Efficient coordination in the lab

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Abstract We follow the example of Gossner et al. (Econometrica 74(6):1603–1636, 2006) in the design of a finitely repeated 2-player coordination game with asymmetric information. Player 1 and Player 2 and Nature simultaneously decide whether to play 0 or 1 and successful coordination requires that all actions coincide. Nature’s moves are known only by Player 1, while Player 2 observes only the history of Nature and Player 1. In such a theoretical setup, efficient transmission of information takes place when Player 1 uses block codification through signalling mistakes. With this in mind, we test coordination in the lab. We first model and establish the appropriate sequence length played by Nature and the block strategy for lab implementability. We show that the majority rule with 3-length is the optimal block codification for a 55-length sequence. Experimental data supports the main results of the original model with respect to the codification rule using signalling mistakes.

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1 Introduction

Asymmetric information is a widespread characteristic in economic relationships. Take, for instance, a duopoly where firms have asymmetric information about the market demand of their product. In situations like these, the lack of information is one of the main drawbacks to reaching an agreement. Where agents’ decisions depend on information disclosure, strategic information transmission may be crucial and, so, sharing information becomes a pivot in allowing agents to reach more profitable agreements. Furthermore, because of strategic concerns, there is a trade-off between revealed information and profits. To paraphrase the words of Crawford and Sobel’s (1982): revealing all information to the opponent is not usually the most advantageous policy. Some decades later, Blume and Ortmann (2007) pointed out the fact that costless messages help in overcoming strategic uncertainty, equilibrium selection problems and coordination failure.

As a benchmark structure, information transmission between a sender and a receiver occurs when a message in a common language is sent through a transmission channel. Specifically, the sender is an agent with private information who sends a message that reveals “some” information to the receiver, who then takes a decision affecting both agents. The present work concerns strategic information transmission under asymmetric information. Specifically, private information of the sender comes from non-player actions, that are only observed by the sender but ignored by the receiver.

In their seminal paper Crawford and Sobel (1982) introduced a one-sided communication model between an informed sender and an uninformed receiver and showed how the conflict of interest had a negative effect on the flow of information transmission. There are many applications of strategic information transmission based on this model. For example, applications to corporations (Watson 1996; Kartik 2005), to operational management (Allon and Bassamboo 2011; Allon et al. 2011) or to political sciences (Gilligan and Krehbiel 1989; Krishna and Morgan 2001).

In our set-up, we consider a sender-receiver situation where interests are aligned. However, some other features of our setting are common to Crawford and Sobel’s framework. First, information is transmitted through a one-sided communication channel. Secondly, the sender, denoted as Player 1, has complete and perfect information about Nature, whereas the receiver, denoted as Player 2, is an uninformed player who knows about Nature’s existence and actions in the past. Thirdly, sharing information is costless for Player 1. Finally, decisions of Player 2 have an effect on both players’ payoffs.

Some other features in our setting are, however, specific to our communication protocol and common with the set-up of Gossner et al. (2003): both players form a team with aligned interests; Nature’s actions are modeled as an i.i.d. process, and players and Nature play in a finitely repeated fashion. Moreover, players have positive payoffs when both match Nature’s move.
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From a theoretical perspective, Gossner et al. (2003) characterize the equilibrium payoff that the team can guarantee against any behaviour of Nature. They construct equilibrium strategies of communication between sender and receiver in an infinitely repeated set-up based on block coding. To be precise, block coding strategies refer to the way in which players communicate their subsequent sequence of actions. In their set-up, the transmission of information occurs while playing, so that the sequence of actions played by the sender is encrypted as messages, and the receiver decodes the messages according to a common team’s codebook.

The aim of our paper is to test in the lab whether under asymmetric uncertainty players whose dominant strategy is to share information are able to actually implement such a kind of block coding-encrypted messages. To do so, we first provide a theoretical characterization of the optimal block strategies for Player 1, considering that players interact a finite number of periods. Secondly, we show that the majority rule with 3-length blocks is optimal for a Nature sequence of length 55. These two variables are fixed for an experiment that fits the model and tests its robustness in the lab.

In our experiment, we implement a specific channel for communication between players. Before the game, a chat is activated for 3 min. In this time, players have the opportunity to write free messages designing their strategies without any explicit cost. This chat allows the players to fix the common codebook and the decoding rules that players may eventually perform when playing the game. Once the chat closes, the 55 actions of Nature are carried out and drawn following an i.i.d. process with law \((\frac{1}{2}, \frac{1}{2})\). Player 1 is informed about the entire sequence played by Nature. Players then play the game for 55 rounds. In round \(t\), Player 1 has the whole sequence of Nature on the screen; his own action, and Player 2’s actions in the past. Nevertheless, Player 2 knows the whole history of moves by Nature and by Player 1. Any verbal communication is forbidden during the game. So, before the game starts, Player 1 may signal to Player 2 specific ways to coordinate and, therefore, reach better payoffs. How much information is transmitted depends on how informative the signal of Player 1 is and also on how receptive Player 2 is to receiving the signal. All this process eventually determines the payoff of both players measured as the number of rounds in which Nature and players’ actions coincide.

We analyze the effectiveness of the chat in transmitting information in the terms of the theoretical model. That is, without specifically analysing the content of the messages in the chat, we test whether players coordinate and, if so, by how much under such conditions and, therefore, whether the model predicts reasonable strategies that could be observed from real heterogeneous agents.

One main finding from our data analysis is that subjects are able to design strategies at three levels of coordination. First, low coordination strategies are those in which the receiver ignores or misunderstands any signal sent by the sender so that coordination occurs by pure chance. Secondly, there are medium coordination strategies where information is successfully transmitted by following a joint coordination code. Finally, the high coordination strategies are those where coordination codes achieve payoffs close to the optimal theoretically predicted. Furthermore, from a logit estimation we find that actions by Player 2 are significantly explained by actions played by Nature and by Player 1. With respect to Player 1’s actions, their signals are precise most of the times.
The paper is structured as follows. Section 2 gives a brief review of related literature on strategic information transmission. In Sect. 3 we describe the theoretical framework of the game. Section 4 describes in detail the experimental environment. In Sect. 5 we present the analysis of the experimental data and highlight the main results. Section 6 presents the conclusions.

2 Related literature

Sobel’s (2010) literature review correctly states the importance of strategic transmission of private information in many areas related to economics and political sciences. A quick look at the state of the art on unmediated communication classifies this type of research into two categories: first, cheap talk games, where information is unverifiable and players can lie at no cost\(^1\); and, secondly, games of persuasion or verifiable disclosure, since it is assumed that information is verifiable and agents can conceal information but do not lie.\(^2\) Our set up is directly related to the first category. The large strand of cheap talk literature was initiated by Crawford and Sobel (1982) where, primarily related to the theory of bargaining, an informed sender sends a possibly noisy signal based on his private information to an uninformed receiver, who then initiates an action that determines the welfare of both. The authors show that when there is some, although not full, common interest, imprecise talk may be necessary and sufficient to sustain credibility. This credibility constraint is necessary for equilibrium communication. Under milder conditions than that of Crawford and Sobel, the recent work by Agastya et al. (2015) completes the analysis by establishing that almost full revelation results as the two players preferences get arbitrarily closer to each other.

The work by Gossner et al. (2006) is also central in this line of research. In their model, a sender transmits information to a receiver with no incentive to cheat. Furthermore, randomness is modelled as a binary, uniform random variable that represents the state of the world. Uncertainty is privately unveiled to the sender but not to the receiver. Although within a different modelisation of uncertainty, Agastya et al. (2014) analyse a context in which the sender has expertise on some but not all the payoff-relevant factors. Such an uncertainty can either improve or worsen the quality of transmitted information, which depends on the effective bias. For symmetrically distributed uncertainty or quadratic loss functions, the authors highlight three results: the quality of information transmission is independent of the riskiness of that uncertainty, it may be suboptimal to allocate authority to the informed player, and despite players’ preferences being arbitrarily close, it is impossible to state that the receiver prefers delegation over authority or vice versa.

As in the model of Crawford and Sobel, in Gossner et al. information transmission does not have an explicit cost. However, there is an implicit cost that comes from the trade-off between the cost and benefit of information transmission. Specific contexts with costly communication are offered by Sobel (2012) and Hertel and Smith (2013). In the first, the case is studied where both sender and receiver undertake a costly

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1 See Farrell and Rabin (1996) for an exhaustive survey.
2 Grossman (1981) and Milgrom (1981) are seminal papers in this line of research.
acquisition of communication capacity. The author points out that models where communication is costly and preferences are aligned can have parallel results to models of costless communication and not aligned preferences. In particular, for any communication cost or difference in preferences, full communication is not possible and failure to communicate is always possible.

In the second paper, Hertel and Smith introduce discrete and costly communication in the setup of Crawford and Sobel. The underlying idea is that words are scarce and costly. The sender can communicate only through the use of discrete messages which are ordered by cost. The state space is richer than the space of messages, since the state space is infinite while the number of messages is finite. The model captures realism since it is impossible to communicate to others the complexity of the real world. Therefore, the precision of communication may be enhanced by spending more in costly effort. In addition, the size of language endogenously emerges due to the cost of communication. As a main result, when players preferences are not aligned, an increase in communication costs may improve communication itself.

