	β_{1j}	standard errors	β_{2j}	standard errors	95% Conf. Interval for β_{2j}	
	coefficient		coefficient			
24	27.314***	(3.473)	26.774***	(0.663)	25.476	28.073
25	29.732***	(6.197)	38.623***	(1.182)	36.306	40.939
26	21.654***	(2.722)	0.050	(0.519)	-0.968	1.067
27	15.512***	(3.444)	49.815***	(0.657)	48.528	51.103
28	28.400***	(5.257)	9.378***	(1.003)	7.412	11.343
29	1.408	(5.804)	16.779***	(1.107)	14.609	18.948
30	50.000***	(0.041)	50.000***	(0.008)	49.985	50.015
31	26.779***	(2.741)	50.117***	(0.523)	49.092	51.142
32	10.204**	(4.375)	26.531***	(0.835)	24.895	28.166
33	38.280***	(4.538)	47.450***	(0.866)	45.753	49.146
34	27.586***	(4.838)	28.485***	(0.923)	26.676	30.293
35	37.595***	(1.640)	50.336***	(0.313)	49.723	50.950

Notes: GLS regression with AR(1) errors, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. *Significance*¹ refers to Wald tests for the hypothesis that $\beta_{2j} = 50$.

The obvious welfare measure that we will use throughout this section will be the average payoff of a matching group (see Table A1 and A2). Figure 6 gives a first indication of the average payoffs and the average distance to 50 of the independent groups aggregated at the treatment level. The maximum payoff is 200 and the aggregated average payoff in N is close to it (198.9). The aggregated average payoff is only slightly lower in P75 (197.0), C (195.4) and CC (194.7) which reflects the longer convergence process in these two treatments compared to N. In all other treatments (P95, AC and CP) the aggregated average payoff is below 190. We summarize this in the following result.

Result 4 *Public extrinsic information is not detrimental to welfare, but if extrinsic information is not public or with public and private extrinsic information we observe considerable welfare losses.*

For statistical support we run non-parametric tests, which we base on all 80 periods.²¹ This gives us a rigorous test of possible welfare effects, since it requires long periods of mis-coordination in the beginning to generate significant differences in average payoffs over all periods. We look first at the welfare implications of sunspots. The average payoff in C rises from 190.2 in the first 20 periods to 199.6 in the last 20 periods. In contrast, in treatments N and P75 (N/P75) the average payoff is in the first 20 periods 193.8 and 198.9 in the last 20 periods. Comparing the average payoffs overall periods in C (195.4) to N/P75 (197.8), we find no significant difference in payoffs (Mann-Whitney, $z = 0.183$, $p > 0.4$, one-sided).²² Thus, while it seems that on average the convergence process in C is a little bit slower than in N and P75 sunspots are not detrimental for welfare.

In the treatments with almost public information, i.e. P95 and AC, the average payoff in the beginning is about 180.6 (185.2) and rises to only 193.1 (193.9) in the last 20 periods. There is no difference in payoffs in these two treatments (Mann-Whitney, $z = 0.641$, $p > 0.5$). However, as the lower average payoffs suggest, there is a difference if we compare P95 and AC with N/P75 and, respectively, with C. We can reject the hypothesis of equal means in P95 and N/P75 (Mann-Whitney, $z = 1.643$, $p = 0.05$, one-sided). The average payoff in P95 is also significantly lower than in C (Mann-Whitney, $z = 1.441$, $p = 0.075$, one-sided).²³

Next we look at the welfare effects of receiving more than one signal. Receiving two public signals as in CC lead subjects to aggregate this information and this reliably creates sunspots. While average payoffs are low in the beginning with 187.5 they rise up to 197.9 in the last 20 periods. Over all periods the average is only slightly lower (194.7) than in C but not statistically significant (Mann-Whitney, $z = 0.160$, $p > 0.4$, one-sided). Payoffs in CC are also not different from payoffs in N and P75 (Mann-Whitney, $z = 0.365$, $p > 0.35$, one-sided).

In treatment CP we observed mainly three convergence patterns. Some groups converged to the sunspot strategy 0/100. Their average payoff is 192.2, which is comparable to CC and C. At least three groups converge to a 25/75 sunspot strategy with an average payoff of 188.5, which is in the range of average payoffs in P95 and AC. Finally, we observe groups who did not converge at all. The average payoff in these groups is 184.4, which is the lowest observed payoff. Over all groups, the average payoffs in Treatment CP are 189.56. Not surprisingly, we can reject the null hypothesis for equal means in C and CP (Mann-Whitney, $z = 2.060$, $p = 0.02$, one-sided) and in N/P75 and CP (Mann-Whitney, $z = 2.741$, $p < 0.01$, one-sided).

²¹ We obtain the same results by running random-effects GLS regressions on individual payoffs allowing to control for group effects.

²² Note that the tests are one-sided because we can only observe negative welfare effects, if any.

