The Power of Sunspots: An Experimental Analysis*

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Abstract:

We present an experiment in which extrinsic information (signals) may generate sunspot equilibria. The underlying coordination game has a unique symmetric non-sunspot equilibrium, which is also risk-dominant. Other equilibria can be ordered according to risk dominance. We introduce salient but extrinsic signals on which subjects may condition their actions. By varying the number of signals and the likelihood that different subjects receive the same signal, we measure how strong these signals affect behavior. Sunspot equilibria emerge naturally if there are salient public signals. Highly correlated private signals may also cause sunspot-driven behavior, even though this is no equilibrium. The higher the correlation 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. Sunspot-driven behavior may lead to welfare losses and exert negative externalities on agents, who do not receive extrinsic signals.

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 information 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 beliefs to 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, i.e., a sunspot could be anything that possibly coordinates the expectations of market participants and breaks the symmetry in coordination problems. For example, lunar phases are publicly observable. They may influence human behavior and mood, and if individuals (mistakenly) attribute economic outcomes to the moon, this perception can become self-fulfilling and moon phases might be used as a coordination device.[2] However, there has to exist a shared understanding about how moon phases (or sunspots) affect behavior, because sunspots are essentially a social phenomena (Duffy and Fisher, 2005).

In the field, it is arguably hard to identify a particular extrinsic event that may affect an agent's choice. Even if such an extrinsic event is identified, it is difficult to establish a causal

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[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, Zheng and Zhu, 2006; Hirshleifer and Shumway, 2007, and references therein) or on college choice (Simonsohn, 2009). Mood might also be reflected in confidence indices, such as the Michigan Consumer Sentiment Index or the Ifo Business Climate Index, which contain some information about the future path of household spending. Others have shown that sports events impact stock-market indices (Edmans, Garcia and Norli, 2007) or expectations about the future personal situation and the economic situation in general (Dohmen et al., 2006). However, in this literature it is difficult to argue that these events do not affect preferences or do not have direct effects on utility. Individuals also often show a tendency to incorporate irrelevant information into their decision, although it is not profitable for them, for example in financial or innovation decisions (e.g., Camerer, Loewenstein and Weber, 1989, Jamison, Owens and Woroch, 2009, or Choi, Laibson and Madrian, 2010).

link between the extrinsic event (sunspot) and an economic outcome. For instance, non-informative signals might be an explanation for excess asset-price volatility when traders condition their actions on such signals, but higher volatility may also be caused by an increased dispersion of private signals or increasing uncertainty.

In this paper, we use a laboratory experiment to explore the impact of extrinsic information on economic behavior. The experimental approach allows us (1) to control the available extrinsic information and its potential meaning and (2) to investigate how such extrinsic information affects coordination and the occurrence of sunspot equilibria. In particular, we hold the institution (game) and the semantics of the extrinsic information fixed over treatments and vary only the extent to which extrinsic information is available and publicly observable. We use a simple two-player coordination game with random matching where players have to pick a number from the interval zero to 100. Players maximize their payoffs by choosing the same number and deviations are punished with a quadratic loss function. Therefore, each coordinated pick of numbers constitutes a Nash equilibrium and payoffs do not depend on the number that players coordinate on. Nevertheless, some numbers are presumably more prominent than others.[3] Picking 50, in particular, is the unique symmetric equilibrium and it is also the Maximin strategy and the risk-dominant equilibrium.[4]

Extrinsic signals (sunspots) in our experiment are binary random variables unrelated to payoffs with realizations being either zero or 100. Thereby, subjects may use the signal as a coordination device by choosing the same number as the signal. 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. In the most favorable case, subjects receive one publicly observable signal, which may provide another focal point for solving the coordination problem besides the risk-dominant choice. These two focal points – risk dominance and sunspot (public observable signal) – differ with respect to their associated risk: following the sunspot (public signal) is riskier than following any other strategy. The risk-dominance criterion allows us to order the different equilibria by the associated level of

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[3] For example, even numbers or multiples of 10 may be more salient than others (e.g. Rosch, 1975).

[4] In the pure coordination game in our baseline setting the notion of risk dominance (Harsanyi and Selten, 1988) provides a natural way to break the payoff symmetry and thus may serve as a focal point. Indeed, Schelling's (1960) focal point concept originated from situations where the formal structure of the game provides no guidance for equilibrium selection, such as in a pure coordination game. For experimental studies of the focal point concept see, for example, Mehta, Starmer and Sudgen (1994), Bosch-Domenech and Vriend (2008), Bardsley et al (2009), Crawford, Gneezy and Rottenstreich (2009) or Agranov and Schotter (2010). Crawford and Haller (1990) show theoretically how players can coordinate via precedents when they lack a common-knowledge description of the game in a repeated setting (see also Blume and Gneezy, 2000, for an experimental test).

strategic risk. Therefore, we can measure the power of sunspots by how far actions are distracted away from the risk-dominant equilibrium. We systematically vary the information structure, i.e., the number of signals and their degree of public availability. For each treatment, we measure the average distance between chosen actions and the risk-dominant strategy and the proportion of groups who are converging to sunspot equilibria. Thus, we can investigate to what extent publicity is necessary for the occurrence of sunspot-driven behavior and how the available information is aggregated.

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 subjects receive just public signals, even when 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, which dominates the force of risk dominance. This is less pronounced in the presence of public *and* private signals since some subjects then condition their actions on the private signal, which prevents full coordination of actions or leads to an intermediate sunspot equilibrium. 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. In the absence of public signals, the risk-dominant equilibrium predominates. However, sunspot-driven behavior can be observed for highly correlated private signals. This implies that the likelihood of sunspot-driven actions is a continuous function of the correlation of signals, while theory predicts sunspot equilibria only if signals of different agents are perfectly correlated.

Whether sunspot-driven behavior or sunspot equilibria occur depends on the group dynamics in the early periods. In treatments with a private signal, sunspot-driven behavior only occurs in groups where in the beginning a critical mass of subjects deviates from the risk-dominant choice. This is also true for the occurrence of sunspot equilibria in treatments with a private and a public signal. If a sufficient proportion of subjects in a group follow the public signal, the group quickly converges to a sunspot equilibrium, while groups that are, in the first periods, torn between following the public or private signal have difficulties to coordinate at all.

Sunspot equilibria are not associated with welfare losses in our coordination game; in fact all equilibria are efficient. However, our setup allows isolating the welfare effects of miscoordination induced by extrinsic information. We find that the payoffs are U-shaped in the power of sunspots, which is measured by the distance of actions from the risk-dominant equilibrium, and hence we find significant differences in average payoffs between treatments. Miscoordination arises from (i) a slower convergence process towards a common strategy or a lack of convergence and (ii) coordination on a strategy that is no equilibrium, and in particular negative externalities from sunspot-driven behavior to agents without signals. Both channels relate or can be thought of as costs arising from a lack of understanding whether or not to condition actions on signals and how to aggregate information.

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 generation's economy, where the sunspot was a blinking square on the 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, which constitutes an endowment shock and leads to a unique equilibrium with alternating high and low prices. After 16 to 20 periods, they shut off the endowment shock by keeping the generation size fixed, which induced multiple equilibria, one stationary and one being a two-period cycle. In four out of five sessions, subjects continued to alternate their price forecasts, but the price paths were substantially off the sunspot-equilibrium predictions. It is also not clear whether alternating predictions are just carried over from experience gathered 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.[5] They

[5] Beugnot et al (2009) explore the effect of sunspots in a setting with a payoff-dominant equilibrium. They use a three-player, two-action coordination game with two equilibria – "work" or "strike" – where "work" is payoff-dominant, weakly risk-dominant and maximin. Their sunspot variable was a random announcement of "work" or

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 four out of nine cases in more informative double auction markets. More interesting, 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. In order to achieve such a common understanding of the sunspot variable, subjects were primed to existence of high and low equilibria in combination with the respective announcement in an initial training phase. However, in sessions without priming and announcements like "the forecast is sunshine (rain)" sunspots did not occur. In our approach a sunspot is semantically salient and sunspot equilibria arise endogenously without any need of training.

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 played according to a correlated equilibrium which led to higher payoffs than in the mixed strategy equilibrium. In a related experiment, Duffy and Feltovich (2010) also find that subjects condition their behavior on a third-party recommendation leading to higher than mixed strategy equilibrium payoffs (good recommendation), but they learn to ignore bad or non-equilibrium recommendations.

Some related experiments explore subjects' responses to recommendations to play a pure-strategy equilibrium in games with multiple equilibria (for example, Brandts and Holt, 1992; Brandts and MacLeod, 1995; Kuang, Weber and Dana, 2007; van Huyck, Gilette and Battalio, 1992).[6] A recommendation can be seen as an extrinsic signal, but by phrasing it as advice, it becomes more salient and is more intrusive than our random signals. A noteworthy finding of this literature is that subjects only follow "credible" recommendations, for example, subjects tend to disregard advice to play an imperfect or a less efficient equilibrium. By contrast, our results show that subjects follow a random coordination device, even if it is riskier to do so and even if such behavior is no equilibrium.

"strike". They find that subjects do not coordinate on a sunspot equilibrium. Instead, there is some convergence towards the efficient non-sunspot equilibrium.

[6] While the recommendations in these experiments mostly come from the experimenter, there are also experiments where advice is given by players of a previous cohort participating in the experiment (see, e.g., Schotter and Sopher, 2003 or Chaudhuri, Schotter and Sopher, 2009, for such "intergenerational" advice in coordination games).

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

$$\pi_i(a_i, a_j) = f(|a_i - a_j|) \tag{1}$$

where $f: R \to R$ 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 ease of presentation, let us assume that $\Psi^i = \Psi$ for both *i* (as in the experiment), although this is not a necessary condition for proving the next lemma. Let $P: (\Phi, \Psi, \Psi) \to [0,1]$ 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* $\{a^{i*}_{\varphi,\psi} | \varphi \in \Phi, \psi \in \Psi\}$ *be a Bayesian Nash equilibrium strategy profile, where* $a^{i*}_{\varphi,\psi}$ *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,* $a^{i*}_{\varphi,\psi} = a^{*}_{\varphi} \quad \forall \psi \in \Psi$ *for any given* $\varphi \in \Phi$.

