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The role of public and private information in a laboratory financial market^{*}

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Abstract

The main advantages of a laboratory financial market with respect to field data are: (i) it allows us a perfect monitoring of the available information to each subject at any moment in time, and (ii) it gives us the possibility of recording subjects' trading activity in the market. In our experimental design the information distribution is endogenous, since the subjects can buy costly private information. Inspired by the debate on the role of rating agencies in the recent financial crisis, additional to the private information we introduce an imperfect public signal. The study of the interplay between public and private information constitutes our contribution to the experimental literature on laboratory financial markets. In particular, in this paper we study the perturbation created by the introduction of a public signal on the information acquisition process and on the price efficiency in transmitting information. We conclude that the public signal might drive the market price if private information is not of good quality, leaving the financial market in "the hands" of the institution which releases the public information.

Keywords: experiments, financial markets, private and public information, rating agencies.

JEL Classification: C92, D82, G14.

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1 Introduction

Financial markets have traditionally been analyzed under the paradigm of the efficient market hypothesis, which states that all relevant information is correctly incorporated into asset prices. Within this framework asset markets are viewed as efficient economic institutions in aggregating private and public information. Nevertheless, only indirect implications of the efficient market hypothesis have been investigated so far (see Shleifer [2000]), since in a real financial market it is impossible to have a full control of the entire information set.

In order to overcome this problem, various experimental studies have attempted to analyze the role of information in laboratory financial markets. In a laboratory financial market, in fact, it is possible to have full control of the information set available to each single trader in each moment, and, additionally, of the entire record of her or his trading activity in the market. We can categorize these experimental studies into two groups¹, on the one hand those studies where information is exogenously given to the traders at no cost. On the other hand, those settings where the information present in the market is endogenous, that is, there exists a market for information that runs parallel to the asset market.

In their seminal paper, Plott and Sunder [1982] study under which conditions perfect information is efficiently incorporated into prices. They address the issue of dissemination of information from a group of fully informed agents (i.e. insiders) to a group of uninformed agents. They conclude that with replication and experience even uninformed traders are able to decipher the true state of the world by simply observing market price.² Plott and Sunder [1988] design a market with three possible dividend states to address the issue of aggregation of diverse pieces of less than perfect (but certain) information owned by different traders. They observe that prices deviate from the rational expectations equilibrium in those markets where traders have heterogeneous preferences. On the contrary, they report that markets converge to the rational expectation equilibrium when traders have homogeneous preferences, since it is easier for them to infer information from the other traders' actions. The review of different experimental studies on information aggregation and dissemination in a setting where (im)perfect information is distributed at no cost suggests that aggregation depends crucially on market features such as common

¹See Plott [2002] and Sunder [1995] for a thoughtful survey on experimental asset markets.

²Watts [1993] replicates the Plott and Sunder's experiments where the presence of insiders is random, finding that the price convergence to the rational expectations equilibrium worsens.

knowledge, information distribution, experience of subjects, etc.³

One important finding is that, even under the best circumstances, information aggregation and/or dissemination (when occurs) is not instantaneous, since the traders need some time to observe the market activity, form conjectures, test them and modify their strategies. Therefore, there is an incentive for costly information creation due to the noisy revelation of information in asset markets (see Grossman and Stiglitz [1980]). Sunder [1992] is the first to study experimentally such problem in connection with the revelation of information in an asset market through prices using two different settings. In a first setting, the price of information is endogenous whereas the number of perfectly informed traders is fixed (i.e. a given number of perfect signal where auctioned off). In a second experimental setting, the price of information is fixed, whereas the number of informed traders is endogenous (and not known by traders). In the first setting, the main finding is that the price of information decreases as traders learn how to extract information from the price observed in the market. In the case of a fixed price for information, the number of informed traders varies among markets, since subjects suffer a sort of coordination problem. When many traders buy information, the price converges quite fast to the rational expectations equilibrium and it is difficult for the informed traders to recover their investment. When only few traders are informed, the markets slow convergence to the equilibrium price allows the informed traders to gain higher profits. A series of experimental studies using different settings inspired by Sunder [1992] conclude that when the distribution of (perfectly) informed traders is not common knowledge in the market, it is harder for the prices to reveal information.⁴ However, in all the previous experiments informed subjects are *insiders*, since the information received is always perfect or certain. Within this framework Hey and Morone [2004] develop a very simple experimental setting where heterogeneous and imperfectly informed agents have to trade a risky asset whose dividend depends on two equiprobable states of the world. In their setting, each trader can buy, at any moment during the trading period, as many signals as (s)he wants. Their results suggest that the aggregation process improves when the quality and quantity of information in the market are higher. Alfarano et al. [2006] add a further element of complexity to the existent literature on asymmetric information introducing an information market where the traders can buy, at a fixed price, an imperfect prediction of the future value of the dividend of a long-lived asset with a certain anticipation. The information is

³See Sunder [1995] for an detailed survey on this issue.

⁴See Copeland and Friedman [1991, 1992] or Camerer and Weigelt [1991], among others and Sunder [1995] for a review.

noisy with decreasing precision when the time horizon increases, and heterogeneous, since every trader gets an idiosyncratic signal. In this more realistic setting, they observe that the quantity of acquired information is rather homogeneous across the periods and the traders prefer short-term rather than long-term information. However, the experimental assets markets is not efficient in transmitting information, as transaction prices are often far away from the fundamental value of the asset.

In general, the experimental literature focuses on the problem of the market efficiency in aggregating private information into prices. An interesting issue, that has not been experimentally investigated so far, is the role of rating agencies or, in general, a public signal in financial markets. There are only few theoretical contributions while several papers have addressed empirically the market impact of the rating agencies. Among the former contributions, Millon and Thakor [1985] demonstrate that information gathering agencies may arise in a world of informational asymmetries and moral hazard. According to them, in a setting in which true firm values are certified by screening agents whose pay-offs depend on noisy ex-post monitors of information quality, the formation of information gathering agencies is justified because it: (i) enables screening agents to diversify their risky payoffs, and (ii) allows for information sharing. However, Millon and Thakor [1985] assume perfect knowledge by the information gathering agency about the underlying risk of the borrower.

Still on theoretical grounds, referring to a multiple equilibria set up, Boot et al. [2006] show that the rating is a coordinating mechanism, providing a “focal point” for firms and investors. However, Carlson and Hale [2006] reach opposite conclusions. They build a game theoretic model of rating agencies in which heterogeneous investors act strategically and predicts that introducing a rating agency to a market that otherwise would have the unique equilibrium, can bring about multiple equilibria.