²³ The average payoffs in AC are slightly higher than in P95 (190.7) and the difference to C is not significant statistically (Mann-Whitney, $z = 0.641$, $p > 0.25$, one-sided)

6 Conclusion

In this paper we have reported evidence for the occurrence of sunspots in the laboratory. In a simple game, inspired by Keynes' beauty contest, we introduce extraneous signals and systematically vary the information structure of the signals in order to control the available extrinsic information and its effect on behavior. Our findings provide direct evidence that extrinsic (public) information can have a substantial impact on collective perceptions, i.e. that it provides a focal point, and therefore sunspot equilibria reliably show up.

We investigated the impact of extrinsic information by manipulating the degree of observability of signals and by introducing multiple signals. As long as the signals are imprecise, i.e. when signals are private and the conditional probability that they are the same is low, subjects tend to ignore them. But, if the precision increases, we observe sunspot-like behavior, even though theoretically no sunspot-equilibria exist. Also, private signals may affect the coordination ability of groups in the presence of public extrinsic information. In this case, additional (private) signals may reduce the impact of sunspots on behavior.

Public extrinsic information is not detrimental for welfare. However, the presence of almost public extrinsic information or public and private information considerably impedes coordination behavior. While the individual losses of following the private information might be small, it affects coordination behavior over the long run.

Finally, we provide evidence that the salience of certain actions (label salience) is no longer effective when extrinsic information is available, even in symmetric games. The introduction of extrinsic information influences subjects' perceptions of focal points and in some cases leads to considerable miscoordination in groups. Hence, our results show the fragility of focal points.

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Appendix

A1 Proofs of Lemmas 1 and 2

Lemma 1. Let $\{a_{\varphi,\psi}^{i*} \mid \varphi \in \Phi, \psi \in \Psi\}$ be a Bayesian Nash equilibrium strategy profile, where $a_{\varphi,\psi}^{i*}$ is a Bayesian Nash equilibrium action played by agent i with public signal φ and private signal ψ . Then, equilibrium actions are the same for both agents and do not depend on the private signal, that is, $a_{\varphi,\psi}^{i*} = a_{\varphi}^* \quad \forall \psi \in \Psi$ for any given $\varphi \in \Phi$.

Proof. We will prove the lemma in three steps.

Step 1. We want to show that the equilibrium must be in pure strategies. For any given set of signals, it must be that

$$a_{\varphi,\psi}^{i*} = \arg \max_x \sum_{\psi \in \Psi} p_{\varphi,\psi^j}^{\psi^i} f(x - a_{\varphi,\psi}^{j*})$$

where $p_{\varphi,\psi^i}^{\psi^j}$ be the probability that the other player receives signal ψ^j when he receives signal ψ^i in state φ .²⁴ The expression to be maximized is strictly concave so the best response must be unique. Hence, it cannot be that in equilibrium they play different actions with positive probability for a same set of signals.

Step 2. Extreme actions played in equilibrium must coincide for both players, that is, $\arg \min_{\psi} \{a_{\varphi,\psi}^{i*}\} = \arg \min_{\psi} \{a_{\varphi,\psi}^{j*}\}$ and $\arg \max_{\psi} \{a_{\varphi,\psi}^{i*}\} = \arg \max_{\psi} \{a_{\varphi,\psi}^{j*}\}$ for $i \neq j$.²⁵ We will show that by contradiction. Suppose that, without loss of generality, $\arg \min_{\psi} \{a_{\varphi,\psi}^{i*}\} < \arg \min_{\psi} \{a_{\varphi,\psi}^{j*}\}$. Let $\bar{\psi} := \arg \min_{\psi} \{a_{\varphi,\psi}^{i*}\}$. Then, it must be that, implies

$$\left. \frac{\partial \sum_{\psi \in \Psi} p_{\varphi,\bar{\psi}}^{\psi^j} f(x - a_{\varphi,\psi}^{j*})}{\partial x} \right|_{x=a_{\varphi,\bar{\psi}}^{i*}} = \arg \max_x \sum_{\psi \in \Psi} p_{\varphi,\bar{\psi}}^{\psi^j} f'(a_{\varphi,\bar{\psi}}^{i*} - a_{\varphi,\psi}^{j*}) > 0$$

²⁴ See that by allowing different probabilities we implicitly allow effects of a public signal.

²⁵ These expressions are well defined given the finite cardinality of private signals, and Step 1.

given that $f'(a_{\varphi, \bar{\psi}}^{i*} - a_{\varphi, \psi}^{j*}) > 0 \quad \forall a_{\varphi, \psi}^{j*}$. Therefore, $a_{\varphi, \bar{\psi}}^{i*}$ cannot be best response.