Proof: see Appendix.■

The assumptions of continuity and differentiability of the payoff function are not necessary and are just assumed for ease 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 signal 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 ($a^{i*}_{\varphi,\psi} = \psi$) 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 $E\left(\pi^i(a)\middle|\psi^i = 0\right) = -25 - a^i/2$), 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, sunspot equilibria exist in which both agents condition their actions on the public signal. Any function $f : \Phi \to [b,c]$ is an equilibrium, provided that both agents follow the same function and, thus, are always 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 (Harsany and Selten, 1988). In its original formulation, risk dominance is a binary relation that does not provide any strict order on the equilibria of our game. There is, however, an alternative notion of risk dominance in which, according to Harsanyi and Selten's heuristic justification, the selected equilibrium results from postulating an initial state of uncertainty where the players have uniformly distributed second-order beliefs on all equilibria. 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. In the following, we will refer to this alternative notion simply as risk dominance.[7]

Another alternative concept is the notion of secure action (see Van Huyck et al., 1990). Based on the maximin criterion of von Neumann and Morgenstern (1947), a secure action is one that maximizes the minimum possible payoff.[8]

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

Lemma2. $a^{i*}_{\psi,\varphi} = \frac{b+c}{2} \forall \psi, \varphi$ *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, one strategy is riskier than another if it can lead to a lower payoff. According to the notion of risk dominance, one equilibrium is riskier than another 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 symmetric, both measures of riskiness can be expressed as a function increasing in 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 extrinsic signal or a combination of extrinsic signals (sunspot) exerts a stronger effect on behavior than another combination, if (after some convergence) the average distance of chosen actions from $(b+c)/2$ is higher. Alternatively, we can say that an information structure is more likely to produce sunspot-driven behavior than another information structure

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[7] Among others, this alternative notion has been used, for example, in Stahl and Haruvy (2004).

[8] 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. The security criterion has also been applied to a game after the deletion of non-equilibrium actions (see, e.g., Stahl and Haruvy, 2004).

if the fraction of groups converging to a sunspot equilibrium or to a sunspot-driven non-equilibrium strategy is larger than in the respective other treatment.

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. In each period, we randomly matched subjects into pairs within a matching group. There was no interaction between subjects from different matching groups and, thus, we can treat data from different matching groups as independent observations. Subjects were aware that they were randomly matched with another subject from their matching group in each period and that they would never face the same subject twice in a row.

Subjects had to choose, independently and simultaneously, 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:

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

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.[9] It is easy to check that this payoff function fulfils the properties of the function characterized in the previous section and that both Lemma 1 and 2 hold for (2).[10]

4.2 Treatments

In the benchmark (Treatment N), subjects played the coordination game with payoff function (2) and received no extrinsic information. In all other treatments, subjects received some extrinsic information (signals) and we varied its publicity (private and public signals) and the number of signals. Extrinsic information was generated as follows. In each period, the computer drew a random number $Z \in \{0,100\}$. Both numbers were equally likely and the

[9] Note also that the minimum payoff is zero, since the maximum distance between two actions is 100.
[10] In contrast to the game in Section 3, subjects could only choose integers between 0 and 100 instead of choosing from an interval of real numbers. Technically, Lemma 1 holds except for differences in actions of ±5 in treatments AC and P95 and differences of ±1 in all other treatments. We do not observe these non-generic equilibria and therefore ignore them in the following analysis.

Table 1. Treatment Overview.

Treatment	Public signals	Private signals per subject	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

Note: *revealed with 90% probability

realization was not disclosed to the subjects (except for Treatment AC). Instead, each subject in a pair received at least one independently drawn signal *s*. With probability $p \in [0.5, 1]$ this signal s is the same as the random number Z, that is, $prob\,(s = 0 \mid Z = 0) = prob\,(s = 100 \mid Z = 100) = p$. Probability *p* measures the precision of signals and is one of our treatment variables.[11] The higher the precision of signals, the higher the correlation between two independently drawn signals is, and the higher the likelihood that both signals are the same. In treatments with private signals, each subject receives an independently drawn signal that is not revealed to the other player. A signal is public if the same signal is released to both players of a pair and subjects know that both of them receive the same signal. We also varied the number of signals subjects receive. In some treatments, subjects either receive a private or a public signal, and in two treatments, they receive two signals: either two public signals or a public and a private signal. Table 1 gives an overview of the different treatments.

In Treatments P75 and P95, both subjects in a pair received independently drawn private signals X_1 and X_2. 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 $p = 0.95$. Thereby, in P75 subjects get the same signal in 62.5% of the cases, while in P95 this probability is 90.5%. According to the theory, sunspot equilibria do not exist for private signals with a *p* value 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.

[11] This 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.

Hence, the set of equilibria is discontinuous in p and by changing the precision of signals we can test for continuity in p.

In Treatment AC, the realization of the random 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 of whether behavior is discontinuous in p, as predicted by theory. In Treatment AC, there exists no sunspot equilibrium since the information is not disseminated to all subjects with probability 1.

In Treatment C, both subjects in a pair received a 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 Y_1 and Y_2, both with $p = 0.75$. Here, any function f mapping pairs of $(Y_1,Y_2,)$ to the interval $[0{,}100]$ is an equilibrium. In Treatment CP, subjects received both a public and a private signal. The public 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 which signal was public and which one was private information. Again, subjects could ignore the private signal and condition their behavior on the public signal that allows for sunspot equilibria. As in Treatment C, any function $f : Y \mapsto [0{,}100]$ is an equilibrium.

4.3 Procedure

Subjects played the game for 80 periods. After each 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 at PCs in random order. Instructions were distributed and read out aloud, and questions were answered in private. Throughout the sessions, students were not allowed to communicate with one another and could not see each other's 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.[12] 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 the subjects understood how their payoff was determined. Second, we wanted to prompt subjects to the fact that neither the number Z nor the signals affected their payoff, and third, the quiz also ensured that subjects could clarify any last-minute questions and that the others understood the game as well.[13] Once all subjects had answered the questions correctly, the experiment started.

We ran a total of 14 sessions with 18 subjects in each session (except for one session with only 12 subjects), which took place between July 2008 to June 2009 at the Technical University Berlin. In total, 246 subjects participated, who were recruited through the online recruitment system ORSEE (Greiner, 2004). 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. Subjects were then paid the sum, in private and in Euros (1 point = 1 Euro cent), as they had earned it in the selected periods. In addition subjects received 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 the data with a quick overview of the aggregate behavioral patterns in the different treatments. We are especially interested in learning whether groups converge to a common strategy and to which strategies they converge in the different treatments. Then, we show how to use the distance of choices from the risk-dominant equilibrium as a measure for the power of sunspots and analyze differences in strategies and convergence across different treatments in detail. In Section 5.4, we analyze the implications of extrinsic information on payoffs.

[12] 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 calculate the resulting payoff.

[13] For instance, in Treatments P75 and P95, 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 if their answer was not correct, the experimenter once again explained the payoff function to make clear that it only depended on the distance between the chosen number and the number chosen by the partner. The full set of questions can be found in the appendix.

Table 2. Coordination Summary.

	Non-Sunspot Treatments				Sunspot Treatments		
Treatment	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)	5 (6)	4 (6)	6 (8)	4 (6)
Strategies:							
"50"	2	2 (3)	3	4	-	1	-
"25/75"	n.a.	-	-	-	-	1 (2)	n.a.
"10/90"	n.a.	-	- (2)	-	-	-	n.a.
"0/100"	n.a.	-	-	1 (2)	4 (6)	4 (5)	n.a.
"Mean"	n.a.	n.a.	n.a.	n.a.	n.a.	-	4 (6)

Note: "Coordinated groups" indicate the number of converged groups according to the strong (weak) criterion.

In order to organize our analysis, we introduce two convergence criteria. A rigorous criterion would demand that all subjects in a group decide for exactly the same strategy without deviation during an extended number of periods. This rigorous criterion is, however, not likely to be observed in an experimental setting. Instead, we introduce two criteria – strong and weak convergence – to identify whether a group has converged or is converging to a common strategy. The *strong convergence* criterion requires that all six subjects in a matching group play according to the same strategy, allowing a deviation of ±1, for periods 65–79. We exclude period 80, because we see some subjects deviating exclusively in the last period. The *weak convergence* criterion requires that at least four subjects in a matching group follow the same strategy, allowing a deviation of ±3, for periods 70–79. These measures allow assessing the ability of groups to coordinate and identifying the strategies they coordinate on.[14]

For converging groups, we identify five types of strategies that were most prominent: 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; 5) "Mean": play the average of both signals. In Treatment CP, strategies 2) to 4) refer to the public signal only. Table 2 summarizes how many groups converged according to our two criteria detailed for the identified strategies.

Table 2 highlights 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

[14] An additional interesting feature of coordination is its speed. Tables C1 and C2 provide the periods in which groups converge to the different strategies.

converge. In treatments with public signals ("sunspot treatments"), most groups coordinate on sunspot equilibria. In treatments with private signals only, most groups converge to the risk-dominant equilibrium, but we also see some groups converging to a non-equilibrium strategy, in which actions depend on signals.

For our further analysis, it is important to note that strategies are symmetric: subjects who choose $a_i = m$ when they receive signal $s = 0$ play $a_i = 100 - m$ when the signal is $s = 100$.[15] In Appendix A2, we show that symmetry not only applies to the strategies subjects converge to; it also applies to actions played during the entire experiment. We can therefore pool the data for symmetric sets of signals and measure the power of sunspots by the distance of chosen actions from 50, independent of whether signals are 0 or 100. For testing the impact of signals on behavior using non-parametric tests, we take averages from each group as independent observations, because from period 2 onwards, individual choices are affected by observing other group members.

5.1 Observation of sunspot equilibria

Figure 1 gives a first impression of the impact of extrinsic information on behavior and the reliable occurrence of sunspots. The figure depicts the average distance to 50 over all matching groups for Treatments N, P75 and C.[16] Without additional information (Treatment N), subjects almost immediately converge to playing $a_i = 50$. With imprecise extrinsic information (P75), subjects learn to ignore the information quickly and also converge to $a_i = 50$. Since in both treatments the average distance to 50 is close to zero, we pool the data of these two treatments (N/P75) when we run non-parametric tests. As explained above, $a_i = 50$ is not just the secure action, but it 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).[17] Thus, in the absence of public signals, it seems very natural for subjects to converge to this strategy.

[Figure 1 about here]

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[15] In treatments CP and CC, symmetry refers to playing *m* when both signals are 0, *100-m* when both signals are 100. When the two signals are different in CP, symmetry means playing *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.

[16] See Appendix D for a more detailed figure for each group separately (Figure D1).

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

If, however, the extrinsic information is publicly available as in Treatment C, there is a clear convergence process towards choosing the action that is indicated by the received signal. All groups of Treatment C converge to playing $a_i = \text{Y}$. This implies that the average absolute distance to 50 is large. In Treatment C, the average distance of actions from 50 is 46.69, 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/P75, where the average distance is 2.04 (Mann-Whitney, $z = 2.739$, $p < 0.01$).