Some of the theoretical models just mentioned have also been tested in the lab. Crawford (1998) reviews the experimental literature on communication games, and Devetag and Ortmann (2007) critically revise some research on coordination failure in the experimental lab studies on coordination games with Pareto-ranked equilibrium. Charness and Grosskopf (2004) analyse which components might make cheap talk effective in the setting of coordination games. In particular, they design an experiment based on a two-player game to test whether information provision about the other player’s actions, and whether costless one-way messages before actions are taken have some influence on coordination. They find that information provision about the other person’s play only enhances coordination when messages are allowed.

Through an experimental approach, Blume and Ortmann (2007) investigate the effects of costless pre-play communication in symmetric coordination games of the stag hunt variety. They find that with repeated interaction, cheap talk preceding games with Pareto-ranked equilibria can substantially facilitate player’s coordination on the Pareto-dominant equilibrium.

Finally, Duffy et al. (2014) test the Hertel and Smith (2013) in the lab. They find that the size of the language endogenously emerges as a function of the costs of communication: higher communication costs are associated with a smaller language. It is found that, relative to equilibrium payoffs, the sender payoffs are decreasing in cost, whereas the receiver has payoffs that are increasing in cost. Moreover, over-communication is also found.

3 Theoretical framework

Our theoretical set-up is based on previous work by Gossner et al. (2003, 2006).

3.1 The one-shot game

Consider the following game with asymmetric information. Nature, Player 1 and Player 2 choose an action 0 or 1, that we denote by \( x, y \) and \( z \), respectively. If the three agents
take the same action, players’ payoff is 1, while 0 otherwise. The payoff function for players in the one-shot version of this game is given by,

$$g(x, y, z) = \begin{cases} 1 & \text{if } x = y = z \\ 0 & \text{otherwise} \end{cases}$$ (1)

The game can also be represented in normal form as:

|   | $z = 0$ | $z = 1$ |
|---|---------|---------|
| $y = 0$ | 1       | 0       |
| $y = 1$ | 0       | 0       |

where Nature chooses the matrix, Player 1 chooses the row, and Player 2 chooses the column. Players 1 and 2 have a common payoff function and, therefore, their incentives are aligned.

In the $n$-stage version of the game, Nature plays a random sequence of actions denoted as $X \in \{0, 1\}^n$ and defined as an i.i.d $(\frac{1}{2}, \frac{1}{2})$ sequence. Before the game is played, Player 1 learns the future realizations of Nature, while Player 2 knows only the law of the Nature’s random process. Players 1 and 2 learn the whole history of actions. Formally, the strategies for players 1 and 2 are defined as,

- a (pure) strategy $Y \in \{0, 1\}^n$ for Player 1 is a sequence of mappings $Y_t : \{0, 1\}^n \times \{0, 1\}^{t-1} \times \{0, 1\}^{t-1} \rightarrow \{0, 1\}$. $Y_t$ describes Player 1’s action at round $t$, which depends on Nature’s sequence $X$ and on players’ actions in rounds previous to round $t$.
- a (pure) strategy $Z \in \{0, 1\}^n$ for Player 2 is a sequence of mappings $Z_t : \{0, 1\}^t \times \{0, 1\}^{t-1} \times \{0, 1\}^{t-1} \rightarrow \{0, 1\}$. $Z_t$ describes Player 2’s action in round $t$ which depends on actions taken by all players in the past.

Therefore, given a sequence $X \in \{0, 1\}^n$ for Nature and a pair of strategies $(Y, Z)$ for players 1 and 2, the induced sequences of actions $(y_n)_n$ and $(z_n)_n$ of players 1 and 2, respectively, are given by the following relations: $(y_n)_n = Y(X)$, $(z_n)_n = Z(X, Y)$. Ultimately, Player 1’s actions only depend on Nature’s actions, while actions of Player 2 depend on Player 1’s and Nature’s actions.

### 3.2 Finite repetition

In situations under asymmetric information, players share information in order to reduce inefficiencies. In line with Gossner et al. (2006) we use similar techniques in the infinite framework, for constructing the strategies implemented by players in a finite repetition environment.

Players’ strategies are defined over blocks of length $m < n$ in such a way that, for any Nature’s sequence $X = (x_m)_m$, the proportion of rounds in which Player 2’s action matches Nature, $z_t = x_t$, is denoted by $q \in [0, 1]$. Moreover, the proportion of rounds in which Player 1’s action matches that of Nature, $y_t = x_t$, conditional on $z_t = x_t$, is
denoted as \( p \in [0, 1] \). Therefore, the proportion of rounds in which \( y_t = z_t = x_t \) is equal to \( p \cdot q \). Given that strategies in this game are defined over the space \( \{0, 1\} \), \( p \cdot q \) also defines each player’s average payoff per round in the long-run.

In our game, Player 1 chooses a sequence \((y_m)_m\) of actions as a signal for Player 2 such that:

- The number of rounds in which \( y_t = z_t = x_t \) is equal to \( \lfloor p \cdot q \cdot m \rfloor \).
- Among the \( \lceil (1 - q) \cdot m \rceil \) rounds in which \( z_t \neq x_t \), it occurs that \( y_t = x_t \) about half of the times, i.e. \( \lfloor \frac{1 - q}{2} m \rfloor \).

After the first block has been played, along each subsequent block Player 2 has to interpret the signal sent by Player 1 in the previous block and then choose her own strategy \((z_m)_m\).

Given a strategy \((p, q)\), the number of \( m \)-length block fulfilling the above properties is computed as the product of three combinatorial\(^3\) numbers. For feasibility, that result should be greater than \( 2^m \):

\[
\left( \frac{m}{mq} \right) \left( \frac{mq}{mwp} \right) \left( \frac{m(1 - q)}{m(1 - q)\frac{1}{2}} \right) \geq 2^m
\]

(2)

### 3.2.1 The information constraint

The construction of strategies according to which players generate codification schemes allows us to write expression (2) using the entropy function (Gossner et al. 2006). Entropy is used to measure information of random variables. Therefore, entropy allows us to summarize both the amount of information transmitted from Player 1 to Player 2 when playing the game and the number of possible ways\(^4\) to connect the number of sequences given by expression (2) with the amount of information shared by players.

The entropy \( H(X) \) of a random variable \( X \) over a finite set \( \Theta \) with distribution \( p \) is \( H(X) = -\sum_{\theta \in \Theta} p(\theta) \log p(\theta) = -\mathbb{E}_X \log p(X) \) where \( 0 \log 0 = 0 \) (by convention \( \log \) is taken in basis 2). The entropy of a random variable depends on its distribution only. Thus, for \( p \in \Delta(\Theta) \) we let \( H(p) = H(X) \) for a random variable \( X \) with distribution \( p \). For a pair of random variables \((X_1, X_2)\) taking values in \( \Theta_1 \times \Theta_2 \) with joint distribution \( p(\theta_1, \theta_2) \), we denote by \( p(\theta_2 \mid \theta_1) \) the conditional probability that \( X_2 = \theta_2 \) given that \( X_1 = \theta_1 \). Define \( h(X_2 \mid \theta_1) = -\sum_{\theta_2 \in \Theta_2} p(\theta_2 \mid \theta_1) \log p(\theta_2 \mid \theta_1) \). Thus \( h(X_2 \mid \theta_1) \) is the entropy of \( X_2 \) when the realization \( X_1 = \theta_1 \) is known. Therefore, the conditional entropy \( H(X_2 \mid X_1) \) of \( X_2 \) given \( X_1 \) is \( H(X_2 \mid X_1) = \mathbb{E}_{X_1} [h(X_2 \mid X_1)] = \sum_{\theta_1 \in \Theta_1} p(\theta_1) h(X_2 \mid \theta_1) \). Direct computation shows that \( H(X_1, X_2) = H(X_1) + H(X_2 \mid X_1) \).

\(^3\) In general, \( \left( \frac{m}{m} \right) \) is defined as \( \Gamma(m+1)/(\Gamma(x+1)\Gamma(m-x+1)) \). Being \( \Gamma(m) \) the Euler gamma function that satisfies \( \Gamma(m) = \int_0^\infty t^{m-1}e^{-t} \, dt \). For \( m(1-q) = 1 \), we consider \( \left( \frac{m(1-q)}{m(1-q)\frac{1}{2}} \right) = 2 \). That means that with one digit is possible to construct the two basic sequences: 0 and 1.

\(^4\) The entropy is also useful to approximate a combinatorial number. For \( 0 < x < 1 \), the combinatorial number \( \left( \frac{m}{mx} \right) \) is upper bounded by \( 2^{mH(x)} \).
From expression (2) we get the information constraint as:

\[ 2^m H(q) 2^{mq} H(p) 2^{m(1-q)} H(1/2) \geq 2^m \tag{3} \]

or

\[ H(p, q) = H(q) + H(p|q) = H(q) + qH(p) + (1-q)H(1/2) \geq 1 \tag{4} \]

where \( H(q) \) is the amount of information available to Player 2 and \( H(p) \) the information available to Player 1. Player 1 has an incentive to share information with Player 2, gathering the total amount of information given by the joint entropy \( H(p, q) \). The fact that the information used by the player cannot exceed the information received leads to an inequality that we call the information constraint. Therefore, the information used by Player 2 cannot exceed the information received from Player 1. Moreover, since the coded information is embedded into the mistaken rounds, there is a trade-off between earnings and errors: the fewer the errors, the more coordination and the higher payoff for players, but also the fewer chances to inform on Nature’s future movement, which in turn reduces future payoffs.