Step 3. In this last step we show that $\arg \min_{\psi} \{a_{\varphi, \psi}^{i*}\} = \arg \max_{\psi} \{a_{\varphi, \psi}^{i*}\}$ for both players. We will again prove it by contradiction. Suppose that it is not the case. We know by the previous step that the extremes must be the same. In that case, the derivative of the expected profits at $\bar{\psi}$ is again positive. In that case, the derivative will be zero if both players play the minimum action in equilibrium and positive for the rest.

Therefore, it must be that $a_{\varphi, \psi}^{i*} = a_{\varphi}^* \quad \forall \psi \in \Psi$ for any given $\varphi \in \Phi$. ■

Lemma 2. $a_{\psi, \varphi}^{i*} = \frac{b+c}{2} \quad \forall \psi, \varphi$ is the both the secure action and the risk dominant equilibrium.

Proof. The minimum payoff that can be obtained given action x is the payoff given by one of the extremes, that is, $\min \{f(x-b), f(c-x)\}$. It is trivial to see that this function is maximized at $x = (b+c)/2$, and therefore playing the middle action maximizes the minimum payoff. Hence, the middle point of the interval is the secure action.

In order to find the risk dominant equilibrium, we must find the action x that maximizes the expected payoff against a player that plays a uniform distribution over all the actions, i.e.,

$$\frac{1}{c-b} \int_b^c f(x-y) dy$$

Suppose, without loss of generality, that $x < \frac{b+c}{2}$.

$$\begin{aligned} \int_b^c f(x-y) dy &= \int_b^x f(x-y) dy + \int_x^{\frac{x+\frac{b+c}{2}}{2}} f(x-y) dy + \int_{\frac{x+\frac{b+c}{2}}{2}}^c f(x-y) dy \\ &\leq \int_b^x f(x-y) dy + \int_x^{\frac{x+\frac{b+c}{2}}{2}} f(x-y) dy + \int_{x-b}^{\frac{b+c}{2}} f(x-y) dy \\ &= \int_b^c f\left(\frac{b+c}{2} - y\right) dy \end{aligned}$$

Hence, $\frac{b+c}{2}$ is the risk dominant equilibrium. ■

A2 Symmetry of actions

We say a strategy is symmetric if the absolute distance of a decision from 50 is the same for both realizations of a signal. Note that for treatments with two signals the distance has to be the same when both signal coincide and when they differ. To test the symmetry of strategies we estimate the following model.

$$|a_{it} - 50| = \beta_1 S100 + \beta_2 period + \alpha_i + u_{it}$$

The dependent variable is the absolute distance to 50 of the decision of individual i . As independent variables we include Period to control for the time trend and a dummy variable, S100, for signal $s=100$. The model also includes a random effect for each individual and we control for repeated decisions of the same subject as well as for dependencies within matching groups. Note that for treatments CC and CP we estimate separate regressions for equal signals ($X_i = Y$) or ($Y=Y$) and unequal signals ($X_i \neq Y$) or ($Y \neq Y$). The relevant variable is the dummy for the signal S100. If decisions are symmetric, the coefficient should be close to zero and insignificant. The regression results are displayed in Table A1. We find for each treatment that the coefficient for S100 is indeed not significantly different from zero. This result also holds if we run the regression for each group separately. Only in 4 out of 60 groups the p-value of the dummy variable S100 is below 5%. In sum, the results of the regressions suggest that subjects treat the decisions as symmetric.

Table A1. Symmetry of decisions

	Dependent variable: $ a_{it} - 50 $							
	P75	P95	C	CP		CC		AC
				equal sig.	unequal sig.	equal sig.	unequal sig.	
Signal=100 (D)	0.350	0.844	0.294	0.494	-0.628	-0.085	0.528	-0.318
	(0.307)	(0.957)	(0.341)	(0.339)	(0.448)	(0.069)	(0.569)	(0.198)
Period	-0.102***	-0.077**	0.089*	-0.049	0.159***	0.010	-0.110**	-0.058
	(0.014)	(0.038)	(0.049)	(0.035)	(0.055)	(0.007)	(0.051)	(0.041)
Constant	6.717***	19.952***	42.914***	36.938***	19.987***	48.610***	7.007**	17.395**
	(0.982)	(6.398)	(4.509)	(2.850)	(3.687)	(0.664)	(3.344)	(7.768)
P	0.000	0.120	0.107	0.015	0.015	0.332	0.050	0.188
chi ²	54.76	4.24	4.47	8.44	8.44	2.203	5.98	3.343
R ²	.072	.009	.035	.005	.0338	.001	.066	.005
N	1440	2880	2880	3456	2304	1728	1152	2662

Note: Random-effects GLS regression, robust standard errors clustered at group level in parentheses, (D) denotes dummy variable, equal signal refers to $x=y=100$ or $x=y=0$, * $p<0.10$, ** $p<0.05$, *** $p<0.01$

Tables

Table A2: Aggregate results of non sunspots treatments.