Result 1 *Sunspot equilibria emerge reliably in the presence of salient (but extrinsic) public signals.*

Table 2 summarizes, for each treatment, the strategies to which different groups converge.[18] First, we can note that in Treatments 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 a strong convergence criterion. In P75 as well as in C, there is one group that needed a considerable time to converge. For instance, in P75, convergence seems harder for group 5. This was caused by a single subject who seemed to condition his actions on the private signal until the end of the game.[19] In Treatment C, all but two groups converge quickly to playing the public signal ($a_i = Y$), although this constitutes the most risky action ex ante. The other two groups (Groups 18 and 22) eventually converge under the weak measure of convergence 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 Sunspot-driven behavior without common signals

Despite the different information structures, theory prescribes that behavior in Treatments P95 and AC should be the same as in Treatments N and P75: 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.[20] We observe similar behavior in both treatments. In P95, the average absolute distance to 50 is about 17.26, whereas the distance is 13.86 in AC (14.83 conditional on receiving a signal). This difference is

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[18] For a more comprehensive overview on each independent group, including the periods of convergence, see Table C1 and C2 in the Appendix.

[19] 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.

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

statistically not significant (Mann-Whitney test, $z=0.48$, $p=0.63$). The picture, however, is mixed when we compare P95 and AC to N/P75. While the average distance is statistically different at the 10%-level in P95 and N/P75 (Mann-Whitney test, $z = 1.643$, $p = 0.06$, one-sided), this is not the case for a comparison between AC and N/P75 (Mann-Whitney test, $z = 0.183$, $p = 0.43$, *one-sided*).

[Figure 2 about here]

Figure 2 plots the average distance to 50 in blocks of 10 periods conditional on receiving a private signal for all groups in P95 and AC. Apparently, when groups play according to the risk-dominant equilibrium, the average distance to 50 in these treatments should be zero. Both treatments show some heterogeneity among groups. Some groups quickly converge to the risk-dominant equilibrium: in P95, half of the groups (Group 8, 9, and 10) converge in a strong sense in periods 7 to 13; in AC, four groups (12, 13, 14, and 16) converge in periods 3, 4, 1, and 13, respectively.

The most interesting finding in Treatments P95 and AC is the behavior of groups who did not converge to an equilibrium: the emergence of *sunspot-driven non-equilibrium* behavior. Unlike the theory predictions, highly precise private signals may not 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 (Groups 6, 7, and 11) throughout the game and dragged actions away from the risk-dominant equilibrium. In two groups (Groups 15 and 17) of Treatment AC, subjects condition their behavior on the signal when it is available and otherwise choose 50. Both groups converge to the sunspot non-equilibrium strategy 0/100. 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 equilibrium theory which describes a discontinuous behavior, i.e., as long as private signals are imprecise, sunspot equilibria do not exist.

Result 2 *Salient extrinsic private signals of high precision may cause sunspot-driven behavior even though this is no equilibrium.*

To capture the dynamics of the convergence process in treatments without sunspot equilibria – N, P75, P95 and AC – we estimate the following regression model:[21]

$$|a_{it} - 50| = \frac{1}{t}\sum_k \beta_{1k} D_k + \frac{t-1}{t}\sum_k \beta_{2k} D_k + u_{it} \qquad (3)$$

[21] This specification was first used by Noussair et al (1995).

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

		Dependent variable: $\lvert a_{it} - 50 \rvert$			
		β_{1k}		β_{2k}	
Group	Treatment	Coefficient	Standard errors	Coefficient	Standard errors
1	N	9.743***	(2.119)	0.861*	(0.442)
2	N	3.576	(2.225)	0.357	(0.464)
3	P75	26.797***	(1.176)	-0.417*	(0.245)
4	P75	27.164***	(2.007)	0.386	(0.418)
5	P75	19.817***	(3.141)	3.931***	(0.655)
6	P95	35.326***	(1.957)	39.640***	(0.408)
7	P95	37.405***	(1.684)	38.708***	(0.351)
8	P95	31.534***	(4.105)	0.408	(0.856)
9	P95	19.778***	(0.833)	-0.582***	(0.174)
10	P95	29.161***	(3.736)	0.613	(0.779)
11	P95	41.190***	(6.805)	18.555***	(1.419)
	$\rho = 0.496$	$R^2 = 0.61$	$N = 5280$		
12	AC	20.109***	(2.378)	-0.292	(0.540)
13	AC	32.452***	(2.128)	-1.090**	(0.478)
14	AC	7.227***	(1.697)	-0.100	(0.333)
15	AC	47.156***	(2.465)	48.696***	(0.560)
16	AC	35.192***	(5.376)	1.759	(1.073)
17	AC	37.176***	(5.761)	34.010***	(1.302)
	$\rho = 0.575$	$R^2 = 0.68$	$N = 2662$		

Notes: OLS regression with standard errors corrected for cross-sectional correlation within matching groups and autocorrelation (AR(1)). Treatment AC only includes observations where the random number Z was revealed to subjects and is thus estimated separately (unbalanced panel). * p<0.10, ** p<0.05, *** p<0.01.

where i is the index for individuals and t the time period. The dependent variable is the absolute distance of the decision to 50, D_k is a dummy variable for group k, and u is the error term. Note that $1/t$ converges to zero as t goes to infinity, whereas $(t-1)/t$ converges to one. Hence, the coefficient β_{1k} measures the origin of the convergence process of group k and the coefficient β_{2k} is the asymptote to which group k converges. Given our matching procedure (random matching within a group of six), we assume that the error term is correlated across subjects, and we also allow for autocorrelation along t. The model allows us to see to which equilibrium groups converge and to test whether the estimates for β_{2k} are significantly different from the risk-dominance prediction. Recall that in AC subjects only receive a signal with $p=0.9$, while in other treatments subjects either receive signals in each period or not at all. For the estimation of model (3), we thus only consider periods in which a subject receives a signal. This results in an unbalanced panel, which requires a different method to calculate the covariance matrix and, hence, we estimate Model (3) separately.[22]

The results of the two regressions are displayed in the top panel (Treatment N, P75 and P95) and bottom panel (Treatment AC) of Table 3. We consider first Treatments N and P75. In line with what was presented, the regression restates that the groups in these two treatments converge to the risk-dominant strategy. This is indicated by the coefficient β_{2k}, which is below 1 for Groups 1 to 4 in Treatment N and P75. Group 5 shows a weaker convergence process, since the β_{2k} coefficient is slightly higher (see also Table C1 in the Appendix), but is still lower than 4. The coefficients for β_{1k}, on the other hand, indicate that Treatment P75 was slightly noisier than in Treatment N in the beginning. While these coefficients are always lower than 10 in Treatment N, they are between 19 and 28 in Treatment P75.

Figure 2 (above) shows a mixed picture for the convergence to the risk-dominant equilibrium in Treatments P95 and AC, which is well reflected in the estimates for β_{2k}. Groups that converge to the risk-dominant equilibrium (8, 9, 10, 12, 13, 14 and 16) have a coefficient β_{2k} lower than 1. As in the case with P75, β_{1k} coefficients tend to be higher than in Treatment N. Groups that converge to sunspot-driven strategies exhibit higher β_{2k} coefficients: Group 6 and 7 in Treatment P95, which weakly converge to Y10, have β_{2k} coefficients close to 40, and Groups 15 and 17 in Treatment AC, which converge to Y, have β_{2k} coefficients higher than 40. Finally, Group 11 in Treatment P95, which does not converge, has an intermediate β_{2k} coefficient compared to the previous cases.[23]

Overall, there is an interesting pattern in all four treatments, given by the correlation between coefficients β_{1k} and β_{2k} (Spearman's $\rho = 0.66, p < 0.01$).[24] Indeed, looking at the behavior in the first 10 periods unmasks a potential reason for the different convergence processes. In groups converging to risk-dominant equilibrium, the predominant decision is 50, which amounts to a fraction of 64% compared to only 18% in the other groups. Thus, it is not surprising that the average distance to 50 over the first 10 periods in groups converging to the

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[22] The computation of the covariance matrix only uses periods that are common to the two panels. Running the regression with all periods yields similar results.

[23] Looking at this group in detail, we see that four subjects chose 50 most of the time and one of them eventually adopted a sunspot-driven strategy (25/75). The remaining two subjects conditioned their choices on the private signal during the whole experiment.

[24] See Figure D2 in the Appendix for a plot of the average distance to 50 in the 10 last periods versus the average distance to 50 in the first 10 periods.

risk-dominant equilibrium is significantly lower than in groups converging to non-equilibrium sunspot behavior (Mann-Whitney test, $z=3.162, p<0.01$). The intuition behind this regularity is that groups with a critical mass of players who started playing the most salient sunspot strategy, i.e., those with a large β_{1k} coefficient, converged to a sunspot strategy, whereas groups with a sufficiently large number of players starting out with ”50”, converged to this equilibrium.

5.3 The effects of multiple signals

In this section, we focus on the treatments with two signals, i.e., CC and CP. 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.[25] The most immediate observation is that in both treatments 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 3 & 4 about here]

Figures 3 and 4 show the average distance to 50 by 10-period 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. All six groups converge to playing the average of the two signals, which seems the most natural focal strategy.[26] This results in a three-cycle sunspot equilibrium with choices of 0 if both signals are zero, 100 if both signals are hundred, and 50 if the signals are unequal. 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. Conditional on both signals being equal, the average distance is 48.97, which is about the same as in Treatment C. If the two signals are unequal, the average distance is 2.79, which is not significantly different from Treatments N/P75. In total, the average distance between actions and 50 is 30.50, because in Treatment CC the two public signals coincide in 62.5% of all cases. This is significantly smaller than in Treatment C (Mann-Whitney, $z = 2.882, p < 0.01$).

Treatment CP provides the most versatile results, because here different types of sunspot equilibria emerge. There are three popular strategies that are implied by the salience of

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[25] For a more comprehensive overview on each independent group, including the periods of convergence, see Tables C1 and C2 in the Appendix.

[26] Five groups coordinate according to the strong convergence criterion, while one group (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.

signals: the risk-dominant equilibrium, following the public signal, and choosing the mean of both signals. In the first period, 32% of all subjects choose 50, 42% follow the public signal, and 60% of decisions are consistent with choosing the mean. As a result we observe only one group (Group 26) resorting to the risk-dominant equilibrium and neglecting both signals from early periods onwards. Five groups (Group 27, 30, 31, 33 and 35) follow the public signal as in Treatment C and the average distance to 50 is about 45.90 in these groups. For the remaining groups, the average distance to 50 is 24.30 and it seems that at least three groups converge to an intermediate sunspot equilibrium in which subjects choose 25 whenever Y = 0 and 75 whenever Y = 100. Note that "25/75" is the maximin response to any non-degenerate distribution of the three popular strategies that we observe in the first period. This may explain why some groups converge to this particular sunspot equilibrium.

Considering all groups of Treatment CP, the average distance of actions to the risk-dominant equilibrium is 35.19, when the public and private signals are the same for a subject and 26.12 otherwise. The Wilcoxon matched-pairs test rejects that distances are the same for equal and unequal signals ($p < 0.01$). Both are significantly larger than in N/P75 or CC for unequal signals ($p < 0.01$). They are significantly smaller than the distances arising in Treatments C or CC for equal signals (Mann-Whitney, $p < 0.02$). Thus, we may say that the public signal has a lower power if combined with a private signal. Compared to Treatments P95 and AC, the distances in Treatment CP are larger, but the difference is significant only when public and private signal coincide.