Ultimately, the number of errors depends on the strategy \((p, q)\) that, for feasibility, must satisfy the information constraint given in (3). Players choose a joint strategy from the set of feasible strategies \(S\). Let \(S\) be the set of pairs \((p, q)\) verifying (3). Taking logarithms, set \(S\) is defined as,

\[ S = \{(p, q) : H(q) + qH(p) + (1-q) \geq 1\} \tag{5} \]

Notice that whenever \(p = 1\) and \(q = 1\), both players have perfect information and the information constraint does not work: \(H(1)+1H(1)+(1-1) = 0 < 1\). Consequently, we confirm that \(S\) is a proper subset of \([0, 1] \times [0, 1]\). Moreover, the information constraint does not depend on the length \((m)\) of the block.

### 3.2.2 Coordination strategies in \(\mathbb{Q}\)

In order to coordinate actions and maximize payoffs, players need to transmit information through actions. In other words, players need to perform a communication system on finite sequences. In order to do that, the number of matches must be an integer number. Some additional definitions are needed with respect to the rational number set \(\mathbb{Q}\).

Given a strategy \((p, q)\) on \(S\), let us define the counterpart in rational numbers as \(\tilde{q}(m) = \lfloor qm \rfloor / m\), \(\tilde{p}(m) = \lfloor pqm \rfloor / \lfloor qm \rfloor\), \(m\) is the size of the block. If \(q \in [0, 1]\) then \(\tilde{q} \in \{0, \frac{1}{m}, \ldots, \frac{m-1}{m}, 1\}\). Similarly, since \(p \in [0, 1]\) then \(\tilde{p} \in \{0, \frac{1}{mq}, \ldots, \frac{m-1}{mq}, 1\}\).

Expression (2) can now be rewritten in terms of rational numbers as,

\[ \left( \frac{m}{m\tilde{q}} \right) \left( \frac{m\tilde{q}}{m\tilde{q}\tilde{p}} \right) \left( \frac{m(1-\tilde{q})}{m(1-\tilde{q})} \right) \geq 2^m \tag{6} \]
Also, the information constraint (4) can be expressed as a rational information constraint:

\[ H(\tilde{q}(m)) + \tilde{q}(m) H(\tilde{p}(m)) + (1 - \tilde{q}(m)) \geq 1 \]  

The set of pairs \((\tilde{p}, \tilde{q})\) is denoted by \(\tilde{S}_m\) in \(\mathbb{Q}\) verifying the rational information constraint:\n
\[ \tilde{S}_m = \left\{ (\tilde{p}, \tilde{q}) \in \mathbb{Z}/m\mathbb{Z} \times \mathbb{Z}/m\mathbb{Z} : \right. \\
\left. \tilde{q}(m) = \left\lfloor \frac{qm}{m} \right\rfloor, \quad q \in [0, 1] \\
\left. \tilde{p}(m) = \left\lfloor \frac{pqm}{qm} \right\rfloor, \quad p \in [0, 1] \\
H(\tilde{q}) + \tilde{q}H(\tilde{p}) + (1 - \tilde{q}) \geq 1 \right\} \]  

\[ H(\tilde{q}(m)) + \tilde{q}(m) H(\tilde{p}(m)) + (1 - \tilde{q}(m)) \geq 1 \]  

Remark 1 The rational information constraint depends on the size of the block \((m)\). 

The following lemma states the existence of rational joint strategies for players 1 and 2 given a fixed length for the block.

Lemma 2 Let \(n > 0\)

- There exists \(m|n\) such that \(\tilde{S}_m \neq 0\).
- Let \(D_n = \{m|n : \tilde{S}_m \neq 0\}\). There exists \(m^* \in D_n\) and \((p^*, q^*) \in \tilde{S}_m^*\) such that \(p^*q^*\) is maximal over \((\tilde{p}(m), \tilde{q}(m)) \in \tilde{S}_m, \forall n \in D_n\).

Proof • For all \(m \in D_m\) consider the family \(\left\{ \left\lfloor \frac{qm}{n} \right\rfloor, \left\lfloor \frac{pqm}{qm} \right\rfloor \right\}_{m \in D_n}\).

Observe that \(\tilde{S}_m \subset [0, 1] \times [0, 1]\) is a compact set. Therefore, the product \(\tilde{p}(m)\tilde{q}(m)\) reaches its maximal value in this set.

From the set of pairs \((\tilde{p}(m), \tilde{q}(m))\) that verify the rational information constraint:

\[ H(\tilde{q}(m)) + \tilde{q}(m) H(\tilde{p}(m)) + (1 - \tilde{q}(m)) \geq 1 \]  

We obtain the optimal pair \((p^*, q^*)\) such that the product \(p^*q^*\) reach the maximal value in \(\tilde{S}_m\).

As the entropy approximation provides an upper bound for a combinatorial number, the rational information constraint in (9) is a necessary but not sufficient condition for a strategy \((\tilde{p}(m), \tilde{q}(m))\) to be implementable. Specifically, in the case of small values of \(m\) like \(m = \{3, 4\}\), a strategy may verify the rational information constraint but not the combinatorial inequality (6). To overcome such cases, we introduce a refinement for

\[ \mathbb{Z} \text{ denotes the set of positive integer numbers.} \]
a strategy to be implementable and define the implementable information constraint in combinatorial terms as,

\[
\binom{m}{m \tilde{q}} \binom{m \tilde{q} \tilde{p}}{m (1 - \tilde{q})} \binom{m (1 - \tilde{q} \tilde{p})}{m} \geq 2^m \tag{11}
\]

Notice that we have added a second term to the left-hand side of inequality (6), representing the total number of \(m\)-length sequences with a number of signaling errors equal to \(m (1 - \tilde{q} \tilde{p})\).

4 Experimental set-up

In this subsection we determine and justify the criteria that a sequence and block lengths have to fulfill in order to be adequate for its implementation in the lab. We then define the optimal strategies given that sequence length. Finally, we describe in detail the design of the experimental session undertaken.

4.1 Sequence and block lengths

In this subsection we try to find a sequence length to be implementable in our experimental design. For this purpose, we explore several possibilities for \(n\), in combination with several block lengths \((m)\). In particular, we look for the block strategy \([\tilde{p}(m), \tilde{q}(m)]\) of length \(m < n\) that maximizes payoffs in the sequence length \(n\). Let us denote by \(G(n, m)\) the total payoff of such an strategy: \(G(n, m) = \tilde{p}(m)\tilde{q}(m)m_{b}(n, m)m\). The term \(m_{b}(n, m)\) denotes the number of blocks of length \(m\) in the sequence of length \(n\), and it is defined as,

\[
m_{b}(n, m) = \begin{cases} \left\lfloor \frac{n}{m} \right\rfloor & \text{if } n \mod m \geq m (1 - \tilde{p}(m)\tilde{q}(m)) \\ \left\lfloor \frac{n}{m} \right\rfloor - 1 & \text{otherwise} \end{cases} \tag{12}
\]

Given that players in the first block are not able to transmit any information, any matching in that block occurs by chance. Let \(n \mod m\) be the remainder of the fraction between \(n\) and \(m\). If \(n \mod m\) is greater than or equal to the number of errors that are necessary to communicate, i.e. \(m (1 - \tilde{p}(m)\tilde{q}(m))\), then the number of blocks generating payoff is given by the minimum integer number \(\left\lfloor \frac{n}{m} \right\rfloor\). Otherwise, the number of blocks is \(\left\lfloor \frac{n}{m} \right\rfloor - 1\).

For a given value of \(m\), the optimal total payoffs \(G^*(n, m)\) can be obtained by a block strategy that maximizes the total payoffs: \(G^*(n, m) = \max_{m} G(n, m)\). Since the solution to this problem is not unique for \(n\), it is established that the optimal block strategy \((\tilde{p}(m^*), \tilde{q}(m^*))\) is the one that has the minimum length, i.e. \(m^* = \min_{m} \arg(G^*(n, m))\). We consider that, in order to be implementable in the lab, block and sequence lengths should be long enough so that subjects are able to learn during the game and, therefore, easily define an optimal strategy during the chat time of the game.
We develop an algorithm that solves the min-max problem. First, we apply lemma 2 in order to construct the strategy set $\tilde{S}_m^\ast$. The interval $[0, 1]$ is divided into $m$ disjoint intervals such that:

$$\frac{x}{m} \leq \tilde{q}(m) < \frac{x + 1}{m}, \quad x = 0, 1, \ldots, m$$

(13)

and the number of times Player 2 matches Nature is denoted by $x$. For any of the $m$ intervals, a rational number exists in the set:

$$\tilde{q}(x|m) = \left\{0, \frac{1}{m}, \frac{2}{m}, \ldots, \frac{m - 1}{m}, 1\right\}$$

(14)

Let $\tilde{p}(m)$ be conditional on $\tilde{q}(m)$ such that:

$$\frac{y}{x} \leq \tilde{p}(m) < \frac{y + 1}{x}, \quad y = 0, 1, \ldots, x, x > 0$$

(15)