The aim of our paper is to study whether the presence of public information (e.g. information provided by a rating agency) can endorse the aggregation process of private information. The research question of our paper is to verify the role of public information in an experimental financial market. Does subjects buy less private information if they have access to public information? Does the public information play a role in the aggregation of available information into prices? If yes, is it detrimental or beneficial for market efficiency?

2 The Experimental Design

We have a market populated by a given number of agents. At the beginning of each trading period, each agent is endowed with m units of an unspecified asset and M units of experimental currency. The asset pays a dividend d at the end of the trading period. The value of the dividend depends on two equally likely states of the world: H and L . If the state of the world is H the dividend d is equal to 10, whereas in L the dividend d is equal to 0. At the beginning of each trading period the true state of the world is determined by the experimenter, but not revealed to the agents.

However, at any moment within a given trading period the agents can buy private signals paying a cost c per signal. Additionally, only in those treatments with public information subjects have access to a public signal, that has no cost to them and it is common to all agents trading in the market. Such signal is made public at the beginning of each trading period. Both (private and public) signals are partially but not totally informative as to the true state of the world. Public signals are at least as good as the private ones. These signals take either the value 1 or 0, such that the probability of getting a public signal 1 (0) is P if the state of the world is H (L) and the probability of getting a public signal of 1 (0) is $1 - P$ if the state of the world is L (H). This means that, if a subject observes a public signal of 1 (0), subject can infer that the asset dividend at the end of the trading period will be 10 (0) with probability P and 0 (10) with probability $1 - P$. Following the same reasoning regarding the private signal, the probability of getting a private signal 1 (0) is p if the true state of the world is H (L) and the probability of getting a private signal 1 (0) is $1 - p$ if the state of the world is L (H). In this way, if a subject purchases a signal that results to be 1 (0), he can infer that the asset dividend at the end of the trading period is expected to be 10 (0) with probability p and 0 (10) with probability $1 - p$. Both, the value of p and P is known by the subjects. Apart from the dividend paid out at the end of each trading period, assets are worthless at the end of the period.

In most respects this experimental design is similar to Hey and Morone [2004], though it differs in the crucial point that in some treatments subjects receive public information. This is an important element of our experimental design, since it allows us to study whether the presence of public information may act as a sort of disciplining mechanism in the market, promoting the aggregation of noisy information⁵. However, this difference does not change the nature of the solution to the model (see section 4) as agents are

⁵See for more details Ferri and Morone [2008]

informed about the relevant parameters: the positive dividend d , the cost of buying a signal c , and the probabilities P and p .

The different treatments implemented as well as the parameters used are displayed in table 1:

Treatment	p	P
1	0.6	-
2	0.8	-
3	0.6	0.8
4	0.8	0.8

Common to all treatments:
 $M = 1000$, $m = 10$, $c = 4$,
 ‡ of subjects=15,
 ‡ of markets per session=10

Table 1: The experimental design and parameters.

The experiment was programmed using the z-Tree software (Fischbacher [2007]). When the subjects arrived to the laboratory the instructions were distributed and a Power Point presentation, was showed on all subjects' computer screens in order to explain the experimental setting and questions where answered. This was followed by 4 practice periods in which particular subjects were asked to perform particular tasks (make a bid, make an ask, buy, sell, and buy one or more signals). The briefing period lasted some 40 minutes.

Each treatment consisted of 10 independent trading periods lasting 3 minutes each. At the beginning of the trading period the dividend was randomly determined by the experimenter and paid out at the end of the trading period. It was unknown to the agents until the end of the trading period. During each trading period subjects were free both to introduce their bids and asks for assets or directly accept any other trader's outstanding bid or ask. Every bid, ask, or transaction concerned only one asset each time, but every agent could handle so much as desired as long as he had enough cash or assets (no short sale was allowed). Additionally, each subject could purchase as many private signals as he wanted during a given trading period, as long as he had enough cash. At the end of a trading period, dividends were paid out and the subject profit was computed as the difference between their initial money endowment ($M = 1000$) and the money held at the end of the trading period, thus the net profit is computed as: (dividend received per asset hold) + (price received per asset sold) - (price paid per asset bought) - (price paid per private signal purchased in the period).

At the end of each session experimenters calculated the subjects' total earnings in ECUs, as the sum of the profit obtained in each one of the 10 trading periods, and paid

them in cash.⁶ The average payoff was about 20 € and each session lasted around 2 hours.⁷

3 The ‘Do Nothing’ Equilibrium

Let us try in this section to provide for an equilibrium which might help to analyze the experimental data. We can say two things: First, we can think that the price in the market *should* converge to the true value of the dividend if the market correctly aggregates the costly information available to the agents. This is the conclusion that would be reached by the literature starting with Grossman and Stiglitz [1976, 1980] on the aggregation of costly information in market contexts. However, the nature of the theory of that strand of the literature does not provide a description of the process by which the market converges, but rather a theory of the equilibrium state of the price in such a market. If we want to address the issue of the description of the price convergence we could rely on the literature on informational cascades in a non-market context introduced by Banerjee [1992] and Bikhchandani et al. [1992] which inspired our experimental setting.⁸ Even in this case, the theory just partially provides an intuition of what could be a theoretical solution. However, we can identify one possible equilibrium in which no agent does anything. This equilibrium is not affected by the presence or not of any public signal.

3.1 Private information

In absence of public information all subjects at the beginning of the trading period will have the same prior, since each subject will be able to evaluate the uninformed expected value of the asset (i.e. $\frac{d}{2} = 5$). If all except one agent is doing nothing, then it is clearly optimal for the remaining agents to do nothing, and this remaining agent can neither buy nor sell (because no one else is selling or buying) and so can only buy signals. But there is no point in buying signals as no use can be made of the knowledge gained. So doing nothing is one possible symmetric equilibrium.

We now argue that this is the only possible equilibrium in a world populated by risk-neutral agents. To demonstrate this, we begin by noting that the expected per-period payoff for any subject who does nothing must be $\frac{m \cdot d}{2}$ because each subject is endowed

⁶One experimental currency unit is equivalent to 2 cents of euro.

⁷Note that agents can make losses. To avoid some of the problems associated with subjects making real losses in experiments, we endowed all agents with a participation fee of 5 €, which could be used to offset losses.