Treatment	Session	Group	Strategy	T_6	T_4	Avg. coord. rate	Avg. payoff (std. dev.)	$ a_i - 50 $ (std. dev.)	
(1)	(2)	(3)	(5)	(6)	(7)	(8)	(9)	(10)	
N	1	1	50	56	40	0.84	198.5 (6.8)	1.44 (5.9)	
N		2	50	42	1	0.96	199.3 (5.2)	0.55 (4.2)	
P75	2	3	50	10	7	0.93	198.9 (5.5)	1.27 (6.4)	
P75		4	50	20	2	0.89	197.1 (11.4)	2.08 (8.6)	
P75		5	50	-	25	0.58	195.1 (9.9)	4.88 (10.5)	
P95	3	6	Y10	-	77	0.51	185.5 (39.4)	39.39 (6.5)	
P95		7	Y10	-	63	0.30	181.6 (38.7)	38.60 (12.6)	
P95		8	50	13	8	0.90	195.8 (19.3)	2.37 (9.7)	
P95		9	50	7	6	0.96	199.2 (5.1)	0.66 (4.5)	
P95		4	10	50	12	12	0.92	196.5 (12.3)	2.44 (10.5)
P95		11	-	-	-	0.31	172.7 (33.5)	20.07 (22.4)	
AC	8	12	50	32	3	0.96	198.5 (8.5)	0.79 (6.1)	
AC		7	13	50	7	4	0.96	198.3 (9.0)	1.04 (7.1)
AC		14	50	16	1	0.97	199.5 (4.0)	0.38 (3.5)	
AC		15	Y	70	46	0.80	188.9 (27.4)	44.94 (14.8)	
AC		16	50	19	13	0.90	195.5 (14.1)	3.71 (12.9)	
AC		17	Y	74	74	0.25	163.6 (48.7)	32.31 (21.8)	

Notes: T_6 (T_4) denotes strict (weak) convergence (earliest period from which all (at least 4) subjects play according to a given strategy, allowing a deviation of ± 1). The avg. coordination rate is the percentage of pairs choosing the same action within a range of ± 1 .

Table A3. Aggregate results of sunspots treatments.

Treatment	Session	Group	Strategy	T ₆	T ₄	Avg. rate	coord.	Avg. payoff (std. dev.)	a _i - 50 (std. dev.)
(1)	(2)	(3)	(5)	(6)	(7)	(8)	(9)	(9)	(10)
C		18	Y	80	68	0.74		196.3 (20.0)	48.31 (5.8)
C	5	19	Y	6	3	0.97		199.9 (1.01)	49.60 (2.38)
C		20	Y	33	6	0.93		197.8 (15.8)	48.76 (6.0)
C		21	Y	2	1	0.99		199.8 (3.2)	49.88 (2.3)
C	6	22	Y	80	57	0.44		182.6 (25.3)	33.99 (21.2)
C		23	Y	49	5	0.94		196.0 (26.1)	49.53 (2.8)
CP		24	Y25	65	60	0.36		193.3 (11.4)	26.00 (11.8)
CP	8	25	-	-	-	0.15		179.9 (32.7)	33.83 (17.8)
CP		26	50	24	8	0.90		194.9 (15.0)	3.49 (12.7)
CP		27	Y	54	38	0.72		192.2 (23.1)	45.49 (12.2)
CP	9	28	-	-	-	0.40		185.3 (19.3)	16.19 (19.0)
CP		29	Y25	-	78	0.41		187.3 (16.9)	19.09 (17.3)
CP		30	Y	33	1	0.99		199.0 (13.3)	49.90 (2.3)
CP	10	31	Y	65	34	0.72		189.8 (29.6)	45.19 (13.0)
CP		32	Y25	-	76	0.34		184.9 (25.0)	25.58 (13.6)
CP		33	Y	77	57	0.63		186.0 (29.4)	41.98 (16.2)
CP	11	34	-	-	-	0.10		188.1 (14.5)	25.09 (16.6)
CP		35	Y	-	29	0.84		194.1 (21.8)	46.95 (10.8)
CC		36	Mean	79	16	0.83		195.3 (14.3)	33.32 (23.0)
CC	12	37	Mean	-	3	0.66		184.6 (35.4)	28.65 (23.5)
CC		38	Mean	20	12	0.91		190.3 (38.5)	30.88 (24.2)
CC		39	Mean	58	4	0.96		198.5 (14.0)	30.08 (24.4)
CC	13	40	Mean	4	1	0.99		199.6 (4.6)	30.00 (24.5)
CC		41	Mean	2	1	0.99		199.9 (1.2)	30.06 (24.5)

Notes: T₆ (T₄) denotes strict (weak) convergence (earliest period from which all (at least 4) subjects play according to a given strategy, allowing a deviation of ± 1). The avg. coordination rate is the percentage of pairs choosing the same action within a range of ± 1 .