For each $m$ interval a set exists expressed as:

$$\tilde{p}(y|x, m) = \left\{0, \frac{1}{x}, \ldots, \frac{x - 1}{x}, 1\right\}, \quad x \neq 0$$

(16)

By programming with Mathematica 7.0, we provide strategy sets $\tilde{S}_m$. Table 3 in “Appendix 1” shows the set of optimal strategies verifying the rational information constraint. As an example, the strategy sets for $m = 2, 3, 4, 5$ are:

$$\tilde{S}_2 = \left\{\left(\frac{1}{2}, 1\right), \left(1, \frac{1}{2}\right)\right\}$$

$$\tilde{S}_3 = \left\{\left(1, \frac{1}{3}\right), \left(\frac{1}{2}, \frac{2}{3}\right), \left(1, \frac{2}{3}\right)\right\}$$

$$\tilde{S}_4 = \left\{\left(\frac{1}{2}, 1\right), \left(1, \frac{1}{4}\right), \left(\frac{1}{2}, \frac{1}{2}\right), \left(1, \frac{1}{2}\right), \left(\frac{1}{3}, \frac{3}{4}\right), \left(\frac{2}{3}, \frac{3}{4}\right), \left(1, \frac{3}{4}\right)\right\}$$

$$\tilde{S}_5 = \left\{\left(1, \frac{1}{5}\right), \left(\frac{1}{2}, \frac{2}{5}\right), \left(1, \frac{2}{5}\right), \left(\frac{3}{5}, \frac{3}{5}\right), \left(\frac{2}{5}, \frac{3}{5}\right), \left(1, \frac{3}{5}\right), \left(\frac{1}{4}, \frac{4}{5}\right), \left(1, \frac{4}{5}\right)\right\}$$

Observe, for example, that the strategy $(1, \frac{3}{2})$ in $\tilde{S}_4$ does not fulfill the implementable information constraint given in (11):

$$\begin{pmatrix} 4 \\ 3 \end{pmatrix} \begin{pmatrix} 3 \\ 3 \end{pmatrix} \left(\frac{1}{2}\right) + \begin{pmatrix} 4 \\ 4 \end{pmatrix} \begin{pmatrix} 4 \\ 1 \end{pmatrix} = 12 \neq 2^4 = 16$$
Therefore, it is not possible to get blocks of length \( m = 4 \) with only one signalling mistake. Moreover, note that 2-length and 3-length blocks are implementable strategies that need only one signalling mistake.

As a matter of fact, given a set of strategies, we are able to build optimal strategies by maximizing total payoffs per block. For the sets just considered above, the optimal strategy sets are:

\[
\tilde{S}_2^* = \left\{ \left( \frac{1}{2}, 1 \right), \left( 1, \frac{1}{2} \right) \right\}
\]
\[
\tilde{S}_3^* = \left\{ \left( 1, \frac{2}{3} \right) \right\}
\]
\[
\tilde{S}_4^* = \left\{ \left( \frac{2}{3}, \frac{3}{4} \right) \right\}
\]
\[
\tilde{S}_5^* = \left\{ \left( 1, \frac{3}{5} \right), \left( \frac{3}{4}, \frac{4}{5} \right) \right\}
\]

Having identified the optimal strategies, the next step is to evaluate each strategy by calculating the payoffs associated with them for a given sequence length \( n = 5, 6, \ldots, N \). Each combination \((n, m)\) leads to exactly \( G(n, m) \) total payoffs.

In addition to that, given that this problem has multiple solutions for the optimal block length \( m^* \), we require that, for a given sequence length \( n \), the length of the block be minimal, that is, \( m^* = \min_m \arg (G^*(n, m)) \).

Table 4 in “Appendix 1” reports the optimal strategies that are implementable in such a set-up. Taking into account all the requirements for the implementability in the lab of a certain sequence length, we set \( n = 55 \). This sequence length corresponds to the optimal block-length \( m = 3 \), as well as the strategy \((1, \frac{2}{3})\), known as majority rule for 3-length blocks. We explain this in more detail in the next subsection.

### 4.2 Optimal strategy for \( m = 3 \)

As previously mentioned, the majority rule strategy for the 3-length block case\(^6\) is optimal. Such strategy is founded on the condition that, in each block after the first stage, Player 2’s actions match Nature’s actions in at least 2 out of the 3 rounds. Player 2’s triple action is either \((0, 0, 0)\) or \((1, 1, 1)\) in each block, whereas Player 1’s actions signal to Player 2 the majority action of Nature in the next block. This signalling is achieved by playing Nature’s majority action of the subsequent block in a signalled

\(^6\) The possible binary sequences of length 3 are: \((0, 0, 0), (0, 0, 1), (0, 1, 0), (1, 0, 0), (1, 1, 0), (1, 0, 1), (0, 1, 1)\) and \((1, 1, 1)\). There are four sequences with majority rule 0, and also four with majority rule 1. The probability of the majority rule ‘equals 0’ is given by \( \text{prob}(\text{majority} = 0) = \text{prob}(000 \cup 001 \cup 010 \cup 100) = 4 \times \frac{1}{8} = \frac{1}{2} \). Similarly, the probability of the majority rule ‘equals 1’ is equal to \( \text{prob}(\text{majority} = 1) = \text{prob}(110 \cup 101 \cup 011 \cup 111) = 4 \times \frac{1}{8} = \frac{1}{2} \). Thus, the probability of two consecutive blocks having the same majority is \( \frac{1}{2} \). The probability of an intended mistake (say \( x \)) becoming a random match is equal to: \( P(x = \text{majority} = 0)P(\text{majority} = 0)P(\text{majority} = 0) + P(x = \text{majority} = 1)P(\text{majority} = 1)P(\text{majority} = 1) = \frac{1}{4} \).
Table 1  Example of the majority rule strategy ($m = 3$)

| Players/Stages | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---------------|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|
| Nature        | 1 | 1 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 0   | 1   | 0   | 0   | 0   | 0   |
| 1             | 0 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0   | 0   | 0   | 0   | 0   | 0   |
| 2             | * | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 0   | 0   | 0   | 0   | 0   |
| Payoff        | * | 0 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 0   | 1   | 0   | 1   | 1   | 1   |

*Any random action taken by Player 2 which payoff is also random

round of the current block. When actions of Player 2 match Nature’s in every round of the current block, then the third round is the one used for signalling the majority rule corresponding to the subsequent block. If the actions of Player 2 match the sequence of Nature in just two rounds, the mismatched round is the one that acts as a signal. Such strategy guarantees a payoff of $2/3$ per round.

Table 1 shows one example of the 3-length majority rule strategy for $n = 16$. Note that there is only one mistake signalled by Player 1’s actions (in bold) and that the total guaranteed payoff is at least 10 ($2 \times 5$ blocks), being the guaranteed average payoff per round is $\frac{10}{16} = 0.625$. Furthermore, the signalling action may match the majority action of the current block $\frac{1}{4}$ of the times. Thus, there is an additional expected payoff of $1.25$ ($\frac{1}{4} \times 5$ blocks). This implies that the expected payoff per round is $\frac{11.25}{16} = 0.70$.

4.3 Experimental design

The experiment was run at the experimental economics lab at the University of Valencia (LINEEX) in Spain, and consisted of two sessions of 60 subjects each, all third and fourth year students of Economics, International Business and Business Administration at that University.

At the beginning of the session students performed several tests individually. First, the Cognitive Reflexion Test (CRT, Shane 2005) was used. The reason for using this is that CRT has a moderate positive correlation with measures of intelligence, such as the Intelligence Quotient test, and it correlates highly with various measures of mental heuristics. Secondly, a Teamwork Test (TwT) of 25 questions was carried out. This test determines how well a person works with other individuals in a group. Specifically, it rates a person’s ability in fifteen different categories related to teamwork: Trust, patience, respect, cooperation, interaction, control, persuasion, responsibility, perseverance, determination, understanding and listening. From the 60 questions of the general test, the 25 chosen for our design are presented in “Appendix 3”. The subjects’ performance in the TwT was afterwards used to rank students from more to less team-collaborative. Thirty pairs were formed so that the pair number 1 was composed by the two most team-collaborative ones, and the pair number 30 was formed by the two least team-collaborative. Following this, subjects were given the instructions of the experiment in hard-copy\textsuperscript{7} and played a pilot of 8 rounds so that they could famil-

\textsuperscript{7} See the translated version from the original in Spanish in “Appendix 2”.
iarize themselves with the environment, although data from the pilot periods are not reported in our results.

As explained in detail in the instructions, the start of the experiment consists of subjects being randomly assigned a permanent role: Player 1 or Player 2.

The decision making of subjects consists in them playing the 55-times-repeated coordination game introduced in Sect. 3. In this game, a no-player, called Prize, was defined as an i.i.d random variable taking value 0 or 1 with probability \( \frac{1}{2} \). Before any player made decisions, a 55-length random sequence was randomly generated. This part of the game was common knowledge.\(^8\)

In an experimental session, players played the coordination game twice. Specifically, a session was divided into two parts. In the first part, named Play 1, subjects played the coordination game for 55 rounds. Immediately afterwards, the second part, named Play 2, was played. Play 2 is exactly the same as Play 1 but Nature plays a different sequence. As a result, the two parts of a session differ just in the fact that, when Play 2 starts, subjects have already played Play 1.