⁸See Hey and Morone [2004] for more details.

with m units of the asset, each of which is worth either d or 0 with equal probability. Suppose now that some subject buys n signals. Because these signals are costly this subject must be expecting to make at least $\frac{m \cdot d}{2} + n \cdot c$ from trading the asset. Because the game is a constant sum game, this must imply that the remaining subjects must be averaging $\frac{m \cdot d}{2} - \frac{n \cdot c}{(s-1)}$ from trading the asset. As this is less than what they would get doing nothing, it is clearly better for them to do nothing, from which it follows that our first subject can not be making at least $\frac{m \cdot d}{2} + n \cdot c$ from trading the asset. In this case, the purchase of n signals can not be worthwhile and, therefore, such behavior is not an equilibrium. This would suggest that we would see no trade in a model in which all the agents are risk neutral.

3.2 Private and public information

Introducing public information will not affect the *no trade* equilibrium, if all agents have the same beliefs about the future value of the dividend and if all agents are equally risk-averse then we would again observe no trade. In fact if the signal of the rating agency is 1 (0) each subject will be able to evaluate the expected value of the asset under the public information, i.e. $d \cdot p$ ($d \cdot (1 - p)$). If all except one agent is doing nothing, then it is clearly optimal for the remaining agents to do nothing and once again, doing nothing is one possible symmetric equilibrium. Following the same root of reasoning as before we can show that this is the only possible equilibrium in a world populated by risk-neutral agents. The expected per-period payoff for any subject who does nothing must be $m \cdot d \cdot P$ ($m \cdot d \cdot (1 - P)$) when subject is endowed with m units of the asset. If a subject purchases n private signals, since such signals are costly, this subject must be expecting to make at least $m \cdot d \cdot P + n \cdot c$ ($m \cdot d \cdot (1 - P) + n \cdot c$) from trading the asset. Because the game is a constant sum game, this must imply that the remaining subjects must be averaging $m \cdot d \cdot P - \frac{n \cdot c}{(s-1)}$ ($m \cdot d \cdot (1 - P) - \frac{n \cdot c}{(s-1)}$) from trading the asset. As this is less than what they would get doing nothing, it is clearly better for them to do nothing, and then for our first subject it is not worthwhile to purchase any signal. This would suggest that we would see no trade in a model in which all the agents are risk neutral.

3.3 Heterogenous beliefs

However, if different agents have different beliefs or different attitudes to risk then some trade may be possible. Consider, for example, a situation in which individual A owns a unit of the asset and is more risk-averse than individual B . Suppose they have the same

beliefs and that the probability is that the dividend will be d . Then A would be happy to sell his or her unit at any price bigger than the P which satisfies the expression:

$$u(P) = \pi \cdot u(d) + (1 - \pi) \cdot u(0)$$

where $u(\cdot)$ is A 's utility function, expressed relative to his present wealth and π is the subject's belief about the true value of the dividend, whereas B would be happy to buy this unit of the asset at any price less than the $(1 - P)$ which satisfies the expression:

$$v(0) = \pi v(d - [1 - P]) + (1 - \pi)v(-[1 - P])$$

where $v(\cdot)$ is B 's utility function, expressed relative to his present wealth.

In general, we should be able to find a price which satisfies these two conditions if B is less risk-averse than A . Thus, if agents have the same beliefs but different attitudes to risk, some trade may be possible. The converse situation, in which agents have different beliefs but the same attitude to risk is somewhat different.

Suppose A and B know that they have the same risk attitude, then if they can find a price at which one wants to buy and the other wants to sell, what can they infer? What they must infer is that they have different beliefs about the probability that the asset is valuable. Let π_A denote A 's probability and π_B denote B 's probability. Then if there exists a price at which A is happy to buy a unit and B is happy to sell a unit it must follow that $\pi_A > \pi_B$; that is, A must be more optimistic than B about the probability that the asset will be valuable. At this point, A must infer from the fact that B wants to sell that $\pi_A > \pi_B$, and B must infer the same from the fact that A wants to buy. If they each assume that the other is rational they may conclude that one or the other or both of them is wrong. But this provides a clue why we might observe trade: everyone thinks that they have better information than the others about what the dividend is going to be. Obviously, this is impossible, but we have already argued that anything other than a *do-nothing* situation can not be an equilibrium in the usual sense used by economists.

We should stress this point: apart from the buying of signals, the game is a constant sum game and there is a total of $\frac{m \cdot s \cdot d}{2}$ given by the experimenter to the n subjects each market period. Apart from the buying of signals, each subject makes on average $\frac{m \cdot d}{2}$ each period. Subjects can guarantee this on average by doing nothing. However, the buying of signals is costly and simply makes the subject average payoff per period less than $\frac{m \cdot d}{2}$. So why would anyone buy signals? And why would anyone else trade with anyone who has bought signals? There seems to be no reason for any activity in our experiment. So where does that leave us? It leaves us with some very simple predictions: First, if we

believe in equilibrium theory in games (which is concerned more with the process than the outcome), then we would expect to see no activity at all. Second, if we believe in the predictions of the Grossman and Stiglitz branch of the literature (which is concerned with outcomes rather than processes), we would expect to see the price converging to the true dividend. But this leaves unanswered the question as to how the market converges. If we believe it converges because everyone thinks that they are better at predicting the true future dividend, then we leave open also the possibility that it converges to the wrong value. But note the paradoxical nature of all of this. If an agent can predict the future value of the asset and can trade on that information (buying at a price less than d when the asset is going to be valuable and selling at a positive price when the asset is going to be worthless) the agent can make a profit. But this must be at some other agent's expense. As all agents know this, why might we observe any trade?

4 Efficient Market Benchmark

Using the Bayesian inference, we can compute the probability that the true state of the world corresponds to the case of the dividend equal to 10 ECU conditioned on the series of signals purchased by all subjects up to an instant of time T , which we denote as $I_T = \{i_1, i_2, \dots, i_t, \dots, i_T\}$. Note that here we do not specify the identity of the subject who purchases the signals but just their sequential order; we refer to I_T as the market information set. The variable i_t takes the value -1 , if it suggests that the dividend is worth 0 ECU, or 1, if it suggests that the dividend is worth 10 ECU. In the following, we omit the currency unit where not necessary.

4.1 Bayesian Inference with private information

The starting formula of the Bayesian inference is:

$$Pr(D = 10|I_T) = \frac{Pr(I_T|D = 10) \cdot Pr(D = 10)}{Pr(I_T)}. \quad (1)$$

$D = 10$ refers to the case of the dividend equal to 10. $Pr(D = 10|I_T)$ is the probability of observing the dividend equal to 10 conditioned on the market information set available at time T . $Pr(D = 10)$ is the prior probability of the event $D = 10$ without information or, equivalently, conditioned on I_0 . $Pr(I_T)$ is the marginal probability (see eq. 5). *Mutatis mutandis*, it is possible to compute the probability that the future state of the world is the dividend equal to 0 ECU, or we can equivalently use the following relation:

$$Pr(D = 0|I_T) = 1 - Pr(D = 10|I_T), \quad (2)$$

since we have just two possible states of the world.