Figures

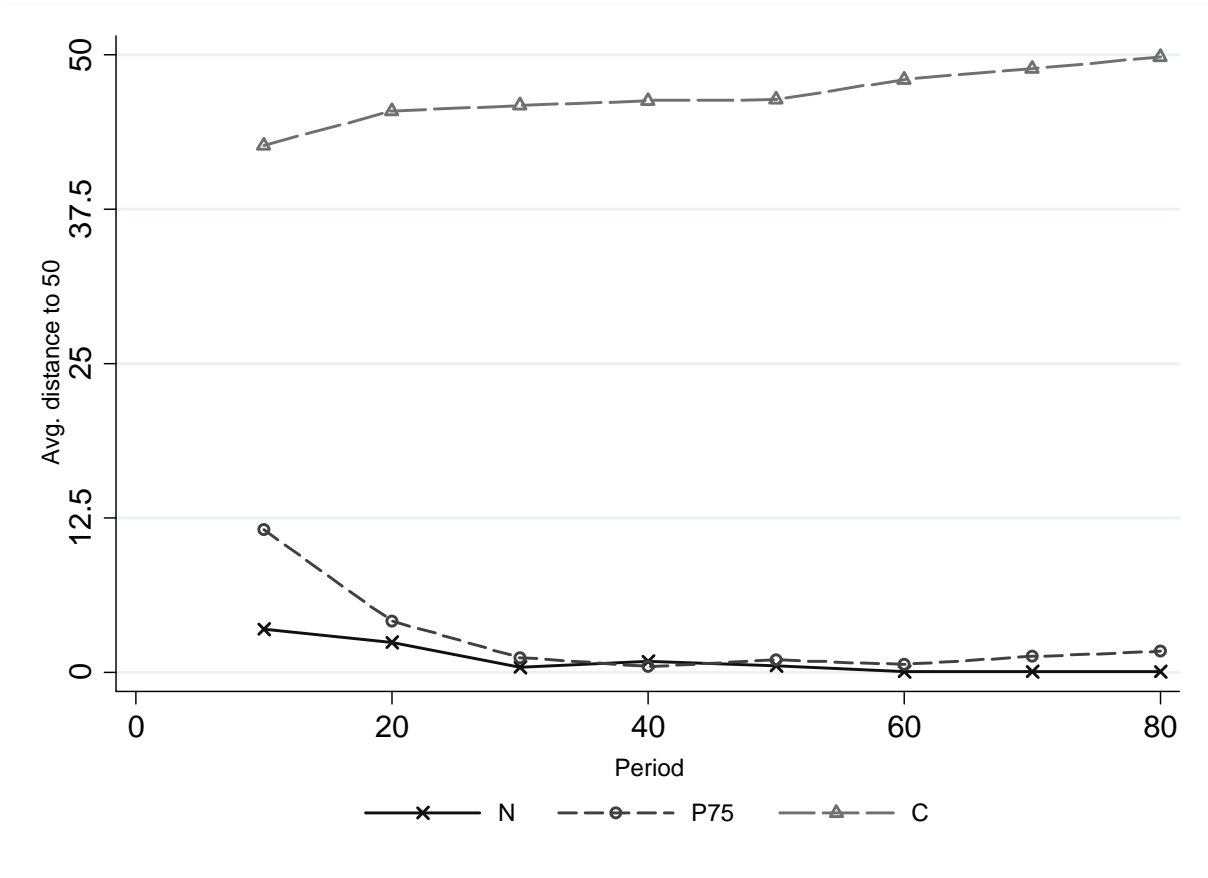


Figure 1: Average distance to 50 over all groups in N, P75 and C.