Both Play 1 and Play 2 in a session have the same structure: first, the 55-length Nature’s sequence is generated and, just before the coordination game was played, there was a pre-play stage of 3 min-chat. During the time of the chat, subjects were allowed to send free-form messages to each other to share information and experience, and could close the chat at any time before minute 3. Otherwise, the chat would automatically close at the end of minute 3. Immediately afterwards, Player 1 was privately informed of the complete sequence played by Nature. Then players played the 55-times-repeated game. At the end of each round, subjects were privately informed of all actions taken and about individual payoffs in that round and in the past.

Players’ payoffs were defined such that, in each round, both players could earn 1 ECU (Experimental Currency Unit) only if both matched the action played by the no-player, and 0 otherwise. No losses were possible. At the end of each Play, subjects were privately informed of their final payoff in that part of the session.

At the end of the session, each participant was privately paid in cash. The ECU/Euro exchange rate was 1 ECU = \( \frac{1}{4} \) Euro. Average payoffs per subject were around 18 Euro.

5 Data analysis and main results

In this section we analyse our experimental data. We first conduct a statistical analysis on the total number of matchings. Secondly, we proceed with the same analysis but for the sub-samples corresponding to Play 1 and Play 2, respectively.

Figure 1 shows the number of matchings obtained in the whole sample (‘All’) and also each subsample (‘Play 1’ and ‘Play 2’). The median number of matchings for the total dataset is 32, which represents 58% success rate in the 55-rounds play. If we compare Play 1 and Play 2, we observe a significant increase in the number of matchings in Play 2, which means that subjects improve coordination in Play 2.\(^9\)

\(^8\) Subjects were informed about the computerized random process as being like tossing a coin.

\(^9\) Wilcoxon signed-rank test for the equality of medians: \( z = 3.701, p = 0.0002 \).
Result 1 Experience matters in coordination of actions. Compared to the first part of the session (Play 1), subjects reach significantly higher levels of coordination in the second part (Play 2).

We identify in our dataset different clusters according to the coordination reached. We apply the MacQueen’s K-means algorithm to the total number of matchings (All),\(^\text{10}\) and later within each cluster we differentiate between strategies chosen in Play 1 or in Play 2. As reported in Table 2, we identify three clusters corresponding to three differentiated coordination levels:

- **Cluster L** (Low coordination): Here we include those strategies in which Player 1 plays Nature’s action and Player 2 plays either randomly or choosing the same action in all rounds. This kind of behaviour is found more frequently in Play 1 than in Play 2. Messages that are common in this cluster are, for instance: “I play Nature and you play the same action 0 or 1, or the fixed sequence 00001111”. Both strategies are naive and have a correspondence with the theoretical \((p, q) = (1, \frac{1}{2})\), an expected payoff of \(\frac{1}{2}\) per period and a total expected payoff over the whole sequence of \(55 \times \frac{1}{2} = 27.5\). As a result, 38 out of 120 strategies are classified within this cluster, with 47% rate of median number of matching over the 55-length sequence. By comparing the number of matchings in Play 1 and Play 2, a significant difference of medians is found in favor of Play 2 (Mann-Whitney test: \(z = 2.108, p = 0.0350\)).

- **Cluster M** (Median coordination): Suboptimal strategies like the one of 2-length block are included here, with a guaranteed per period payoff of 1 and a per period

\(^{10}\) In this algorithm, the applied measure of distance is the sum of absolute differences, known as the \(L1\) distance. Each centroid is the component-wise median of the points in that cluster: \(d(x, c) = \sum_{j=1}^{p} |x_j - c_j|\).
Table 2  Number of matchings per coordination cluster

| Statistics | Play 1 | Play 2 | All |
|------------|--------|--------|-----|
|            | L      | M      | H   | L    | M    | H    | L    | M    | H    |
| Average    | 24.67  | 29.63  | 35.35 | 26.65 | 32.15 | 38.27 | 25.55 | 30.76 | 37.00 |
| Median     | 26     | 30     | 35   | 27   | 32   | 39   | 26   | 31   | 37   |
| SD         | 2.52   | 1.78   | 2.31 | 3.55 | 2.19 | 2.41 | 3.14 | 2.32 | 2.76 |
| Rate (%)   | 47     | 55     | 64   | 49   | 58   | 71   | 47   | 56   | 67   |
| Obs.       | 21     | 16     | 23   | 17   | 13   | 30   | 38   | 29   | 53   |

‘Rate’ refers to a matching percentage defined as the quotient between the median and the length of sequence \( n = 55 \).

expected payoff of \( \frac{5}{2} \). Therefore, the total payoff for the 55-length sequence lies within the interval \([27.5, 34.37] \). With this level of coordination we find messages for Player 1 such as: “Let us start playing 1, and whenever you see that I change, you should change too in the next round”. In our data, 29 out of 120 are classified in this cluster, with means a 56% rate of median number of matching over the 55-length sequence. By analysing each play, the rate of success is 3% higher in Play 2 compared to Play 1, which is also reflected by a higher median (Mann-Whitney test: \( z = 2.695, p = 0.0070 \)).

- Cluster \( H \) (High coordination): Here we find, among others, the optimal 3-length block strategies, with a guaranteed per period payoff of \( \frac{2}{3} \) and a per period expected payoff of \( \frac{3}{2} \). The total payoff for the whole sequence lies in the interval \([36.66, 41.25] \). The number of strategies implemented within this cluster was 53 out of 120, meaning a 67% rate of median number of matching over the 55-length sequence. Moreover, the number of matchings is significantly higher in Play 2 than in Play 1, and in this case the difference is the highest of all clusters (Mann-Whitney test: \( z = 4.068, p < 0.001 \)). Despite the high rate of matchings in this cluster, just 2 out of 53 possible strategies performed the optimal majority rule as defined in Sect. 4.2. However, we observe in our data a similar (to the optimal) strategy that is immersed in messages sent by Player 1 such as: “By default, we both play 0; if I see a run of three 1s, I will play 1 three times and you should also play 1 in the next two rounds”.

The clustering of our observations is useful when looking for any relation between coordination levels and subjects’ performance in the CRT and TwT at the beginning of the experimental session. At an aggregate level, Fig. 2 plots the distribution of subject pairs’ TwT scores by Play and coordination cluster. The horizontal axis represents, at two levels, Play 1 in the outside part with the three clusters, and Play 2 at the inside part of the graph with the three clusters per cluster of Play 1. We observe that there are pairs of subjects with very different TwT scores in every coordination cluster, independently of being in Play 1 or Play 2. Therefore, we find no relation between TwT scores and coordination levels. This is confirmed by the coefficient of Pearson’s correlation between the number of matchings and TwT scores which is not significant (\( \rho < 0.1, p > 0.3 \)). In the same way, no correlation is found between coordination
Efficient coordination in the lab

Fig. 2 TwT (pair) scores by Play and coordination cluster

and CRT scores ($\rho < 0.15$, $p > 0.25$), and also no correlation between TwT and CRT scores ($\rho < 0$, $p > 0.1$).

At an individual level, the subjects performance of the TwT reveals, however, some interesting facts. Option 4 “Always” was the most marked, between 44 and 87%, in the questions related to trust (Q1), respect (Q5, Q6 and Q7) or cooperation (Q9 and Q11), among others. The correlation analysis shows correlation, at the conventional levels of significance, between the coordination clusters and TwT questions related to trust (Q1), respect (Q6), cooperation (Q9, Q10, and Q11), control (Q14), perseverance (Q20), determination (Q22), understanding (Q23), and listening (Q24). Although trust and listening are the only questions emerging as significant (at 10 and 5%, respectively) in Play 1, other categories of the TwT arise as much more relevant for coordination in Play 2: respect and cooperation exhibit a significant and positive correlation with the three coordination clusters L, M and H ($\rho = 0.2284, 0.1965, 0.1932$) at 5%, respectively.

5.1 Coordination strategies in the lab

In our theoretical game, coordination takes place tacitly but not randomly. Players jointly define a coordination strategy before playing the game, which ensures their matching and payoff. High coordination strategies convey more information, which Player 2 decodes according to a joint coordination rule and matches Nature’s action in proportion $q$, which is denoted as $\text{Prob}(\text{Player 2} = \text{Nature})$ in probability terms. Player 1 makes one or more mistakes to inform his partner about Nature’s future play. Thus, Player 1 matches both Player 2 and Nature’s action in the proportion...
Fig. 3 Player 2’s matching frequency, by cluster

$p_1$ or $\text{Prob}(\text{Player 1} = \text{Nature} | \text{Player 2} = \text{Nature})$, otherwise Player 1 only matches Nature’s action in proportion $p_2$ or $\text{Prob}(\text{Player 1} = \text{Nature} | \text{Player 2} \neq \text{Nature})$.

As far as the corresponding experimental strategies for the aforementioned proportions, we find that overall, concerning proportion $q$, a powerful significant difference exists of medians between both plays ($z = -3.610$, $p = 0.0003$). Additionally, as Fig. 3 shows, the median values increase in coordination clusters, this effect being higher in Play 2. The contrary occurs in the case of proportions $p_1$ and $p_2$, where no median differences are found between plays ($z = 0.936$, $p = 0.3494$; $z = -0.738$, $p = 0.4608$).