Let us now assign the values to the different terms of eq. (1) as a function of:

- p is the probability that a single private signal is correct;
- $q = 1 - p$ is the probability that a single private signal is incorrect;
- N_T is the number of signals in the information set available up to time T ;
- n_T is the number of 1s and $N_T - n_T$ is the number of -1s in the information set.

Since we compute the probability $Pr(D = 10|I_T)$, the signals -1s and 1s refer to the true state of the world $D = 10$. In other words, the case $i_t = 1$ suggests that the dividend is 10, on the contrary, the case $i_t = -1$ suggests an asset worths zero.

In the following, when not necessary, we will omit the time variable T from the variables n_T and N_T . The first term of eq. (1) is given by:

$$Pr(I_T|D = 10) = p^n \cdot q^{N-n}, \quad (3)$$

which is the probability of observing a given sequence of signals I_T . Given that the two states of the world are, by construction, equiprobable, the prior probability is given by:

$$Pr(D = 10) = Pr(D = 0) = \frac{1}{2}. \quad (4)$$

The marginal probability takes the form:

$$Pr(I_T) = Pr(I_T|D = 10) \cdot Pr(D = 10) + Pr(I_T|D = 0) \cdot Pr(D = 0) = \frac{1}{2}p^n \cdot q^{N-n} + \frac{1}{2}p^{N-n} \cdot q^n. \quad (5)$$

Putting together eqs. (1), (3), (4) and (5), we obtain:

$$Pr(D = 10|I_T) = \frac{p^n \cdot q^{N-n}}{p^n \cdot q^{N-n} + p^{N-n} \cdot q^n} = \frac{1}{1 + \left(\frac{q}{p}\right)^{2n-N}}. \quad (6)$$

The term $2n - N$ is the difference of 1s and -1s signals in I_T . If we define:

$$\eta_T = \sum_{t=1}^T i_t = 2n_T - N_T, \quad (7)$$

as the aggregate net signal available at time T , the previous equation takes the form:

$$Pr(D = 10|I_T) = \left[1 + \left(\frac{q}{p}\right)^{\eta_T}\right]^{-1}, \quad (8)$$

and

$$Pr(D = 0|I_T) = 1 - Pr(D = 10|I_T) = \left[1 + \left(\frac{p}{q}\right)^{\eta_T}\right]^{-1}. \quad (9)$$

According to eq. (8), we can identify several interesting cases:

- If $p = 1$ and therefore $q = 0$, $Pr(D = 10|I_T) = 1$, which is independent of N_T , when not zero. It is the case of fully informative signals.
- If $q = p = 0.5$ then $Pr(D = 10|I_T) = 0.5$. Purchasing signals does not provide any new information compared to the starting condition of equiprobability of the two states of the world.
- If $\eta_T = 0$, i.e. an equal number of 1s and -1s, $Pr(D = 10|I_T) = 0.5$. It is obviously the case at the beginning of the trading when there are no signals in the market, and also might arise by chance during the experiment.

4.2 Bayesian inference with private and public information

The previous Bayesian inference formulas are based on the condition of constant quality of signals, i.e. p is invariant across the signals. We can easily generalize the previous formulas to signals of heterogenous quality. In our experimental setting, in fact, we have several treatments with the contemporaneous presence of private signals of quality p and a single public signal of quality $P \geq p$.⁹ In order to account for the impact of the public signal in the Bayesian inference, let us define as P the probability that the public signal is correct and $Q = 1 - P$, the probability that the public signal is incorrect. The variable S will take the value 1 if the public signal suggests a dividend equal to 10ECU or -1 if it suggests a worthless dividend. Eq. (3) is then modified as follows:

$$Pr(I_T, S = 1|D = 10) = P \cdot [p^n \cdot q^{N-n}] , \quad (10)$$

and

$$Pr(I_T, S = -1|D = 10) = Q \cdot [p^n \cdot q^{N-n}] . \quad (11)$$

Using eqs. (10) and (11), we can easily modified eq. (8) in order to take into account the public signal:

$$Pr(D = 10|I_T, S) = \left[1 + \left(\frac{Q}{P} \right)^S \left(\frac{q}{p} \right)^{\eta_T} \right]^{-1} . \quad (12)$$

In order to illustrate the previous formula, let us focus on a simple example. Considering the values of $P = 0.8$ and $Q = 0.2$ of our experimental setting, let us assume that there are no private signals in the market up to time T and that the only information is the public signal, which is available at the beginning of the trading period. Therefore, $\eta_T = \eta_0 = 0$ and $Pr(D = 10|I_T, S = 1) = 0.8$ or $Pr(D = 10|I_T, S = -1) = 0.2$

⁹The quality of a signal is defined according to the probability of being correct.

depending on the value suggested by the public signal. Therefore, the subjects at the beginning of the trading period are not ignorant about the future state of the world, i.e. $Pr(D = 10) = Pr(D = 0) = 0.5$, but they are biased in favor of one of them, induced by the presence of the public signal.

As a further illustrative example of eq. (12), in Figure 1(b) we plot the probability of observing a dividend $D = 10$ as a function of the net information η_T present in the market at time T , for different qualities of the private signals¹⁰. Additionally, we can observe the influence of a correct or incorrect public signal. A high and positive net signal is in favor of a higher chance of observing a positive final dividend, conversely, a negative net signal indicates a higher chance of a worthless final dividend. We can, then, note that in the case of a quality of the signal $p = 0.6$, it is necessary a net signal $\eta_T \geq +12$ in order to be almost certain (with a confidence level of 1%) to have a dividend equal to 10ECU. A net signal $\eta_T \leq -12$ indicates with almost certainty a dividend 0ECU. The presence of a correct (incorrect) public signal creates a bias towards one or the other case, or, equivalently, it decreases (increases) the critical net signal in order to identify with almost certainty the final dividend. In the case of a higher quality of the signal, it is drastically reduced the value of the net signals necessary to reasonably identify the final dividend.