The data also allow us to compare the power of private signals in Treatment CP with treatments in which the private signal is not combined with a public signal: the difference between actions chosen in situations with equal and unequal signals is 9.07 on average. We can compare half of this value, 4.54, with the effect of private signals (measured by the average distances of actions from 50) in Treatments P75 and P95. The effect of private signals in CP seems to lie between the effect in Treatments P75 and P95 (2.74 and 17.25 respectively), but these differences are not significant ($p = 0.31$ and $p = 0.64$). Hence, we can reject the idea that the power of the private signal in Treatment CP differs from the power of a private signal without a coexisting public signal.

Result 3 *The presence of multiple signals has no impact on coordination as long as signals are public (as in CC). However, an additional private signal can considerably impede the convergence process (as in CP).*

Table 4 Regression - Sunspots – CP

	Dependent variable: $\lvert a_{it} - 50 \rvert$					
	β_{1k}		β_{2k}			
Group	Coefficient	Standard errors	Coefficient	Standard errors	95% Conf. Interval for β_{2k}	
24	32.477***	(3.291)	25.558***	(0.628)	24.328	26.788
25	37.577***	(9.177)	33.511***	(1.750)	30.081	36.942
26	32.452***	(4.537)	1.492*	(0.865)	-0.204	3.188
27	20.833***	(5.412)	47.201***	(1.032)	45.178	49.224
28	35.199***	(6.152)	14.918***	(1.173)	12.618	17.217
29	3.57	(7.145)	20.090***	(1.363)	17.419	22.761
30	49.317***	(1.060)	49.941***	(0.202)	49.545	50.337
31	17.220***	(5.219)	47.112***	(0.995)	45.161	49.063
32	17.423***	(5.902)	26.064***	(1.126)	23.858	28.270
33	19.806***	(6.195)	43.543***	(1.182)	41.227	45.859
34	31.280***	(5.342)	24.597***	(1.019)	22.600	26.594
35	33.634***	(5.114)	47.888***	(0.975)	45.977	49.800
	$\rho = 0.404$	$R^2 = 0.73$	$N = 5760$			

Notes: OLS regression with standard errors corrected for cross-sectional correlation within matching groups and autocorrelation (AR(1)). * $p<0.10$, ** $p<0.05$, *** $p<0.01$.

Again, we can use the regression model (3) to investigate the convergence process in CP. The results are displayed in Table 4. The β_{2k} coefficients confirm that five out of the 12 groups (Group 27, 30, 31, 33, and 35) converge to the sunspot equilibrium ($a_i = Y$). The upper bound of the 95% confidence interval of the β_{2k} coefficient is at least 49 for four groups (Groups 27, 30, 31, 35), while it is slightly above 45 for Group 33.[27] As mentioned above, some groups converge to the 25/75 equilibrium. The regression results indicate that the asymptote β_{2k} lies in a 95% confidence interval around 25 for three groups (Groups 24, 32, 34), while another group (Group 29) converges to 20.[28]

Unlike the results presented in the previous section, the β_{1k} coefficients give us no clear direction for the convergence patterns; the Spearman's correlation between β_{1k} and β_{2k} is $\rho = 0.08, p < 0.81$. However, there is a positive relation between the distance to the risk-dominant

[27] Note that for all five groups the β_{2k} coefficient is larger than the β_{1k} coefficient and that the difference between the two coefficients gives a good indication of the convergence speed (see also Table A3).

[28] According to our convergence criteria, we only classify Groups 24, 29 and 32 as converging to a 25/75 equilibrium, but not Group 34. In Group 29 as well as in Group 34 there is one subject constantly playing the risk-dominant strategy. While the remaining subjects in Group 29 adapt a 25/75 strategy, Group 34 is the least coordinated group.

equilibria in the first and in the last 10 periods of a group (see also Figure D3 in the Appendix). The larger the distance in the first 10 periods, the more likely a group converges to the sunspot equilibrium. Indeed, the correlation between the distance in the first and last 10 periods is highly significant (Spearman's $\rho = 0.92, p < 0.01$). Going back to Figure 4 suggests that situations in which the public and private signal coincides determine which group converges to the sunspot equilibrium ($a_i = Y$). In all five sunspot groups, subjects quickly follow the public signal, which results in a significantly larger distance from 50 compared to the other groups (Mann-Whitney, z = $2.191, p < 0.03$). In all groups, except Group 25 and 26, subjects quickly converge to an intermediate strategy. In situations with unequal signals (public and private signals do not coincide) it needs a considerable time span until groups converge either to the sunspot equilibrium or to the intermediate sunspot equilibrium (25/75). Nevertheless, it is also the case that in the five sunspot groups the distance to 50 is already higher in the first 10 periods than in other groups, when the public and private signal is unequal (Mann-Whitney, z = $2.191, p < 0.03$).

Which of the other groups eventually converge to an intermediate sunspot equilibrium is less clear. The average distance of groups converging to this intermediate equilibrium (Group 24, 32, and 34) is 27.98, whereas it is 24.54 for the other groups (Group 25, 26, 28, and 29). Surprisingly, it seems that in the latter groups the behavior is more polarized, meaning that subjects either follow the public signal (0 or 100) or choose 50 in about 78% of cases in the first 10 periods, compared to only 34% in the other groups. This also results in more coordinated behavior (33% vs. 7%), which may have led to less adaptive behavior in those groups not converging to the intermediate sunspot equilibrium. Overall this suggests, as in the non-sunspot treatments, that groups with a critical mass of subjects following the public signal or with sufficiently adaptive behavior converge to a sunspot equilibrium.

The evidence from Treatment CP shows that the effect of signals is not additive. The other treatments have shown that a single private or public signal does not prevent coordination. However, if the two signals are displayed simultaneously, the difficulty of coordination increases considerably (see Figure 4 and Table C2 in the Appendix). Despite some variance, convergence to an equilibrium takes a surprisingly long time, if it happens at all. This fact is exemplified by the three groups that never coordinate their actions. In Treatment CP, a subject needs to learn that (i) the private signal should be ignored, even though public signals matter, and (ii) it may be good to condition one's action on the public signal, even though it is as irrelevant as the private signal. Apparently, this learning process takes longer than learning only one of these points, as in the other treatments.

5.4 Welfare

The previous results clearly show that different information structures induce very different behavior. We have seen that pure 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 chosen. Hence, following or neglecting sunspots need not affect welfare. What matters, however, is whether and how fast subjects convergence to an equilibrium. If a certain information structure results in a slower convergence process, we observe frequent miscoordination in the early periods and thus welfare losses.

[Figure 5 about here]

The obvious welfare measure that we use throughout this section is average payoffs in the groups. Figure 5 relates each group's average payoff conditional on the signal combination to the average distance from 50 and reveals an interesting U-shaped pattern. The figure also displays the prediction (fitted line) from a regression of average group payoffs on average distance and squared average distance along with the 95% confidence interval to visualize this U-shaped pattern.

Groups that converge quickly to the risk-dominant equilibrium achieve almost the maximum payoff of 200. In Treatments C and CC, salient public signals are so powerful that subjects quickly coordinate on a sunspot equilibrium, resulting in payoffs that are also close to the maximum (195.37 in C and 194.69 in CC). In Treatments P95, AC, and CP, different groups coordinate on different strategies – not all of them equilibria – and the average distance to 50 varies. Non-equilibrium strategies go along with welfare losses, even if all subjects use the same strategy. Intermediate differences from 50 are associated with lower average payoffs, even for groups who finally coordinate on a 25/75 sunspot equilibrium, because the convergence process is slower than in other groups. On average, the payoff in these three treatments is well below 190. In Treatment AC, subjects who condition their choices on the signal exert a negative externality on those who do not receive a signal. Without a signal, choosing 50 is the best choice, because it minimizes the loss, given that the others follows the signal. The externality shows up in the average payoffs of Group 15 and 17, where subjects who do not receive a signal get average payoffs of only 150.00 and 157.23. This is considerably lower than in any other information condition and treatment. We summarize this in the following result.

Result 4 *Extrinsic public or imprecise private information is not detrimental to welfare, but if extrinsic private signals are highly correlated or public signals are combined with private information we observe considerable welfare losses.*

For statistical support we run non-parametric tests, which we base on all 80 periods.[29] This gives us a rigorous test of possible welfare effects, since it requires long periods of miscoordination in the beginning to generate significant differences in average payoffs over all periods. We first look at the welfare implications of sunspots. The average payoff in C rises from 190.26 in the first 20 periods to 199.60 in the last 20 periods. In Treatments N and P75 (N/P75) the average payoff is 193.76 in the first 20 periods and 198.89 in the last 20 periods. Comparing the average payoffs over all periods in C (195.37) to N/P75 (197.77), we find no significant difference in payoffs (Mann-Whitney, $z = 0.183, p > 0.8$). 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 highly correlated private signals, P95 and AC, the average payoff in the beginning is about 180.65 (P95) and 185.17 (AC) and rises to only 193.09 (P95) and 193.96 (AC) in the last 20 periods. There is no difference in payoffs between these two treatments (Mann-Whitney, $z = 0.641, p > 0.5$). The payoffs in both treatments are lower than in N/P75 and C. We can reject the hypothesis that the average payoff in P95 (188.56) and N/P75 is the same at the 10%-level (Mann-Whitney, $z = 1.643, p = 0.1$), but not for the comparison with C (Mann-Whitney, $z = 1.441, p = 0.15$). The average payoffs in AC are slightly higher than in P95 (190.72) and there is neither a significant difference to C (Mann-Whitney, $z = 0.641, p > 0.5$) nor N/P75 (Mann-Whitney, $z = 0.913, p > 0.36$).

Next we look at the welfare effects of receiving more than one signal. Receiving two public signals as in CC leads subjects to aggregate this information and this reliably creates sunspots. While average payoffs are low in the beginning, with 187.50, they rise up to 197.86 in the last 20 periods. Over all periods, the average is only slightly lower (194.69) than in C, but not statistically significant (Mann-Whitney, $z = 0.160, p > 0.8$). Payoffs in CC are not different from payoffs in N/P75 (Mann-Whitney, $z = 0.365, p > 0.7$) either.

In Treatment CP, we observed mainly three convergence patterns. One group converged to the risk-dominant strategy with an average payoff of 194.95. Five groups converged to the sunspot strategy 0/100. Their average payoff is 192.21, which is comparable to CC and C. At

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[29] We obtain the same results by running random-effects GLS regressions on individual payoffs.

least three groups (Group 24, 32, and 34) converge to a 25/75 sunspot strategy with an average payoff of 188.78, 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 184.39. Over all groups, the average payoff in Treatment CP is 189.56. Not surprisingly, we can reject the null hypothesis for equal means in C and CP (Mann-Whitney, $z = 2.060, p < 0.04$) and in N/P75 and CP (Mann-Whitney, $z = 2.741, p < 0.01$). Comparing average payoffs in Treatment CP with Treatments P95 and AC, we find no significant differences ($p > 0.1$). The fact that average payoffs in CP are lower than in P75 and C and similar to those in Treatments P95 and AC, indicates that the effect of private signals may be larger when combined with a public signal, even though we rejected the hypothesis of a different power measured by actions' distance.