Regarding the correlation between players’ decisions, we find, on the one hand, that proportion $p_1$ is negatively correlated to proportion $q$ ($\rho = -0.474$, $p = 0.0001$). In other words, because Player 1 uses mistakes to inform Player 2 about Nature’s subsequent actions, the higher the value of $p_1$, the lower the number of mistakes is and, therefore, the lesser the amount of information is transmitted. This results in Player 2 having fewer chances of matching Nature, so $q$ diminishes. On the other hand, the proportion $p_2$ is uncorrelated with the proportions $q$ and $p_1$ since the corresponding coefficients of correlation are not statistically significant at conventional levels. This means that the Player 1’s decision is taken randomly (theoretical optimal value is $p_2 = \frac{1}{2}$) when Player 2 does not match Nature.

Result 2 Player 2’s actions are induced by the actions of Player 1. Information transmission takes place through Player 1’s mistakes, that are interpreted by and converted into right choices by Player 2.

\[11\] It is applied Wilcoxon signed-rank test for the equality of medians.
5.2 Logit model estimation

In Sect. 4.1, we characterized the optimal proportions for a finite sequence of Nature of length 55, the corresponding strategy being the majority rule for 3-length blocks. According to the theoretical model, codification rules implicitly define Player 1 and Player 2 matching proportions, which, in turn, determine the long term average payoff. In this subsection we estimate logit models of players’ behaviour where the event ‘match’ takes value 1 and the event ‘unmatch’ takes value 0.

We modelize first the behavior of Player 2. If information transmission exists, the decisions of Player 2 will depend on Nature and the previous decisions of Player 1. This is included in the model by lagging one and two periods, respectively, the variable representing Player 1’s actions. We include, moreover, two dummy variables to catch the effect of coordination clusters M and H. Furthermore, the model estimation with the entire data-set includes session and Play dummies.

Regarding the model for estimating the behavior of Player 1, we estimate the probability \( p_1 \) which is conditional on Player 2 matching Nature’s action, and then we estimate the probability \( p_2 \) which is conditional on Player 2 not matching Nature’s action. In this case, the only explanatory variable is Nature’s action. Dummies per cluster and per session are also included.

Table 5 in the “Appendix 1” reports the logistic regression marginal effects of probabilities \( q, p_1 \), and \( p_2 \) for the entire sample and for each play.

With respect to players 2 behaviour, we find a significant and positive effect of Nature intervention on \( q \). In other words, when Nature’s action changes from ‘0’ to ‘1’ in the next period, we get that \( q \) is significantly higher, and viceversa. That might be interpreted as that Player 2 is more likely to choose 1 than 0 in any specific round, independently of what the other type of player does.

Analysing the entire sample, we find significant both the one and the two lagged actions of Player 1. Interestingly, when Player 1 changes his action from ‘0’ to ‘1’ in the next round, \( q \) diminishes one period later, but increases two rounds later. It seems that Player 1 switches from ‘0’ to ‘1’, but Player 2 does not react in the next round, but she does in the second. Similarly, when Player 1 changes his action from ‘1’ to ‘0’ in the next round, Player 2 reacts in the next period and plays ‘0’, but chooses 1 one period later. As a result, Player 2 seems to react differently to signals ‘0’ and ‘1’ from Player 1.

Furthermore, clusters M and H of Play 2 have significant positive effects on coordination. In relation to the marginal effects for Play 1 and Play 2, we observe a significant reduction of \( q \) whenever Player 1 swiches from ‘0’ to ‘1’.

Regarding the behaviour of senders, a positive marginal effect between the probability \( p_1 \) and Nature indicates that Player 1 follows Nature, although with some tendency to play ‘1’. However, in Play 2, Nature does not have a significant effect on the probability \( p_1 \), which might indicate that Player 1 is indifferent between playing ‘0’ or ‘1’. Moreover, players 1 that belong to cluster H signal mistakes to inform players 2 at the cost of reducing \( p_1 \). Finally, clusters M and H have significant positive effect on proportion \( p_2 \), except in Play 1 where those are not relevant.
6 Conclusions

How efficiently players are able to coordinate under certain conditions in the lab is the scope of this paper. We have implemented an experiment based on the sender-receiver set-up considered in Gossner et al. (2003, 2006), where optimal strategies of communication between sender and receiver are designed using blocks. The authors model the uncertainty coming from Nature playing a binomial random variable as, with probability $1/2$, taking the value “0” or “1”. The two players are characterized by their information available: the sender has private information on the future state of Nature, while the receiver has just public information about the history of Nature’s past states. The role of the strategic interaction is crucial since the gains of players are mutually conditional.

In order to create the correct experimental environment for testing the set-up described above, we have shown that the length $n = 55$ is appropriate so that the finite sequence can be randomly generated. We have then provided a theoretical characterization for strategies designed and implemented under that experimental environment.

In our experiment, we have implemented a specific channel for communication between players so that, prior to playing the game, a chat was activated for 3 min. During that time, players had the possibility to write free messages and design their strategies at no cost. Furthermore, we have analysed the effectiveness of the chat on transmitting information in terms of the theoretical model. In other words, without explicitly analysing the messages sent through the chat, we have tested whether and to which extent players did coordinate and, therefore, whether the model predicts reasonable strategies that could be observed from real heterogeneous agents.

We find that subjects design strategies at three levels of coordination. First, strategies are used at low level where the receiver ignores or misunderstands the sender’s message, coordinating actions by pure chance. Secondly, there is a medium level of coordination in which strategies successfully transmit information by following a joint coordination code. A third level of coordination, the richest, is where coordination codes achieve payoffs close to the optimal predicted by the theoretical model. Overall, we confirm that subjects coordinate their actions with experience, arriving at high levels of coordination in the second play of the session. From a logit estimation of the matching probabilities, we find that the behaviour of receivers is significantly explained by actions taken by Nature and by senders.

Summarising, we conclude that communication through actions increases coordination and reduces inefficiencies. Players follow a type of strategies consisting in block strategies, a theoretical evidence already proved in repeated games literature in general and in Gossner et al. in particular. Finally, it is remarkable that very little experience is enough to be able to implement strategic signalling by the senders with the use of mistakes. It has been shown that it is possible to transmit information even in complex setups like dynamic environments under uncertainty.

A Appendix 1: Tables

See Tables 3, 4 and 5.
Table 3 Optimal strategies for blocks of length $m = \{2, 3, 4, \ldots, 27\}$ under a rational information constraint

| $m$     | $(p^*, q^*)$       | $p^*q^*$ |
|---------|--------------------|----------|
| 2       | $(1, \frac{1}{2}), (\frac{1}{2}, 1)$ | $\frac{1}{2}$ |
| 3       | $(1, \frac{2}{3})$ | $\frac{2}{3}$ |
| 4       | $(1, \frac{3}{4})$ | $\frac{3}{4}$ |
| 5       | $(1, \frac{5}{8}), (\frac{3}{4}, \frac{4}{5})$ | $\frac{3}{5}$ |
| 6       | $(1, \frac{4}{8}), (\frac{5}{6}, \frac{5}{6})$ | $\frac{2}{3}$ |
| 7       | $(1, \frac{3}{8}), (\frac{5}{8}, \frac{7}{8})$ | $\frac{5}{7}$ |
| 8       | $(1, \frac{2}{8}), (\frac{5}{8}, \frac{7}{8})$ | $\frac{3}{4}$ |
| 9       | $(\frac{7}{8}, \frac{8}{9})$ | $\frac{7}{9}$ |
| 10      | $(\frac{8}{9}, \frac{9}{10})$ | $\frac{4}{5}$ |
| 11      | $(1, \frac{8}{11}), (\frac{5}{8}, \frac{9}{17}), (\frac{8}{17}, \frac{10}{11})$ | $\frac{8}{17}$ |
| 12      | $(1, \frac{9}{12}), (\frac{9}{11}, \frac{10}{12}), (\frac{10}{12}, \frac{11}{12})$ | $\frac{3}{4}$ |
| 13      | $(1, \frac{10}{13}), (\frac{10}{11}, \frac{11}{13}), (\frac{10}{12}, \frac{12}{13})$ | $\frac{10}{13}$ |
| 14      | $(\frac{11}{12}, \frac{12}{13}), (\frac{11}{13}, \frac{13}{11})$ | $\frac{11}{13}$ |
| 15      | $(\frac{12}{13}, \frac{13}{12})$ | $\frac{4}{5}$ |
| 16      | $(1, \frac{12}{16}), (\frac{12}{13}, \frac{13}{16}), (\frac{12}{14}, \frac{14}{16}), (\frac{12}{15}, \frac{15}{16})$ | $\frac{3}{4}$ |
| 17      | $(1, \frac{13}{17}), (\frac{13}{14}, \frac{14}{17}), (\frac{13}{15}, \frac{15}{17}), (\frac{13}{16}, \frac{16}{17})$ | $\frac{13}{17}$ |
| 18      | $(\frac{14}{15}, \frac{15}{18}), (\frac{14}{16}, \frac{16}{18}), (\frac{14}{17}, \frac{17}{18})$ | $\frac{7}{9}$ |
| 19      | $(\frac{15}{16}, \frac{16}{19}), (\frac{15}{17}, \frac{17}{19})$ | $\frac{15}{19}$ |
| 20      | $(\frac{16}{17}, \frac{17}{20}), (\frac{16}{18}, \frac{18}{20})$ | $\frac{4}{5}$ |
| 21      | $(1, \frac{16}{21}), (\frac{16}{17}, \frac{17}{21}), (\frac{16}{18}, \frac{18}{21}), (\frac{16}{19}, \frac{19}{21}), (\frac{16}{20}, \frac{20}{21})$ | $\frac{16}{21}$ |
| 22      | $(1, \frac{17}{22}), (\frac{17}{18}, \frac{18}{22}), (\frac{17}{19}, \frac{19}{22}), (\frac{17}{20}, \frac{20}{22})$ | $\frac{17}{22}$ |
| 23      | $(\frac{18}{19}, \frac{19}{23}), (\frac{18}{20}, \frac{20}{23}), (\frac{18}{21}, \frac{21}{23})$ | $\frac{18}{23}$ |
| 24      | $(\frac{19}{20}, \frac{20}{24}), (\frac{19}{21}, \frac{21}{24}), (\frac{19}{22}, \frac{22}{24})$ | $\frac{19}{24}$ |
| 25      | $(\frac{20}{21}, \frac{21}{25}), (\frac{20}{22}, \frac{22}{25})$ | $\frac{4}{5}$ |
| 26      | $(\frac{21}{22}, \frac{22}{26})$ | $\frac{21}{26}$ |
| 27      | $(\frac{21}{22}, \frac{22}{27}), (\frac{21}{23}, \frac{23}{27}), (\frac{21}{24}, \frac{24}{27}), (\frac{21}{25}, \frac{25}{27})$ | $\frac{7}{9}$ |
### Table 4  Optimal implementable strategies for sequences of length $n = \{5, 6, \ldots, 60\}$