4.3 Efficient market price

A market is efficient if all available and relevant information is incorporated into the price of the asset at each instant of time. In our simple experimental setting, it means that the the information set includes all information purchased by the traders, I_T . The equilibrium price, under risk neutrality assumption, is given by:

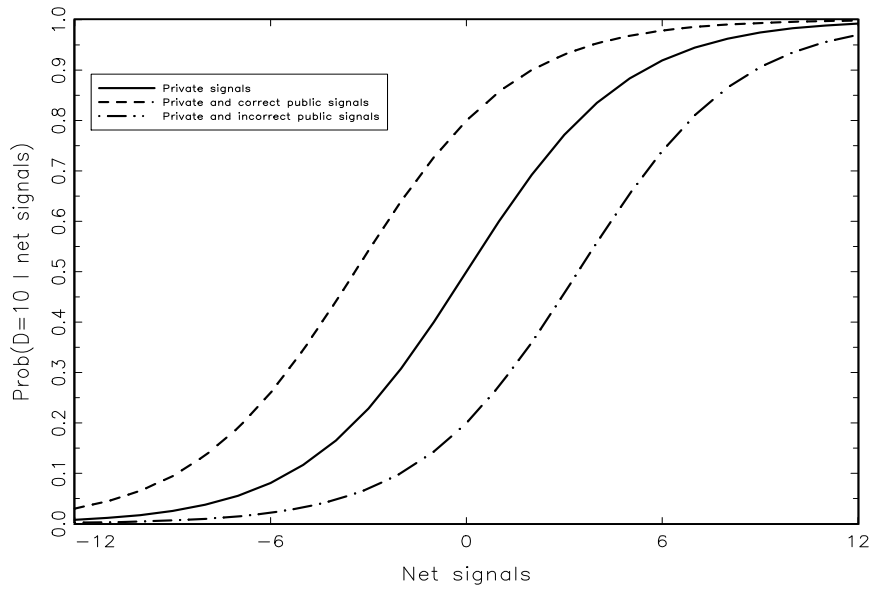
$$\text{price} = 10 \cdot Pr(D = 10|I_T) + 0 \cdot Pr(D = 0|I_T) = 10 \left[1 + \left(\frac{q}{p} \right)^{\eta_T} \right]^{-1}. \quad (13)$$

In the presence of a public signal S , the previous formula is:

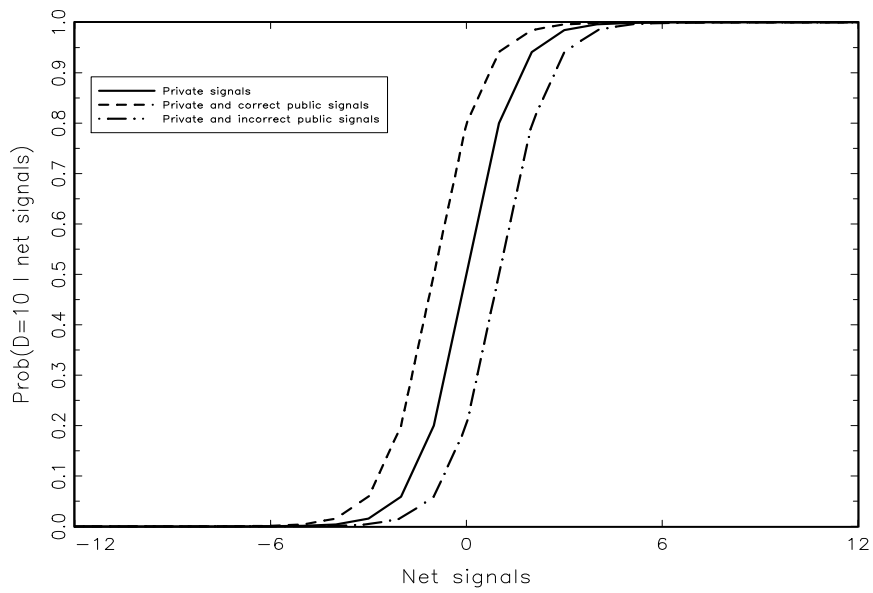
$$\text{price} = 10 \cdot Pr(D = 10|I_T, S) + 0 \cdot Pr(D = 0|I_T, S) = 10 \left[1 + \left(\frac{Q}{P} \right)^S \left(\frac{q}{p} \right)^{\eta_T} \right]^{-1}. \quad (14)$$

The net signal in the market can be thought as $\eta_T = \sum_{n=1}^N \eta_{n,T}$, i.e. the sum of the net signals over all subjects. The previous formula means that if a subject buys a signal, the information is incorporated into the price correctly and instantaneously as if the market information would be available to all subjects.

¹⁰Without loss of generality, we might draw the graph in the case $D = 0$.



(a) Low quality of the private signal ($p=0.6$)



(b) High quality of the private signal ($p=0.8$)

Figure 1: Probability of observing a future dividend $D = 10$ as a function of the aggregate net private signal. The three curves refer to the case of correct, absence or incorrect public signal, respectively.

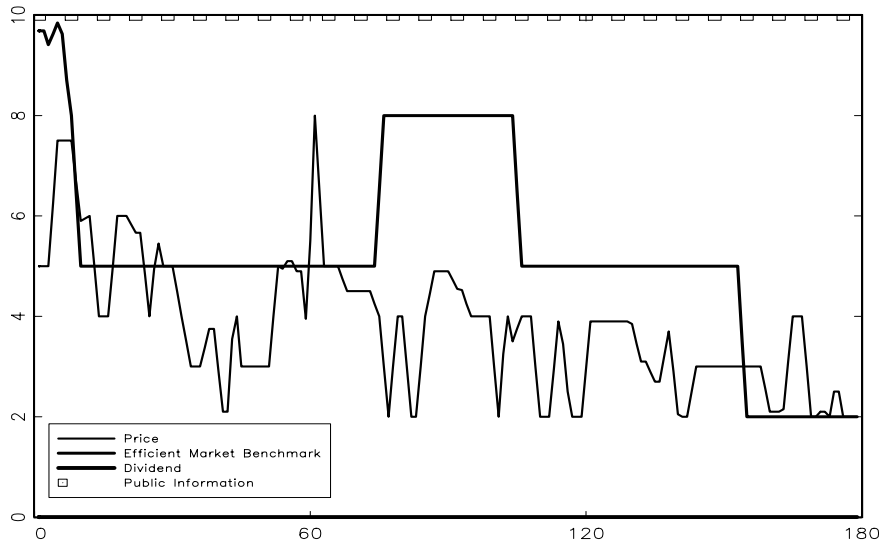


Figure 2: The figure shows the graph of T4M9 as an illustrative example.