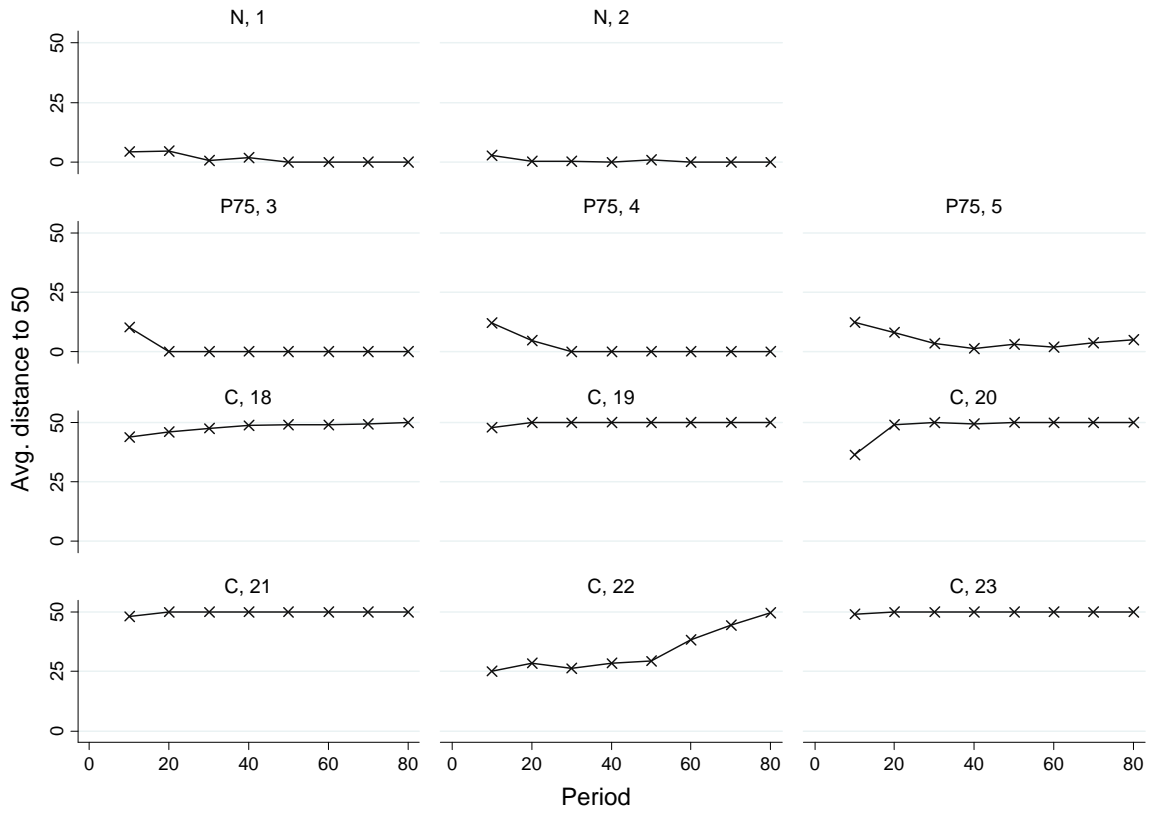


Figure 2: Average distance to 50 by blocks of 10 periods in treatments N, P75 and C.

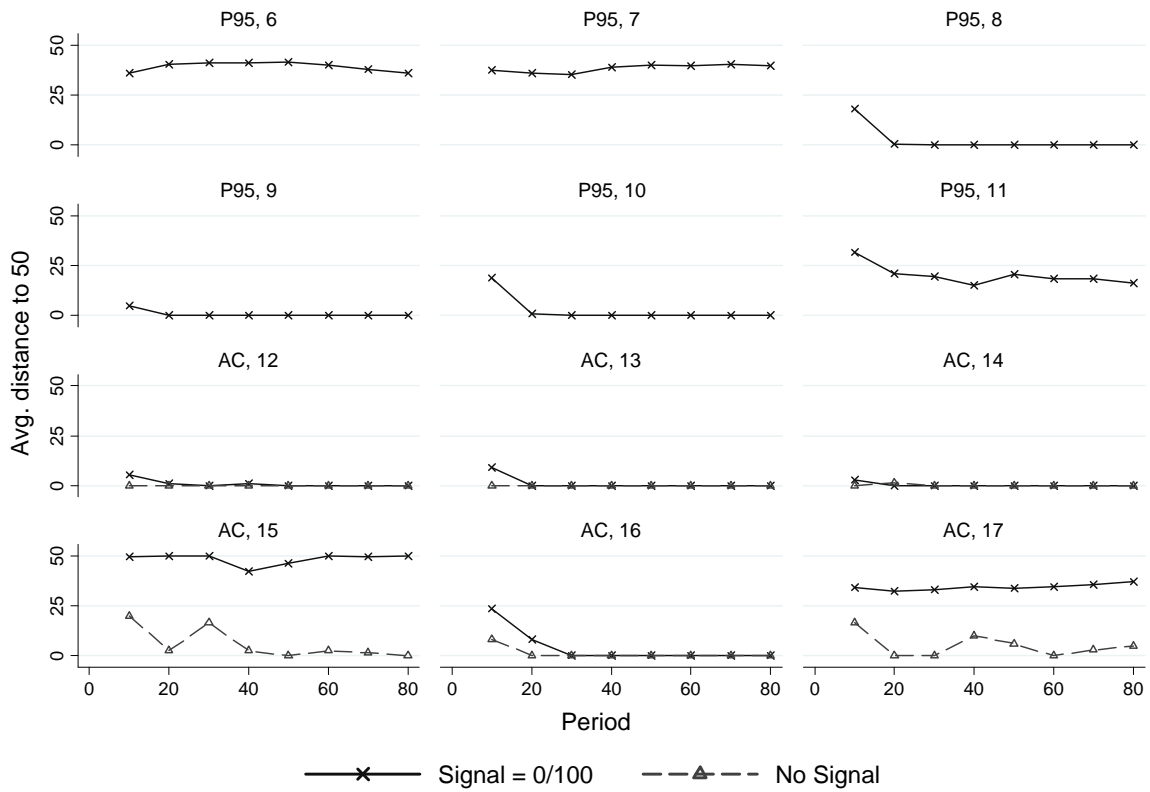


Figure 3: Average distance to 50 by blocks of 10 periods in treatments P95 and AC.