[Figure 6 about here]

The average payoffs are also a measure for convergence to an equilibrium strategy. The three convergence patterns in Treatment CP can be nicely detected in Figure 6. The figure shows how average payoffs and strategies change from the first half to the second half of the experiment. Each group is represented by four identical markers, which indicate the relationship of the average distance from 50 and the payoffs conditional on equal and unequal signals. The arrows show how distance and payoffs change over time. With the exception of group 25, distances in situations with $X_i = Y$ and $X_i \neq Y$ converge towards each other, which means that subjects respond less to the private signal. Payoffs always increase from the first to the second half of the experiment due to the improved coordination within groups. It is further interesting to note that groups starting out with distances above 25 for unequal signals converge to the sunspot equilibrium 0/100. Groups with average distances between about 15 and 35 in the first half seem to converge towards a 25/75 sunspot equilibrium (indicated by the large circle at the upper edge of Figure 6).

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 extrinsic signals and systematically vary the information structure of 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, and therefore sunspot equilibria reliably show up.

We investigated the impact of extrinsic information by manipulating the correlation of individual signals and by introducing multiple signals. As long as the signals have a small correlation, i.e., when signals are private and the conditional probability that two subjects receive the same signal is low, subjects tend to ignore them. But, if the correlation increases, we observe sunspot-driven behavior, even though theoretically no sunspot equilibria exist.

Two public signals are easily aggregated and generate an interesting three-cycle sunspot equilibrium, which has not been observed in other sunspot experiments. On the other hand, if private signals are combined with an extrinsic public signal, the impact of sunspots on behavior is smaller than in games with pure public information. The ability of groups to coordinate is impeded by such a combination, which results in lower average payoffs. This also shows that the effect of private signals is larger in the presence of a public signal, which leads to an interesting conclusion: in economies where private signals could impede coordination, adding an extrinsic public coordination device with similar semantics may make it even more difficult to coordinate actions.

Extrinsic public information is not detrimental to welfare. However, the presence of highly correlated private information and the combination of public and private signals considerably impedes coordination and results in lower payoffs. While the individual losses arising from strategies that condition actions on private signals might be small, such behavior affects the strategies of others and prolongs the time that subjects need to coordinate. If not all agents receive extrinsic signals, those who condition their actions on them exert a negative externality on agents not receiving signals.

Taking up the literature on focal points, we provide evidence that the salience of certain actions –choosing 50 – is no longer effective when extrinsic information is available, even in (payoff-) symmetric games. The introduction of extrinsic information influences subjects' perceptions of focal points and may lead to considerable miscoordination. Hence, our results show the fragility of focal points.

The game form that we employed uses risk dominance for measuring the power of sunspots. Whether the power of sunspots may be sufficiently strong to distract agents from a payoff-dominant equilibrium is an open question. However, since risk dominance seems to be working well in measuring the power of extrinsic signals, we envision that our game form may be used for testing the salience of other messages or signal combinations. Tentatively, one may use similar experiments for measuring common understanding of messages phrased in ordinary language.

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Figures

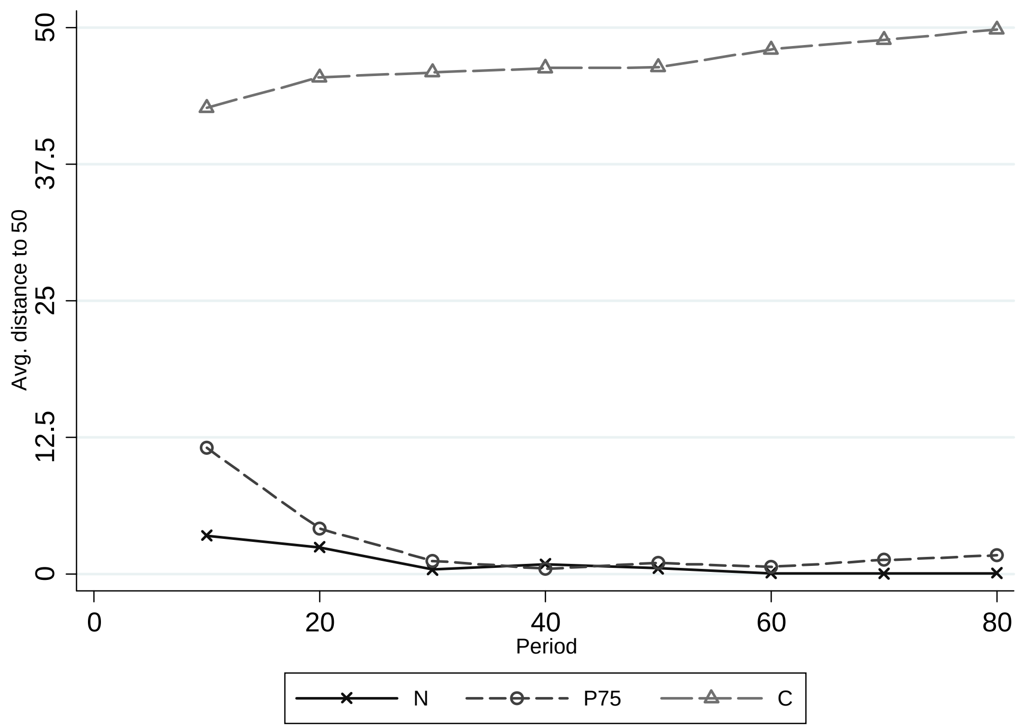

Figure 1: Average distance to 50 over all groups in N, P75 and C.

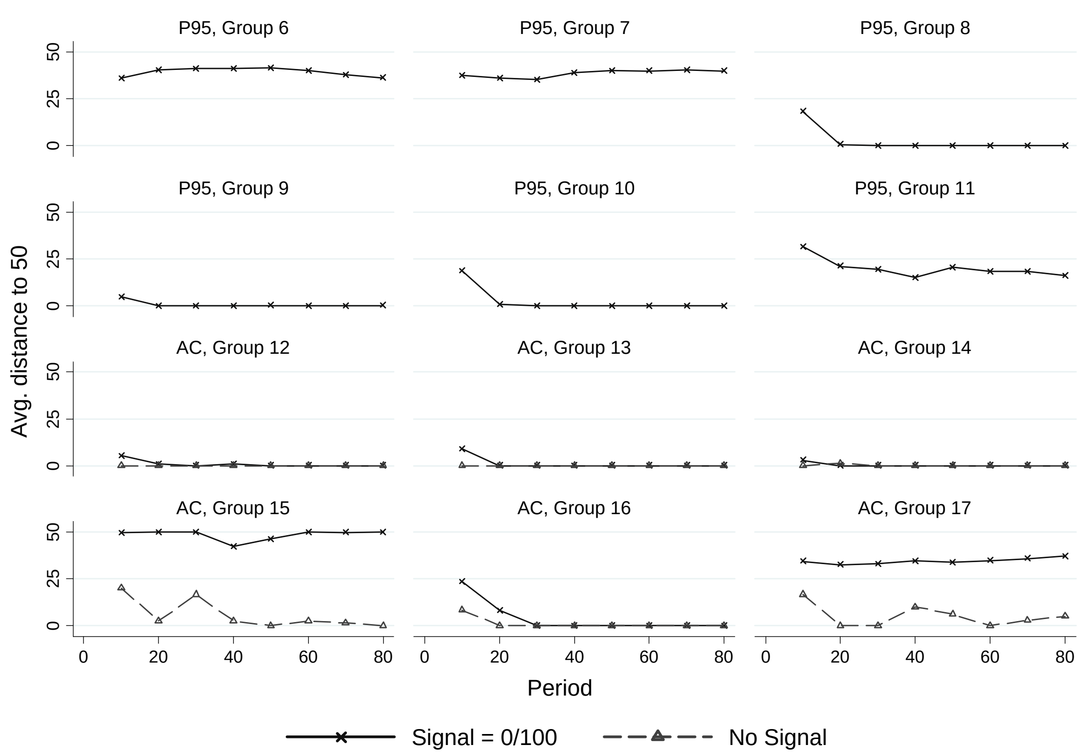

Figure 2: Average distance to 50 by blocks of 10 periods in Treatments P95 and AC.

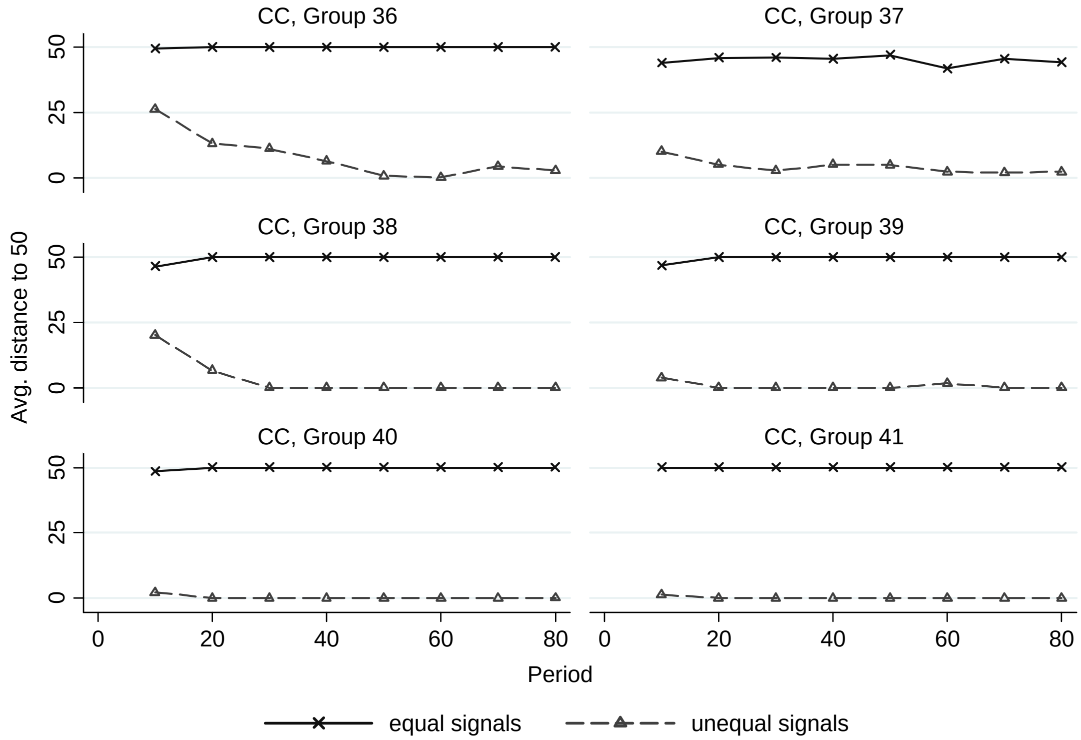

Figure 3: Average distance to 50 by blocks of 10 periods in Treatment CC.