| $n$ | $m^*$ | $p^*$ | $q^*$ | $p^*q^*$ | Gain/block | $m^*(1 - p^*q^*)$ | $nb(n, m^*)$ | Total earnings |
|-----|-------|-------|-------|----------|------------|------------------|--------------|---------------|
| 5   | 2     | 1     | $1/2$ | $1/2$    | 1          | 1                | 2             | 2             |
| 6   | 2     | 1     | $1/2$ | $1/2$    | 1          | 1                | 2             | 2             |
| 7   | 3     | 1     | $2/3$ | $2/3$    | 2          | 1                | 2             | 4             |
| 8   | 3     | 1     | $2/3$ | $2/3$    | 2          | 1                | 2             | 4             |
| 9   | 2     | 1     | $1/2$ | $1/2$    | 1          | 1                | 4             | 4             |
| 10  | 3     | 1     | $2/3$ | $2/3$    | 2          | 1                | 2             | 4             |
| 11  | 3     | 1     | $2/3$ | $2/3$    | 2          | 1                | 3             | 6             |
| 12  | 5     | 3/4   | $4/5$ | $3/5$    | 3          | 2                | 2             | 6             |
| 13  | 3     | 1     | $2/3$ | $2/3$    | 2          | 1                | 4             | 8             |
| 14  | 3     | 1     | $2/3$ | $2/3$    | 2          | 1                | 4             | 8             |
| 15  | 3     | 1     | $2/3$ | $2/3$    | 2          | 1                | 4             | 8             |
| 16  | 3     | 1     | $2/3$ | $2/3$    | 2          | 1                | 5             | 10            |
| 17  | 3     | 1     | $2/3$ | $2/3$    | 2          | 1                | 5             | 10            |
| 18  | 3     | 1     | $2/3$ | $2/3$    | 2          | 1                | 5             | 10            |
| 19  | 3     | 1     | $2/3$ | $2/3$    | 2          | 1                | 6             | 12            |
| 20  | 3     | 1     | $2/3$ | $2/3$    | 2          | 1                | 6             | 12            |
| 21  | 3     | 1     | $2/3$ | $2/3$    | 2          | 1                | 6             | 12            |
| 22  | 3     | 1     | $2/3$ | $2/3$    | 2          | 1                | 7             | 14            |
| 23  | 10    | 7/8   | $4/5$ | $7/10$   | 7          | 3                | 2             | 14            |
| 24  | 10    | 7/8   | $4/5$ | $7/10$   | 7          | 3                | 2             | 14            |
| 25  | 3     | 1     | $2/3$ | $2/3$    | 2          | 1                | 8             | 16            |
| 26  | 3     | 1     | $2/3$ | $2/3$    | 2          | 1                | 8             | 16            |
| 27  | 3     | 1     | $2/3$ | $2/3$    | 2          | 1                | 8             | 16            |
| 28  | 3     | 1     | $2/3$ | $2/3$    | 2          | 1                | 9             | 18            |
| 29  | 3     | 1     | $2/3$ | $2/3$    | 2          | 1                | 9             | 18            |
| 30  | 13    | 9/10  | $10/13$| $9/13$   | 9          | 4                | 2             | 18            |
| 31  | 3     | 1     | $2/3$ | $2/3$    | 2          | 1                | 10            | 20            |
| 32  | 6     | 4/5   | $5/6$ | $2/3$    | 4          | 2                | 5             | 20            |
| 33  | 10    | 7/8   | $4/5$ | $7/10$   | 7          | 3                | 3             | 21            |
| 34  | 3     | 1     | $2/3$ | $2/3$    | 2          | 1                | 11            | 22            |
| 35  | 3     | 1     | $2/3$ | $2/3$    | 2          | 1                | 11            | 22            |
| 36  | 11    | 8/9   | $9/11$| $8/11$   | 8          | 3                | 3             | 24            |
| 37  | 3     | 1     | $2/3$ | $2/3$    | 2          | 1                | 12            | 24            |
| 38  | 3     | 1     | $2/3$ | $2/3$    | 2          | 1                | 12            | 24            |
| 39  | 3     | 1     | $2/3$ | $2/3$    | 2          | 1                | 12            | 24            |
| 40  | 3     | 1     | $2/3$ | $2/3$    | 2          | 1                | 13            | 26            |
| 41  | 18    | 13/15 | $5/6$ | $13/18$  | 13         | 5                | 2             | 26            |
| 42  | 18    | 13/15 | $5/6$ | $13/18$  | 13         | 5                | 2             | 26            |
| \( n \) | \( m^* \) | \( p^* \) | \( q^* \) | \( p^* q^* \) | Gain/block | \( m^*(1 - p^* q^*) \) | \( nb(n, m^*) \) | Total earnings |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 43  | 10  | 7/8 | 4/5 | 7/10 | 7   | 3   | 4   | 28  |
| 44  | 10  | 7/8 | 4/5 | 7/10 | 7   | 3   | 4   | 28  |
| 45  | 20  | 15/16 | 4/5 | 3/4 | 15  | 5  | 2   | 30  |
| 46  | 3   | 1   | 2/3 | 2/3 | 2   | 1   | 15  | 30  |
| 47  | 11  | 8/9 | 9/11 | 8/11 | 8   | 3   | 4   | 32  |
| 48  | 11  | 8/9 | 9/11 | 8/11 | 8   | 3   | 4   | 32  |
| 49  | 15  | 11/12 | 4/5 | 11/15 | 11  | 4   | 3   | 33  |
| 50  | 15  | 11/12 | 4/5 | 11/15 | 11  | 4   | 3   | 33  |
| 51  | 15  | 11/12 | 4/5 | 11/15 | 11  | 4   | 3   | 33  |
| 52  | 3   | 1   | 2/3 | 2/3 | 2   | 1   | 17  | 34  |
| 53  | 10  | 7/8 | 4/5 | 7/10 | 7   | 3   | 5   | 35  |
| 54  | 24  | 9/10 | 5/6 | 3/4 | 18  | 6   | 2   | 36  |
| 55  | 3   | 1   | 2/3 | 2/3 | 2   | 1   | 18  | 36  |
| 56  | 25  | 19/20 | 4/5 | 19/25 | 19  | 6   | 2   | 38  |
| 57  | 25  | 19/20 | 4/5 | 19/25 | 19  | 6   | 2   | 38  |
| 58  | 11  | 8/9 | 9/11 | 8/11 | 8   | 3   | 5   | 40  |
| 59  | 11  | 8/9 | 9/11 | 8/11 | 8   | 3   | 5   | 40  |
| 60  | 11  | 8/9 | 9/11 | 8/11 | 8   | 3   | 5   | 40  |
Table 5  Logit model marginal effects (‘match’ =1 and ‘unmatch’ =0)