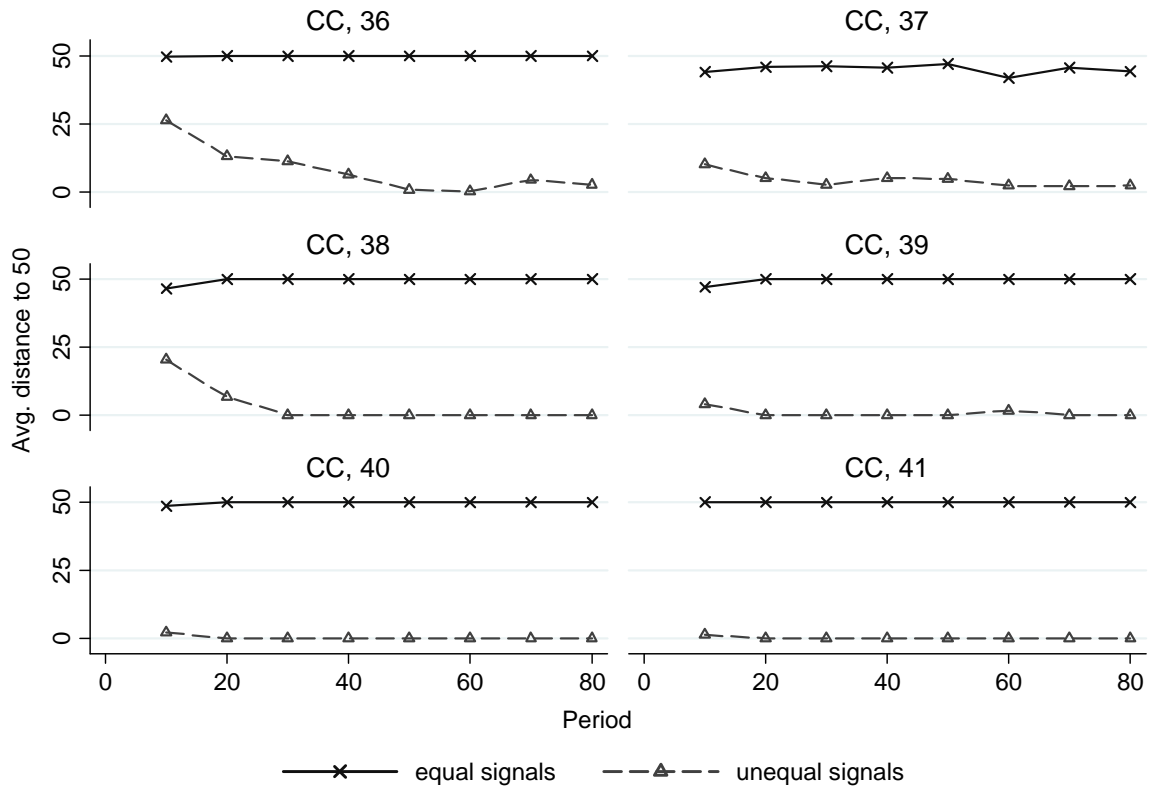


Figure 4: Average distance to 50 by blocks of 10 periods in treatment CC.