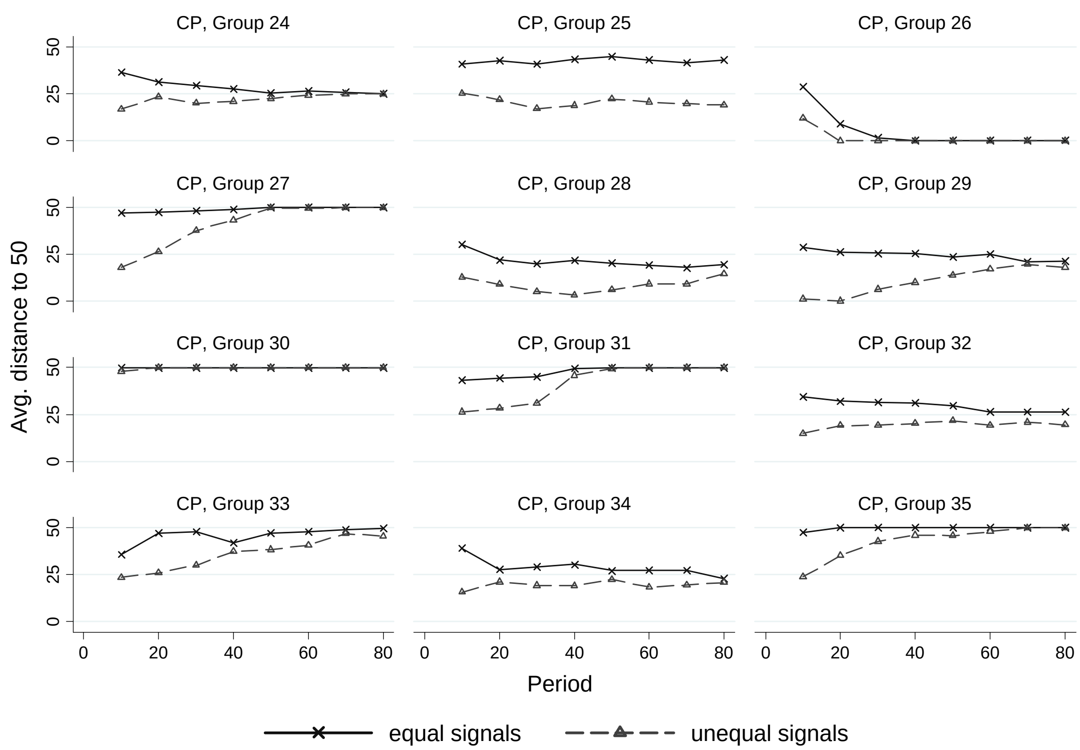

Figure 4: Average distance to 50 by blocks of 10 periods in Treatment CP.

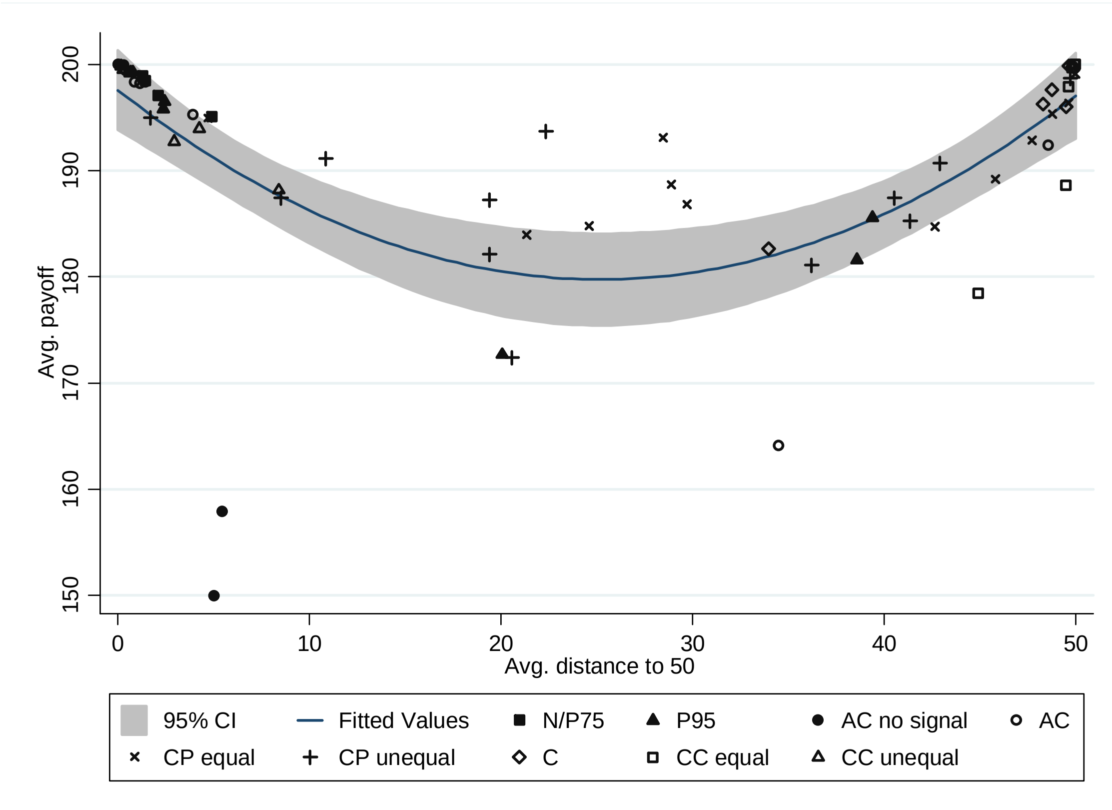

Figure 5: Relationship of average distance to 50 to the average payoff across treatments.

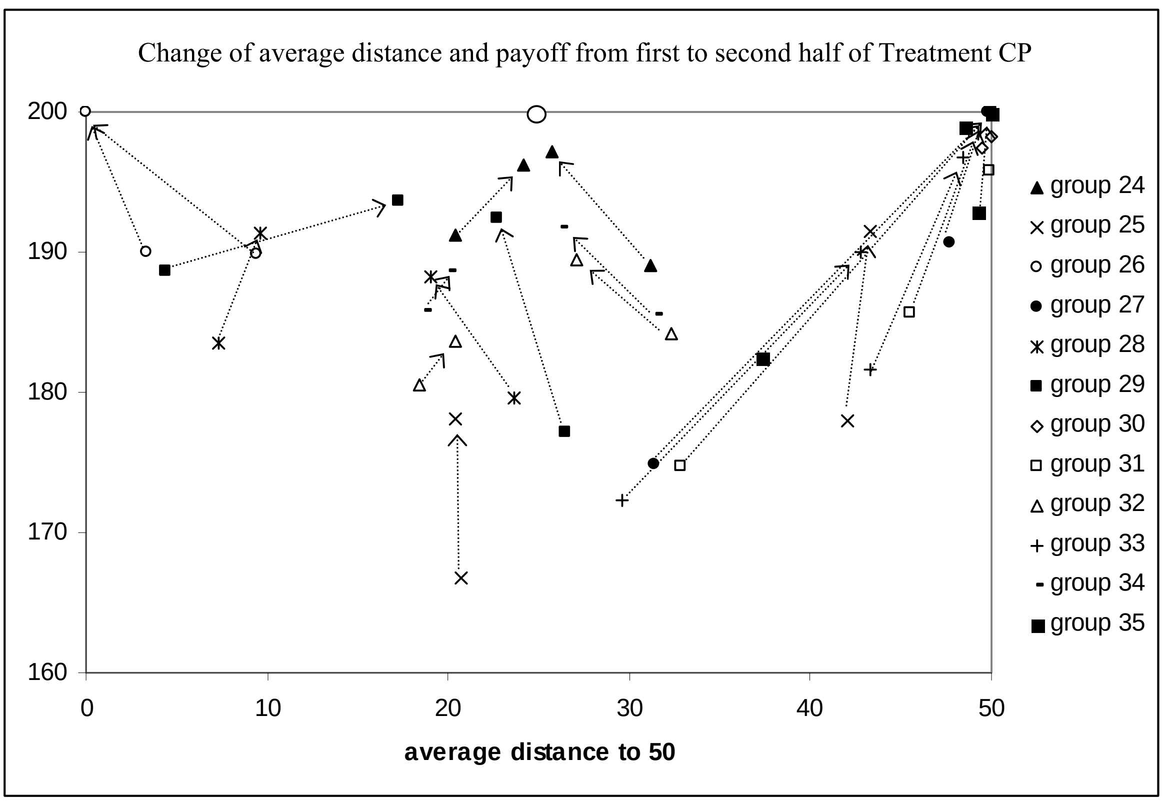

Figure 6: Change of average distance and payoff over time in CP.

Appendix

A Proofs of Lemmas 1 and 2

Lemma 1. *Let* $\left\{a^{i*}_{\varphi,\psi} \middle| \varphi \in \Phi, \psi \in \Psi\right\}$ *be a Bayesian Nash equilibrium strategy profile, where* $a^{i*}_{\varphi,\psi}$ *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,* $a^{i*}_{\varphi,\psi} = a^{*}_{\varphi}$ $\forall \psi \in \Psi$ *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

$$a^{i*}_{\varphi,\psi} = \arg\max_x \sum_{\psi \in \Psi} p^{\psi^j}_{\varphi,\psi^i} f\left(x - a^{j*}_{\varphi,\psi}\right)$$

where $p^{\psi^j}_{\varphi,\psi^i}$ is the probability that the other player receives signal ψ^j when he receives signal ψ^i in state φ.[30] 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, $\arg\min_\psi \left\{a^{i*}_{\varphi,\psi}\right\} = \arg\min_\psi \left\{a^{j*}_{\varphi,\psi}\right\}$ and $\arg\max_\psi \left\{a^{i*}_{\varphi,\psi}\right\} = \arg\max_\psi \left\{a^{j*}_{\varphi,\psi}\right\}$ for $i \neq j$.[31] We will show that by contradiction. Suppose that, without loss of generality, $\arg\min_\psi \left\{a^{i*}_{\varphi,\psi}\right\} < \arg\min_\psi \left\{a^{j*}_{\varphi,\psi}\right\}$. Let $\overline{\psi} := \arg\min_\psi \left\{a^{i*}_{\varphi,\psi}\right\}$. Then, it must be that

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

given that $f'\left(a^{i*}_{\varphi,\overline{\psi}} - a^{j*}_{\varphi,\psi}\right) > 0$ $\forall a^{j*}_{\varphi,\psi}$. Therefore, $a^{i*}_{\varphi,\overline{\psi}}$ cannot be a best response.