5 Results

Probably the easiest way to summarize the results of our experiments is to show graphs of the trading activity in each of the 10 markets of each of the 4 treatments. These are presented in Figures from 8 through 13 included in the Appendix. Each panel of these figures refers to one particular market. An example is reported in Figure 2, where we displayed the 9th market of Treatment 4 (i.e. T4M9). On each panel the vertical axis shows the price at which the trade took place and the horizontal axis shows the time at which the trade took place. The small solid line is the trading price, the bold solid line (either 10 or 0) above each market period shows the actual true dividend (revealed to the participants just at the end of the trading period). The bold and less erratic line indicates the price computed using eq. (13) or, when the public signal is available, eq. (14), which we denote as Bayesian price. The squares indicate the public signal (either around 10 or 0), which is available to the subjects before the trading session starts. Note that there are some cases where the Bayesian price and the bold line of the dividend coincide.

A simple inspection of these figures shows that there is a lot of activity. The subjects buy information, post bids and asks (which, however, are not visible in the Figures), and trade. The “do nothing” equilibrium seems to be not a meaningful description of the trading behavior of the subjects in any of the considered treatments. In order to analyze the market dynamics, we will focus attention on two aspects of the experiment: the information acquisition and aggregation of information into market prices.

5.1 Analysis of the Market for Information

A crucial aspect of our experimental design is that the quantity of information available in the market is endogenous. We can therefore analyze whether or under which conditions the traders could discover the true state of the world. At this point we will focus attention on the private information quality, the availability of public information and the information quantity, which are the relevant characteristics in the analysis of the information acquisition process.

5.1.1 Private Information Quality

As a first step we analyze the number of private signals as a function of its quality and the presence of a public signal. Figure 3 shows the distribution of the private signals purchased across treatments. We observe that the number of purchased signals is *significantly* higher in Treatment 2 ($p = 0.8$) as compared to Treatment 1 ($p = 0.6$).¹¹ When we introduce a public signal, this pattern is confirmed as shown in Figure 3 when comparing Treatments 3 ($P = 0.8, p = 0.6$) and 4 ($P = 0.8, p = 0.8$).¹² We can conclude that:

Result 1: *Subjects purchase more signals the higher their quality.*

5.1.2 The Availability of Public Information

Another interesting finding is related to the impact of a public signal on the number of purchased signals. Fixing the quality of the private signal, the introduction of a public signal *significantly* reduces the number of private signals purchased by traders. This phenomenon is observed when comparing Treatment 1 (Treatment 2) to Treatment 3 (Treatment 4) in Figure 3. Therefore, we can infer that the presence of a public information has a sort of *crowding-out* effect on the acquisition of private signals, i.e. a substitution of part of market information provided by several private signals with a single public signal. The crowding-out effect might be considered quite a natural consequence of the introduction of a *public* information. We can summarize our findings as follows:

Result 2: *The access to public information reduces the quantity of private information in the market: the crowding-out effect.*

¹¹A Mann-Whitney test rejects the null hypothesis at a 1% significance level.

¹²A Mann-Whitney test rejects the null hypothesis at a 1% significance level.

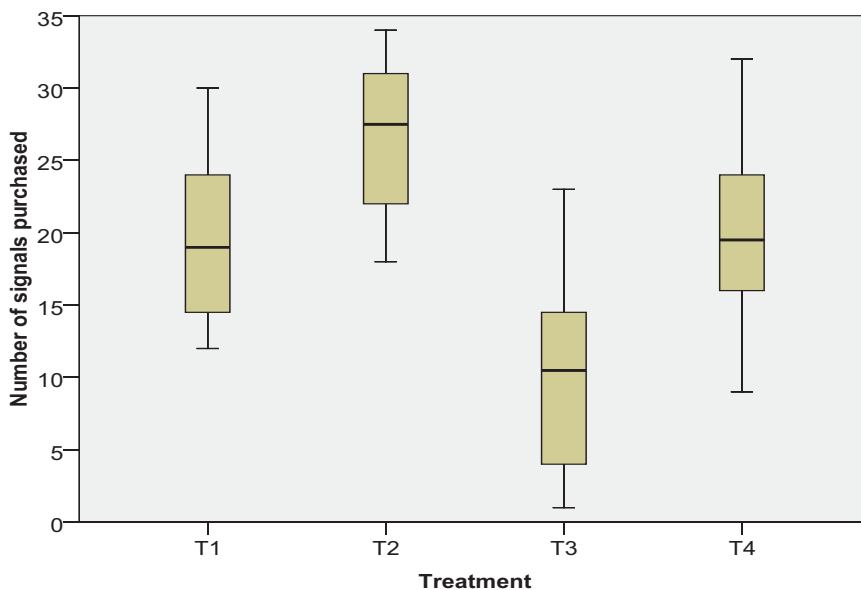


Figure 3: Number of private signals purchased per treatment.

However, it remains an open question whether the presence of a public signal compensates for the missing information due to the decrease of the number of private signals in the aggregation of the market information. In other words, is the introduction of a public information neutral, beneficial or detrimental for the overall information acquisition process? In order to address this question let us quantify how close the traders were to discover the true value of the dividend. We rely then on eqs. (13) or (14) which depend on the information set I_T being efficiently used. The efficient market hypothesis is based on the idea that the traders make an optimal use of the available information, which might probably be a strong (behavioral) assumption. However, such an assumption allows us not to consider any *ad hoc* behavioral rules in describing the trading activity of the subjects. Moreover, the efficient market benchmark can be thought as the upper bound of the efficiency in the utilization of the market information. Taking into account all this, let us introduce the following measure of information efficiency of a market:

$$E_{BD} = \frac{1}{60} \sum_{t=120}^{180} \frac{|B_t - D|}{10}, \quad (15)$$

where B_t is the Bayesian price given in eq. (14), D is the dividend and t denotes the seconds in a trading period.¹³

¹³The choice of averaging over the last trading minute is a compromise between having good statistics for

Using eq. (15) we can evaluate whether the introduction of a public signal is beneficial for the overall information efficiency, that is, whether the introduction of the public signal compensates for the missing private signals due to the crowding-out effect.¹⁴ This means that the introduction of a public signal does not alter the distribution of the information efficiency in the markets, and therefore the market potential to discover the true value of the dividend. We can conclude that the presence of public signal entirely compensates for the crowding-out effect, i.e. the additional information that it provides is sufficient to counterbalance the reduction of private information present in the market, under the assumption of an efficient utilization of the information.

Result 3: *The crowding-out effect due to the public information does not reduce the information efficiency in the markets: the impact of the public information turns out to be neutral.*

5.1.3 The Quantity of Private Information

Up to now we have compared the information available to the traders across the treatments, namely, the effect of the private signal quality and the introduction of a public signal. Now we would like to evaluate whether the information present in the markets is sufficient to discover the true value of the dividend. Since the private information is costly, to buy more or less signals than the necessary level makes the information acquisition process inefficient. Then it comes the question: Are the traders optimally, under or over informed?