|                | Probability $q$ | Probability $p_1$ | Probability $p_2$ |
|----------------|-----------------|-------------------|-------------------|
|                | All Play 1 Play 2 | All Play 1 Play 2 | All Play 1 Play 2 |
| Nature        | .1758 .2242 .1094 | .0136 .0200 .0100 | .0408 .1170 − .0316 |
|               | (11.77)*** (10.73)*** (5.09)*** | (2.87)*** (2.96)*** (1.51) | (2.00)** (4.26)*** (− 1.00) |
| Player 1      | − .02543 − .0654 | .02040 | − .0336 − .0490 − .0187 |
|               | (− 1.49) (− 2.72)*** | (1.00) | (− 2.10)** (− 2.18)** (− 83) |
| Player 1(− 2) | .0469 − .0450 | .0484 | (3.12)*** (2.08)*** (2.33)** |
| Play 2        | .0548            |            | (4.30)*** |
| Session 1     | .0290 .0040 .0530 | − .0043 .0073 − .0141 | − .2599 − .2264 − .2634 |
|               | (2.28)** (1.49) | (1.46) | (− 1.03) (− 1.23)** |
| Cluster M     | .0936 .0896 .1032 | .0073 − .0002 .0123 | .1578 − .0144 .3786 |
|               | (5.96)*** (4.03)*** | (1.03) | (− 3.25)*** |
| Cluster H     | .2216 .0209 .2327 | − .0197 − .0210 − .0154 | .0238 − .0373 .1192 |
|               | (16.07)*** (10.45)*** | (12.04)*** | (− 3.25)*** |
| N             | 6360 3180 3180  | 3923 1844 2079  | 2686 1456 1230  |
| Log likelihood| − 4063.1497 − 2066.7571 − 1984.8934 | − 443.4864 − 175.9878 − 261.9934 | − 1732.9547 − 948.2938 − 746.4859 |
| Pseudo $R^2$  | .0524 .0520 .0507 | .0407 .0687 .0362 | .0655 .0535 .1232 |
| predicted prob.| .6038 .5653 .6415 | .9793 .9850 .9759 | .4594 .4465 .4797 |
| Goodness      | .6415 .6185 .6716 | .9747 .9788 .9711 | .6332 .6401 .6894 |

The measure of goodness is based on the $2 \times 2$ hits and misses table. The threshold probability is 0.5. Within parenthesis are the pseudo t values of estimators: ***,**,* denote 1, 5 and 10% significance levels, respectively.
B Appendix 2: Instructions to subjects (translated from Spanish)

You are going to participate in an experimental session that will give you the possibility to earn some money in cash. How much money you will ultimately take will depend on luck and your and others’ decisions. Please switch off your mobile phone and leave your things to one side. For your participation in the session you need just the instructions and the computer on your desk. Please raise your hand if you have any questions, and one of us will see to it privately.

In this experiment, you will be paired with another participant, who will not change throughout the session. None of you will know the identity of the other throughout the session. A pair is composed of two types of participants: ‘Type 1’ and ‘Type 2’. At the beginning of the session, the computer will randomly assign you one of the two roles and display it on your screen. The experiment is divided into two parts of 55 rounds each. Both parts are identical. At the beginning of each part, the computer will randomly determine, for every round, a value that may be either 0 or 1. This zero/one 55-sequence will be called ‘Prize’. In each round, the probability that the action of the Prize is associated to 0 or to 1 is exactly the same: 50% (it is like tossing a coin). The value of Prize will be determinant for your earnings in every round, according to the rules that follow.

Each round, your decision making consists in choosing either 0 or 1. In each pair, the two participants simultaneously choose either 0 or 1 taking into account that:

– If the decisions of both participants coincide with that of the Prize, they both get 1 ECU each in that round.
– If at least one decision within the pair does not coincide with that of the Prize, then both get nothing in that round.

At the beginning of each part, you will have 3 min to communicate with your partner through a chat. You may end the chat at any time before the end of minute 3 by clicking on the option ‘Exit from the chat’. Every message sent through the chat will be recorded and carefully analyzed by the experimenters. At the end of each round, your screen will display information concerning the value of the ‘Prize’ (0 or 1), the decision of your partner (0 or 1) and your own decision in that round.

To be ‘Type 1’ or ‘Type 2’ has consequences:

– If you are ‘Type 1’, at the beginning of each 55-rounds part, and after using the chat to communicate with your partner, you will be aware of the 55-rounds sequence of values of the Prize that corresponds to that part of the session. You will be the only one to know the Prize.
– If you are ‘Type 2’, you will be aware of the value of each action of the Prize once both participants have decided, that is, at the end of each round.

Moreover, ‘Type 2’ knows that just ‘Type 1’ will be aware of the Prize sequences for each Play just after the 3-min chat. Also, Type 1 knows that Type 2 will be aware of Prize’s and Type 1’s actions at the end of each round, immediately after the decision of the two participants.

Earnings

At the end of each part of the experimental session, the number of winning rounds will be revealed to the participants. At the end of the session, you will be paid in cash.
your total payoff, that is, the total number of rounds, considering the two parts, in which you won 1 ECU. The exchange rate between ECUs and Euros is 1 ECU = 1/4 Euro.

C Appendix 3: Teamwork Test (TwT)

The 25 questions chosen from the general TwT are presented below. The answer to each question was categorical so that the subject had to choose among these 4 possibilities: “Always”, “Sometimes”, “Occasionally”, “Rarely”. Within parenthesis we specify the category to which each question belongs.

Q1. Do others think you are trustworthy? (Trust)
Q2. Do you generally believe what an authority tells you? (Trust)
Q3. Do you mind waiting for others to finish their work? (Patience)
Q4. Do you tell people that you have been waiting for them for a long time? (Patience)
Q5. Do you find yourself interrupting others? (Respect)
Q6. Do you give another person your full attention when speaking with him or her? (Respect)
Q7. Do you consider it disrespectful to ignore another person? (Respect)
Q8. Do you take on whatever task given to you without complaint? (Cooperation)
Q9. Are people often telling you that you cause problems? (Cooperation)
Q10. Is your idea of cooperation telling people what to do? (Cooperation)
Q11. Do you share your space and possessions? (Cooperation)
Q12. Would you rather voice your opinion via email than in person? (Interaction)
Q13. Do your like to be the leader in a group project? (Control)
Q14. Are you frustrated if someone else has power over you? (Control)
Q15. Do you get upset when things dont go as you planned them? (Control)
Q16. Do you easily persuade people to believe you? (Persuasion)
Q17. Do you grab all the acclaim for group success? (Responsibility)
Q18. Do you consider yourself a perfectionist? (Perseverance)
Q19. Can you easily admit if you are wrong in a situation? (Perseverance)
Q20. Can you move on from disappointments quickly? (Perseverance)
Q21. Do you usually achieve your goals? (Determination)
Q22. Do you drop out of projects, programs, or groups? (Determination)
Q23. Are you understanding when unexpected problems arise? (Understanding)
Q24. Can you sit and read a book for longer than 30 min? (Listening)
Q25. Have people often told you that you are a good listener? (Listening)

References

Agastya M, Bag PK, Chakraborty I (2014) Communication and authority with a partially informed expert. RAND J Econ 45(1):176–197
Agastya M, Bag PK, Chakraborty I (2015) Proximate preferences and almost full revelation in the Crawford–Sobel game. Econ Theory Bull 3(2):201–212
Allon G, Bassamboo A (2011) Buying from the babbling retailer? The impact of availability information on customer behaviour. Manag Sci 57(4):713–726
Allon G, Bassamboo A, Gurvich I (2011) “We will be right with you”: managing customer expectations with vague promises and cheap talk. Oper Res 59(6):1382–1394
Blume A, Ortmann A (2007) The effects of costless pre-play communication: experimental evidence from games with Pareto-ranked equilibria. J Econ Theory 132:274–290
Charness G, Grosskopf B (2004) What makes cheap talk effective? Experimental evidence. Econ Lett 83(3):383–389
Crawford V, Sobel J (1982) Strategic information transmission. Econometrica 50(6):1431–1451
Crawford V (1998) A survey of experiments on communication via cheap talk. J Econ Theory 78:286–298
Devetag G, Ortmann A (2007) When and why? A critical survey on coordination failure in the laboratory. Exp Econ 10(3):331–344. https://doi.org/10.1007/s10683-007-9178-9
Duffy S, Hartwig T, Smith J (2014) Costly and discrete communication: an experimental investigation. Theory Decis 76(3):395–417
Farrell J, Rabin M (1996) Cheap talk. J Econ Perspect 10(3):103–118
Gilligan TW, Krehbiel K (1989) Asymmetric information and legislative rules with a heterogeneous committee. Am J Polit Sci 33:459–490
Gossner O, Hernández P, Neyman A (2003) Online matching pennies. Discussion paper 316, The Hebrew University of Jerusalem
Gossner O, Hernández P, Neyman A (2006) Optimal use of communication resources. Econometrica 74(6):1603–1636
Grossman SJ (1981) The informational role of warranties and private disclosure about product quality. J Law Econ 24(3):461–483
Hertel J, Smith J (2013) Not so cheap talk: costly and discrete communication. Theory Decis 75(2):267–291
Kartik N (2005) Information transmission with almost-cheap talk. Technical report. www.najecon.org
Krishna V, Morgan J (2001) Asymmetric information and legislative rules: some amendments. Am Polit Sci Rev 95(2):435–452
Milgrom PR (1981) Rational expectations, information acquisition, and competitive bidding. Econometrica 49(4):921–943
Shane F (2005) Cognitive reflection and decision making. J Econ Perspect 19(4):2542. https://doi.org/10.1257/089533005775196732
Sobel J (2010) Giving and receiving advise. In: Presented at the econometric society 10th world congress. Mimeo, University of California San Diego
Sobel J (2012) Complexity versus conflict in communication. In: 46th annual conference on information sciences and systems (CISS). IEEE, pp 1–6
Watson J (1996) Information transmission when the informed party is confused. Games Econ Behav 12(1):143–161