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[30] See that by allowing different probabilities we implicitly allow the effects of a public signal.
[31] These expressions are well defined given the finite cardinality of private signals and Step 1.

Step 3. In this last step, we show that $\arg\min_{\psi}\{a^{i*}_{\varphi,\psi}\} = \arg\max_{\psi}\{a^{i*}_{\varphi,\psi}\}$ 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 $\overline{\psi}$ 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 $a^{i*}_{\varphi,\psi} = a^{*}_{\varphi} \quad \forall \psi \in \Psi$ for any given $\varphi \in \Phi$. ■

Lemma 2. $a^{i*}_{\psi,\varphi} = \frac{b+c}{2} \forall \psi, \varphi$ *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 who 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 $x < \frac{b+c}{2}$.

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

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

B Symmetry of actions

Here we show the symmetry of the actions played during the experiment. This allows us to then pool the data for symmetric sets of signals and measure the power of sunspots by the distance of chosen actions from 50, independent of whether signals are 0 or 100. In treatments with one signal, we say a strategy is symmetric if subjects choose action $a_i = m_i$ when they receive signal s = 0 and choose $a_i = 100 - m_i$ when the signal is s = 100. For treatments with two signals, symmetry refers to playing m when both signals are 0, *100-m* when both signals are 100. When the two signals are different in CP, symmetry means playing 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 situations without signals. To test the symmetry of strategies we estimate the following model:

$$a_{it} = \beta_1 S100 + \beta_2 period + \alpha_i + u_{it} \quad \text{(B1)}$$

The dependent variable is the decision of individual i. We transform this variable to $a_i = 100 - m_i$ when the private signal is s = 100 (as in P75, P95, and AC), when the public signal is s = 100 (as in C and CP), or when the public signal Y_1 is s = 100 (as in CC). Thus the dependent variable a_{it} always measures the distance to zero irrespective of the signal realization. As independent variables we include "Period" to control for the time trend and a dummy variable, "S100", which equals 1 if the private signal equals 100 (in P75, P95, or AC) or the public signal equals 100 (in C, CP, or Y_1 in CC). For Treatment AC, we consider only observations in which the random number Z was revealed to the subjects. For Treatments CP and CC we estimate separate regressions for equal signals ($X_i = Y$) or ($Y_1 = Y_2$) and unequal signals $(X_i \neq Y)$ or $(Y_1 \neq Y_2)$. For Treatment CC, we also test whether the constant equals 50, which amounts to both public signals having the same impact on behavior.

The regression results are displayed in Table B1. We only report the results of a random effects model as specified in (B1) in which we control for repeated decisions of the same subject as well as for dependencies within matching groups. Alternatively, we used a simple OLS model with clustering at the group level, which does not impose any restriction on the correlation within groups. Our variable of interest is the dummy for the signal "S100". If decisions are symmetric, the coefficient β_i should be close to zero and insignificant. Indeed we observe for treatments P75, P95, C and CC that the coefficient for "S100" is not significantly different from zero. The same is true for treatment CP when the signals are equal. In CP with unequal signals and in AC we find that "S100" is significant at the 5%-level, but numerically small. This is mainly due to one matching group in each of the two treatments. If we exclude these two groups the coefficient for "S100" is insignificant in both regressions. The OLS regressions with clustering at the group level yield insignificant coefficients in all treatments (including all groups).

Table B1. Symmetry of decisions

	Dependent variable: a_{it}							
	P75	P95	C	CP		CC		AC
				equal sig.	unequal sig.	equal sig.	unequal sig.	
Signal=100 (D)	0.319	-1.086	-0.212	-0.280	-1.878**	0.019	-0.443	0.962**
	(0.917)	(1.099)	(0.511)	(0.449)	(0.939)	(0.485)	(0.447)	(0.471)
Period	0.076***	0.058*	-0.118**	0.043	-0.198***	-0.039	0.018***	0.043
	(0.018)	(0.034)	(0.055)	(0.038)	(0.062)	(0.029)	(0.006)	(0.048)
Constant	44.623***	31.245***	8.726*	13.675***	34.617***	3.662*	49.403***	33.916***
	(1.236)	(6.446)	(4.780)	(2.789)	(3.916)	(2.004)	(0.463)	(7.617)
chi²	27.60	3.93	6.40	2.86	10.37	2.85	11.00	11.58
R^2	0.039	0.006	0.043	0.003	0.044	0.005	0.002	0.003
N	1440	2880	2880	3456	2304	1728	1152	2662

Notes: Random-effects GLS regression with robust standard errors clustered at group level in parentheses. (D) denotes dummy variable, equal signal refers to ($X_i = Y$) or ($Y_1 = Y_2$) and unequal signals to ($X_i \neq Y$) or ($Y_1 \neq Y_2$). Treatment AC only includes observations where the random number Z was revealed to subjects. For CC, the constant is not significantly different from 50 ($p=0.20$). * p<0.10, ** p<0.05, *** p<0.01

C Additional tables

Table C1: Aggregate results of non-sunspot treatments.

Treatment	Session	Group	Strategy	T_6	T_4	Avg. coord. rate	Avg. payoff (std. dev.)	$\lvert a_i - 50 \rvert$ (std. dev.)
(1)	(2)	(3)	(5)	(6)	(7)	(8)	(9)	(10)
N	1	1	50	56	14	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	-	20	0.58	195.1 (9.9)	4.88 (10.5)
P95	3	6	10/90	-	67	0.51	185.5 (39.4)	39.39 (6.5)
P95		7	10/90	-	63	0.30	181.6 (38.7)	38.60 (12.6)
P95		8	50	13	10	0.90	195.8 (19.3)	2.37 (9.7)
P95	4	9	50	7	3	0.96	199.2 (5.1)	0.66 (4.5)
P95		10	50	12	7	0.92	196.5 (12.3)	2.44 (10.5)
P95		11	50	-	80	0.31	172.7 (33.5)	20.07 (22.4)
AC	7	12	50	32	2	0.96	198.5 (8.5)	0.79 (6.1)
AC		13	50	7	2	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	8	15	0/100	70	1	0.80	188.9 (27.4)	44.94 (14.8)
AC		16	50	19	7	0.90	195.5 (14.1)	3.71 (12.9)
AC		17	0/100	-	70	0.25	163.6 (48.7)	32.31 (21.8)

Notes: T_4 denotes the earliest period from which at least 4 subjects play the same strategy until the last but one period, allowing a deviation of ±3. T_6 denotes the earliest period from which all 6 subjects play the same strategy until the last but one period, allowing a deviation of ±1. The avg. coordination rate is the percentage of pairs choosing the same action within a range of ±1 over all periods.

Table C2. Aggregate results of 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)
C		18	0/100	80	10	0.74	196.3 (20.0)	48.31 (5.8)
C	5	19	0/100	6	3	0.97	199.9 (1.01)	49.60 (2.38)
C		20	0/100	33	6	0.93	197.8 (15.8)	48.76 (6.0)
C		21	0/100	2	1	0.99	199.8 (3.2)	49.88 (2.3)
C	6	22	0/100	80	55	0.44	182.6 (25.3)	33.99 (21.2)
C		23	0/100	49	3	0.94	196.0 (26.1)	49.53 (2.8)
CP		24	25/75	65	59	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	0/100	54	28	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	25/75	-	55	0.41	187.3 (16.9)	19.09 (17.3)
CP		30	0/100	33	1	0.99	199.0 (13.3)	49.90 (2.3)
CP	10	31	0/100	65	29	0.72	189.8 (29.6)	45.19 (13.0)
CP		32	25/75	-	76	0.34	184.9 (25.0)	25.58 (13.6)
CP		33	0/100	77	22	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	0/100	56	9	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: T_4 denotes the earliest period from which at least 4 subjects play the same strategy until the last but one period, allowing a deviation of ±3. T_6 denotes the earliest period from which all 6 subjects play the same strategy until the last but one period, allowing a deviation of ±1. The avg. coordination rate is the percentage of pairs choosing the same action within a range of ±1 over all periods.

D Additional figures

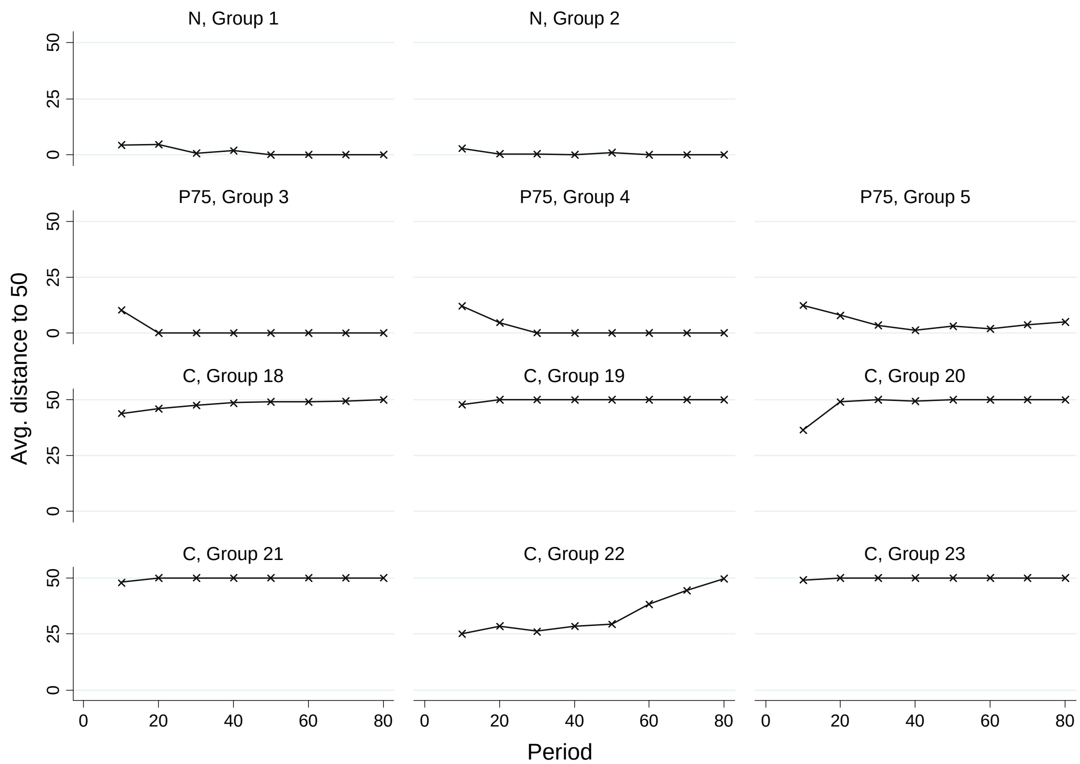

Figure D1: Average distance to 50 by blocks of 10 periods in Treatments N, P75 and C.