In order to evaluate whether the information I_T is sufficient to discover the true dividend value, we have to set a confidence level to the information efficiency measure introduced in eq. (15). In principle, setting a threshold value on eq. (15), we can compute the minimum net private signal (η_T in eq. (7)) sufficient to discover the true dividend value for a given confidence level. The net private signal is defined as the number of correct private signals minus the number of incorrect private signals conditioned on the true divi-

E_{BD} and analyzing the last part of the trading activity, where the number of purchased private signals is very low (between zero and few signals depending on the market) and therefore the Bayesian price is almost constant over time. The results are robust with respect to the considered time interval for the average if one chooses around one minute or less.

¹⁴A Kolmogorov-Smirnov test cannot reject the null hypothesis that the distribution of E_{BD} is the same in T1 (T2) when compared to T3 (T4).

dividend¹⁵. In Table 2 we give the minimum values of the net private signal which guarantees aggregation at 1% and 10% confidence levels across the implemented treatments¹⁶. These sort of critical values can be visualized from casual inspection of Figures 1(a) and 1(b).

	Only private signals	Correct public signal	Incorrect public signal
$p = 0.6$	12(6)	8(3)	15(9)
$p = 0.8$	4(2)	3(1)	5(3)

Table 2: Minimum net private signal in order to identify the true dividend value in the different cases of our experimental setting, at 1% (10%) confidence level.

Figure 4 shows the distribution of the net private signal across the four treatments. Let us start with the treatments where just private information is available to the subjects and evaluate the impact of an increase in the quality of the private signals. In the majority of cases¹⁷ the net private signal of Treatment 1 is not sufficient for discovering the true state of the world. From the box plot, in fact, we observe that the median is under the minimum net signal of 6 given a confidence level of 10% (see Table 2). If the quality of the private signal increases, the picture changes dramatically. In Treatment 2 the net private signal is well above the critical threshold (see Table 2), and, in fact, all markets can potentially discover the value of the dividend both at 1% as well as 10% confidence levels. From Table 2 and Figure 4 we conclude that when the quality of information is low, subjects tend to be under-informed, that is, the overall net private signal is not enough to discover the true state of the world. On the contrary, when private information is more precise, subjects are over-informed, that is, the overall net private signal is always more than enough to discover the true value of the dividend.

¹⁵In order to understand the computation, let us give some illustrative examples: the net private signal of market 1 in session 1 of Treatment 1 is +2; the net private signal of market 2 in session 1 of Treatment 1 is +2; the net private signal of market 3 in session 1 of Treatment 1 is -2.

¹⁶We are aware that the chosen confidence levels are quite arbitrary. As a partial justification of our choice, the 1% level is based on the granularity of the prices, i.e. the traders cannot post bids and asks under 1/10ECU. The level of 10% is somehow a less conservative choice and is below the precision of the public signal. Anyhow, we have run a sensitivity analysis to test the robustness of our results with respect to the choice of the confidence levels, showing that the conclusion of our analysis does not change (material upon request).

¹⁷The net private signal is sufficient at the 1% confidence level in 3 out of 20 cases (T1S1M5, T1S1M9 and T1S2M8), while it is sufficient at the 10% threshold in 7 out of 20 cases (T1S1M4, T1S1M5, T1S1M7, T1S1M9, T1S2M7, T1S2M8, T1S2M10). The individual markets can be easily identified in the Figures included in the Appendix.

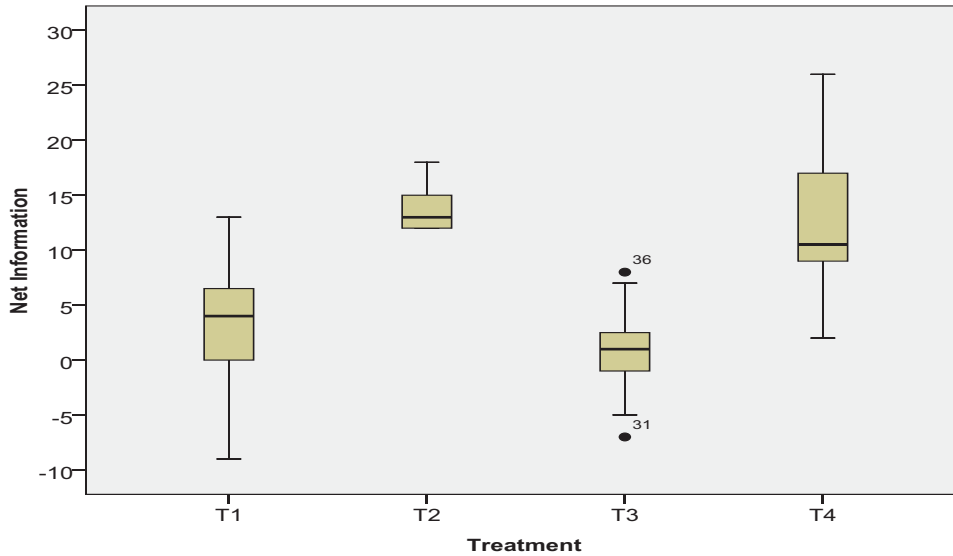


Figure 4: Net private signal per treatment.

Let us consider now the treatments where public information is available. In Treatment 3, in the majority of cases the net private signal is not sufficient for discovering the true state of the world.¹⁸ We can conclude that when the private information has a low quality, whether it is available or not a public signal, the traders are under-informed.

In Treatment 4 the subjects are still over-informed¹⁹ since the net private signal is almost always above the critical level.

Result 4: *The traders are largely under-informed when the quality of the private signal is low and over-informed when the quality is high, independently of the availability of a public information.*

¹⁸The net private signal is never sufficient at the 1% confidence level, while it is sufficient at the 10% confidence level in 2 out of 20 cases (T3S2M2, T3S2M4), basically because the net private signal is 3 or higher and the public signal is correct. The individual markets can be easily identified in the Figures included at the end of the paper.

¹⁹The net private signal is above the minimum required level at both 1% or 10% confidence level in all cases but one (T4M9).