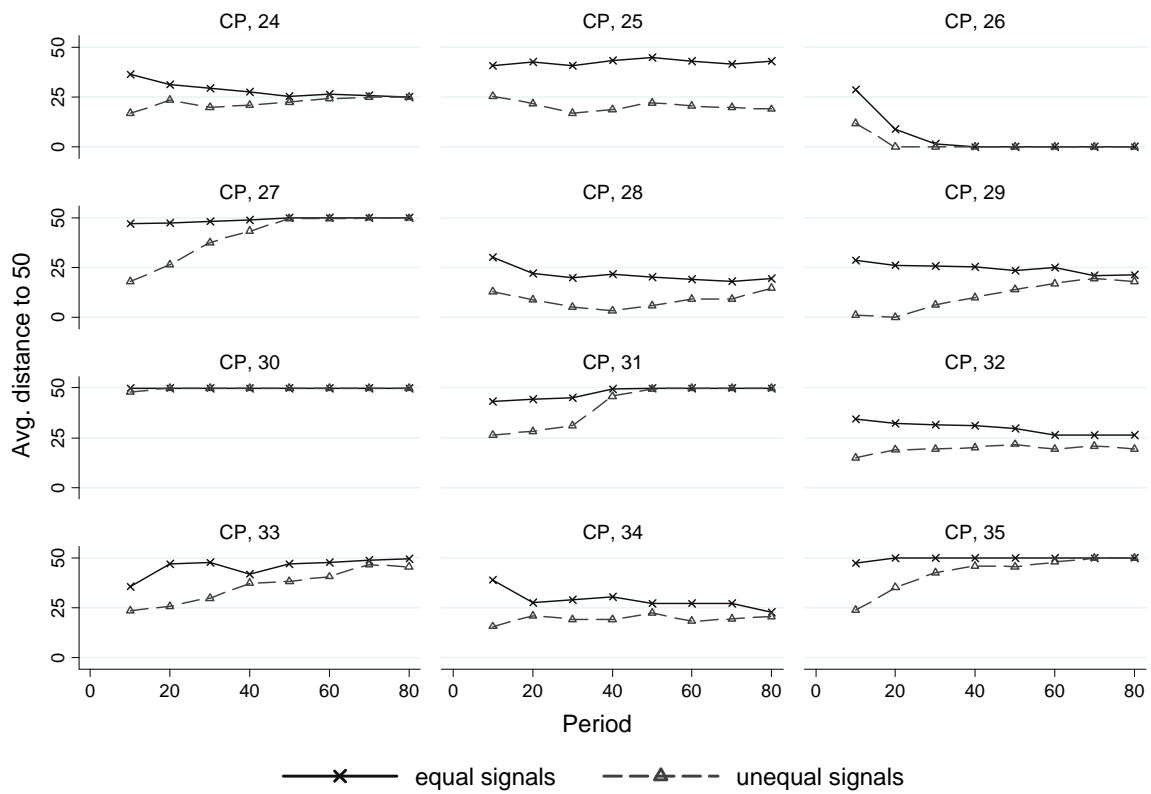


Figure 5: Average distance to 50 by blocks of 10 periods in treatment CP.

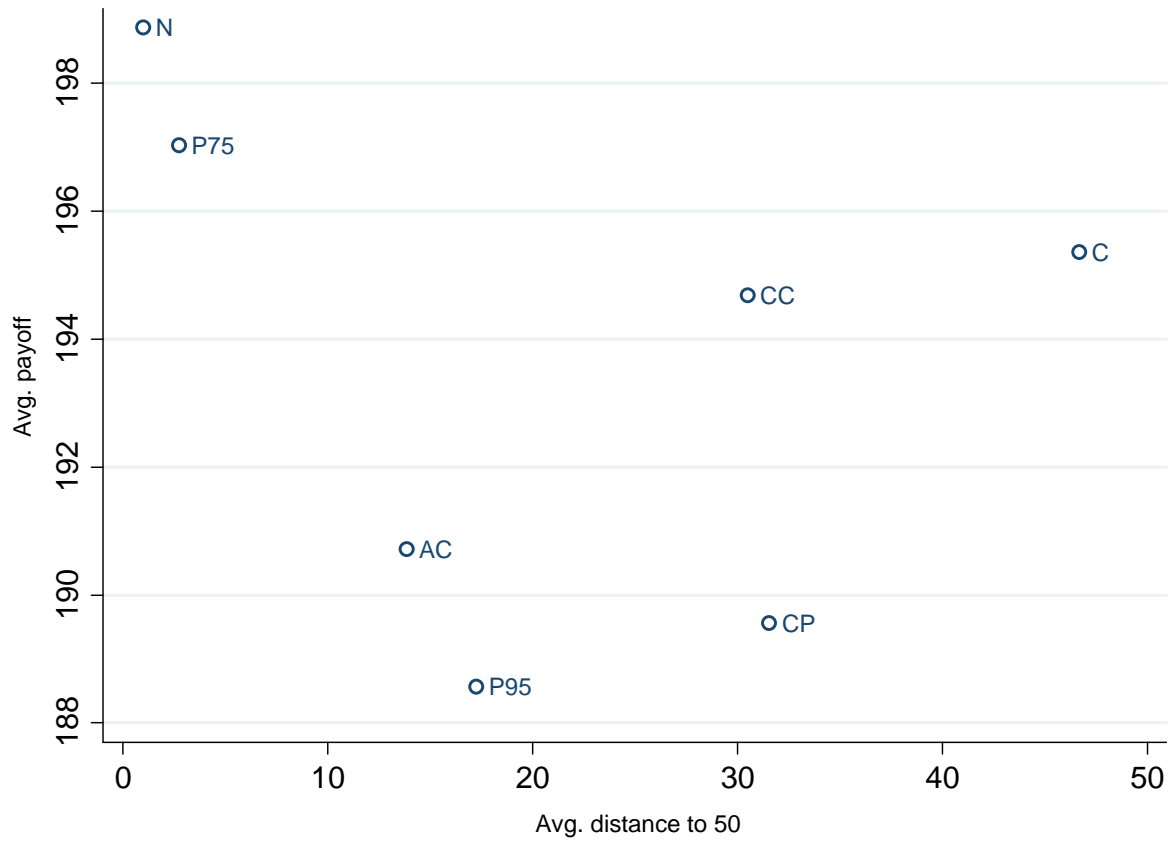


Figure 6: Relationship of average distance to 50 to the average payoff across treatments.