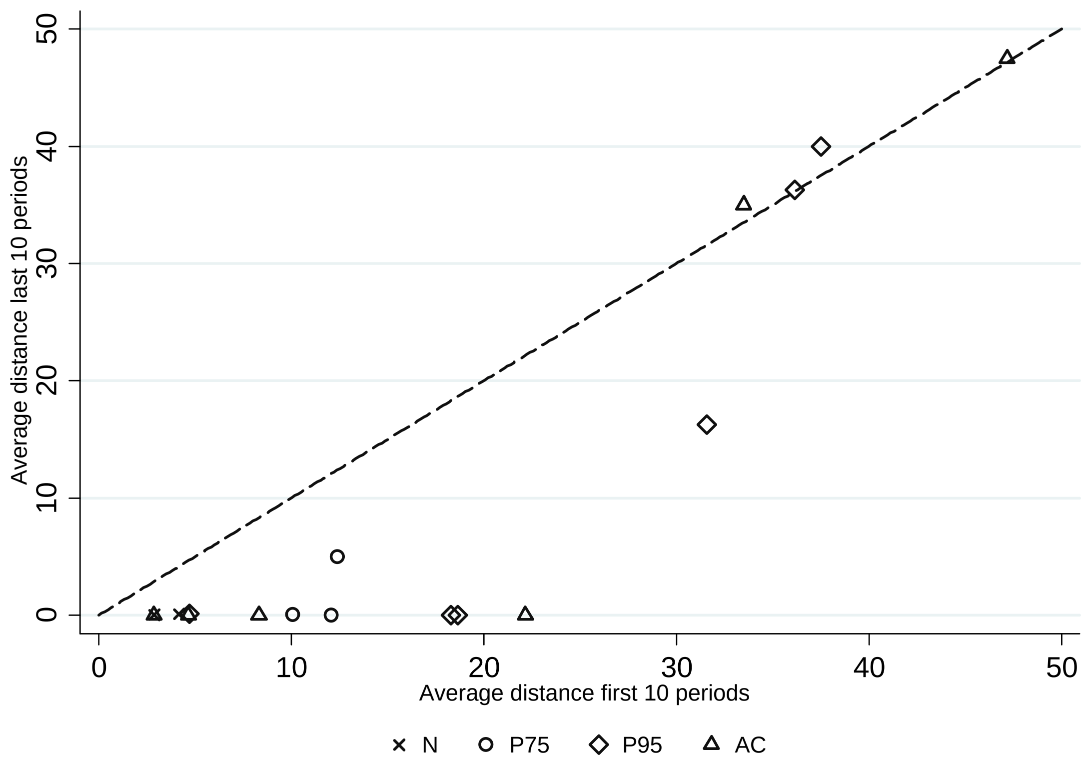

Figure D2: Average distance to 50 in the last 10 periods as a function of the average distance to 50 in the first ten periods (non-sunspot treatments).

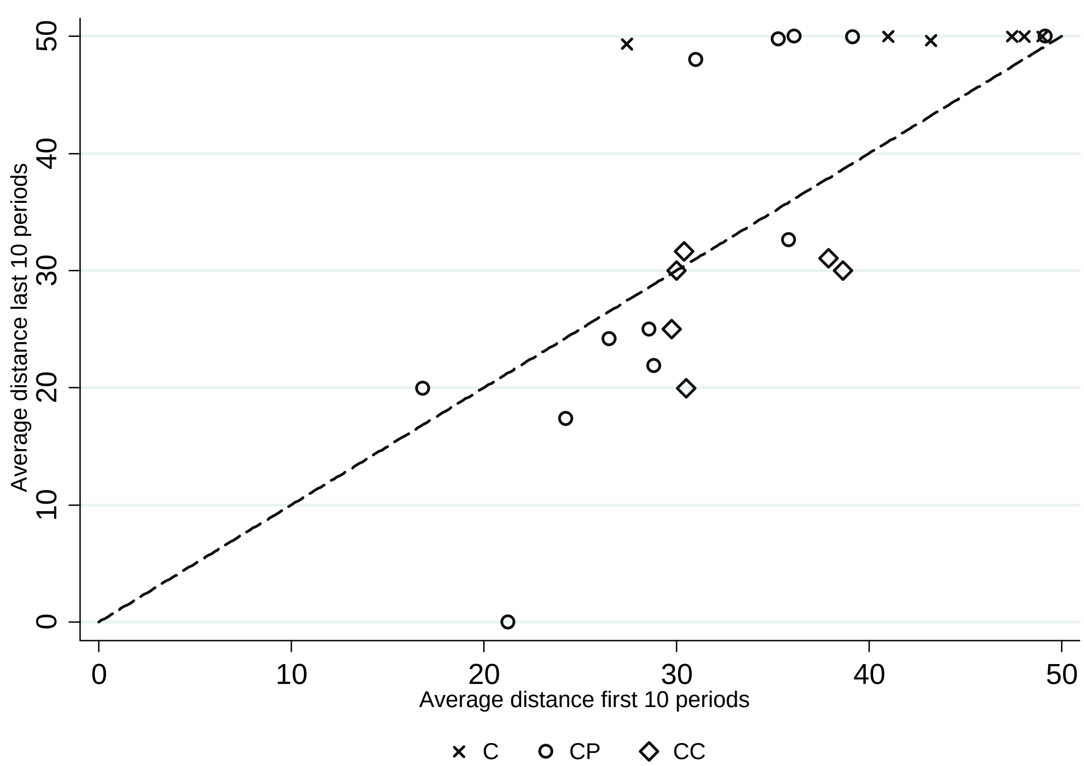

Figure D3: Average distance to 50 in the last 10 periods as a function of the average distance to 50 in the first ten periods (sunspot treatments).

E Sample instructions for Treatment CP

The experiment in which you are participating is part of a research project. Its aim is to analyze economic decision behavior.

The experiment consists of 80 rounds in total. The rules and instructions are the same for all participants. In each round, you have to make a decision. All rounds are completely independent. Your income from the experiment depends on your decisions and the decisions made by the other participants. Please read all instructions carefully and thoroughly.

Please note that you are not permitted to speak to the other participants or to exchange information with them for the duration of the entire experiment. Should you have a question, please raise your hand, and we will come to you and answer your question. Please do not ask your question(s) in a loud voice. Should you breach these rules, we will be forced to exclude you from the experiment.

At the end of the experiment, the computer will randomly draw 10 of the 80 rounds, which will become relevant for your payoff. Your payoff will then be determined according to the sum of your earnings from these selected rounds. In addition, you will receive 3 Euro for participating in the experiment.

Description of the Experiment

At the beginning of the experiment, three groups of six participants each are randomly and anonymously formed. These groups remain unaltered for the entire experiment. At no point are you told who is in your group.

In each round, you are randomly and anonymously paired with another participant from your group (referred to as your partner from now on). This means that you can be paired with the same participant from your group several times in the course of the experiment, albeit not in two successive rounds. Neither you nor your partner is told the other's identity.

1. Information at the Beginning of Each Round

At the beginning of each round, the computer randomly draws a number ***Z***. The number ***Z*** is equally likely either to have the value **0** or **100**. This means that in 5 out of 10 cases, on average, the number ***Z*** takes the value 0, and in 5 out of 10 cases, it takes the value 100. The number ***Z*** is the same for you and your partner.

At the time of the decision, the number ***Z*** is not known. Instead, you receive two independent hints for the number ***Z***:

Shared hint *Y*:

You and your partner both receive a shared hint ***Y*** for the number ***Z***. This hint can be either 0 or 100 and is randomly determined. With a probability of 75%, hint ***Y*** has the same value as the number ***Z***. With the remaining probability of 25%, the hint will have the other value. The shared hint is the same for both of you.

Private hint *X*:

In addition to the shared hint ***Y***, you will receive a private hint ***X*** for the number ***Z***. Your partner also receives a private hint ***X***.

The private hint can be either 0 or 100 and is randomly determined. With a probability of 75%, the private hint ***X*** has the same value as the number ***Z***. With the remaining probability of 25%, the private hint ***X*** will have the other value.

Your private hint and the private hint of your partner are independently drawn, i.e., both private hints can be different. You are not told which private hint your partner has received, and your partner is not told which private hint you have received.

If the shared and the private hint are the same, the probability of both being correct is 90 percent. In other words, if you have received two similar hints, then in 9 out of 10 cases these correspond to the number ***Z***.

If the shared and the private hint are different, then both values of the number ***Z*** are equally probable.

2. Your Decision

In each round, you have to decide on a number between 0 and 100 (incl. 0 and 100). Once you have made your decision, you have to click on the OK button on the corresponding computer screen. Once all participants have made their binding decisions, a round is finished.

3. Your Earnings

Your earnings depend on how close your decision has come to your partner's decision.

$$\text{Your earnings (in Euro cents)} = 200 - \frac{2}{100}\left(\textit{Your decision} - \textit{Your partner's decision}\right)^2 .$$

In other words: your earnings in each round are 200 Euro cents at the most. These 200 Euro cents are reduced by the distance between your decision and your partner's decision.

The distance is squared, so that higher distance leads to a disproportionate loss compared to a smaller distance. The closer your decision is to your partner's decision, the higher your earnings are.

The following table gives you an overview of possible earnings. In this table, only distances in steps of 20 are shown. Please note that distances may be any integer between 0 and 100. In the table, you can also see that you are able to earn a maximum of 200 Euro cents (top-left field) and a minimum of 0 Euro cents (bottom-right field).

Distance from your partner's decision	Earnings
0	200
20	192
40	168
60	128
80	72
100	0

Calculator

You have a calculator at your disposal in each round. In order to use the calculator, you can note your own decision and test as many of your partner's decisions as you wish. The calculator then calculates your earnings for the relevant data entered. In the first 5 rounds, the calculator is active for 20 seconds. During this time, you may carry out as many calculations as you wish. After that, the calculator becomes inactive and you must make your decision. From the 6th round onwards, the calculator is only active for 10 seconds and you can make your decision at once.

Information at the End of a Round

At the end of a round, you are given the following information:

- **The number *Z***
- **The shared hint *Y***
- **Your private hint *X***
- **Your decision**
- **Your partner's decision**
- **The discrepancy between your decision and your partner's decision**
- **Your earnings**

Control Questions

1. Is everyone given the same hint X?
   - *Yes, everyone is given the same hint X /*
   - *No, everyone receives his own hint, i.e., your hint X can be different from your partner's hint X.*
2. Is everyone given the same hint Y?
   - *Yes, everyone is given the same hint Y*
   - *No, everyone receives his own hint Y, i.e., your hint Y can be different from your partner's hint Y.*
3. Your earnings in a round depend on ...
   ...the distance between your chosen number and your partner's chosen number
   ...the number Z
   ...the private hint X
4. Are you always paired with the same partner? *Yes / No*
5. How many of the 80 rounds are randomly chosen by the computer in order to determine your earnings?