5.2 Analysis of the Price Efficiency

In the previous section we have shown that the introduction of a public signal of good quality compensates the crowding-out effect on the private signals. Our previous analysis, however, is based on the strong assumption of optimal utilization of the information by the experimental subjects and, therefore, using the Bayesian market price as benchmark. In this section, we analyze the convergence of the *market price* to the Bayesian benchmark under different qualities of the costly private information and the introduction a public information. In other words we would like to know what the traders have done as a function on what they could have done. As a measure of market efficiency we use:

$$E_{BPR} = \frac{1}{60} \sum_{t=120}^{180} \frac{|B_t - PR_t|}{10}, \quad (16)$$

where B_t is the Bayesian price given in eq. (14), PR_t is the market price and t denotes the seconds in a trading period (See footnote 13). With this measure we can easily quantify the deviation from what the traders could have achieved using efficiently the available information and what they really do in their trading activity. In order to discriminate whether the market reached efficiency we set a 10% threshold, i.e. $E_{BPR} < 0.1$.²⁰

Let us consider the effect of an increase in the quality of the information on our price efficiency measure. Figure 5 shows the distribution of E_{BPR} across the different treatments. If we compare Treatment 1 to Treatment 2, there is a striking difference in terms of efficiency in the aggregation of the available information into prices, being such difference statistically *significant*. The same pattern is observed when comparing Treatment 3 and Treatment 4. Therefore we can conclude that the treatments where the private signal has a higher quality turn out to be more efficient in incorporating information into prices. If we take into account Result 1, the efficiency of prices in incorporating the information increases with the information available to the traders in the market. Put it differently, increasing information efficiency leads to an increase in price efficiency.

Result 5: *More information available to the traders in the market, either in quantity or quality, increases price efficiency.*

What happens when a public signal is released in the markets? From Figure 5 when comparing Treatment 1 (Treatment 2) to Treatment 3 (Treatment 4) we can see that the

²⁰We could have chosen a more conservative level. However, given the noisy nature of the experimental data, such a level seems to be appropriate, see for example Levitt and List [2007].

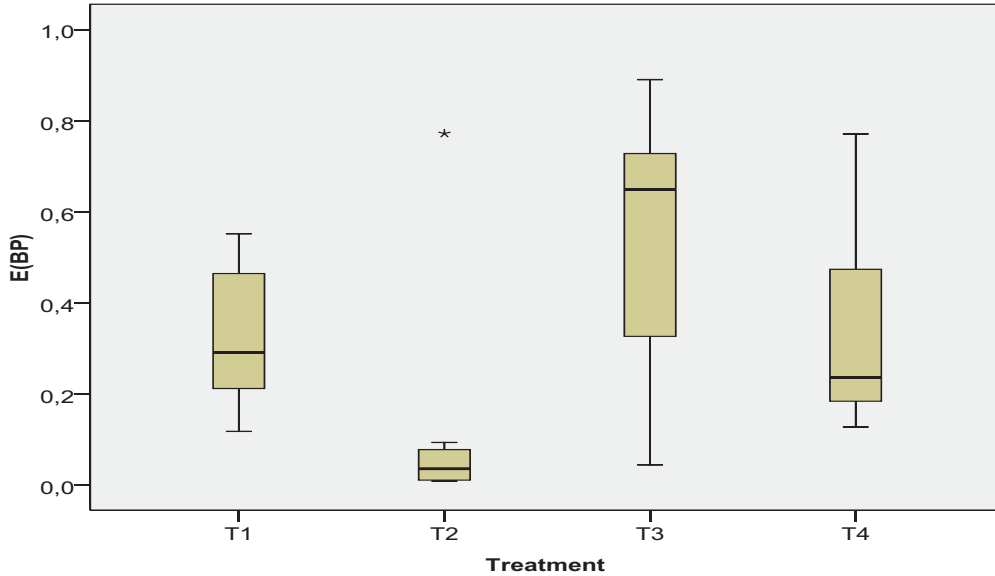


Figure 5: Time average of absolute difference between Bayesian and market price.

introduction of a public signal *significantly* reduces price efficiency²¹, independently of the quality of the private information. Additionally, the public information *significantly* increases the dispersion of the efficiency measure.

From Result 3 we know that the reduction in the number of private signals is compensated by the public signal. This implies that the introduction of the public information does not affect the informational efficiency of the markets. Then, which is the origin of the striking difference across treatments in the market performance when aggregating information into prices? Does the public information play a role in the aggregation of the available information into prices? If yes, which is this role?

In order to visualize the difference between information efficiency and price efficiency in Figure 6, we display the relationship between E_{BD} and E_{DPR} for the different treatments. The lines represent the 10% confidence level. Let us start from Figure 6(b). We can see that in Treatment 2 the high informational efficiency of the markets translates into a high price efficiency, that is, prices do incorporate all the relevant information. In fact, in Treatment 2 all but one markets²² are below the confidence level of 10%. For a better visualization of the price behavior see Figure 10. From Result 3 we know that the

²¹A Mann-Whitney test rejects the null hypothesis at a 1% significance level.

²²In the market T2M2 one subject bought almost all assets, since (s)he had three private signals indicating a dividend 10 ECU. Her/his own Bayesian price was 9.94 ECU. The price then increased up to almost 8 ECU with a true dividend equal to 0 ECU. However (s)he was wrong.

informational efficiency in Treatment 4 is the same as in Treatment 2. However, in Figure 6(b) we observe that the market performance to incorporate information into prices is definitely worst.

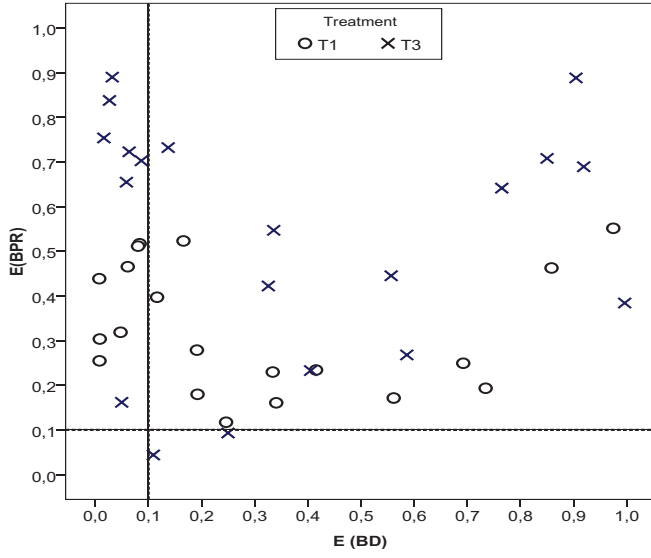
Therefore, we claim that the introduction of a public information is responsible for the worsening in the price efficiency of the markets. Consider that, despite being a high quality signal, i.e. $P = 0.8$, there is a 20% probability that the public signal is *wrong*. If such information constitutes a focal point for the traders, this could lead to a higher deviation of the market price when compared to the Bayesian benchmark, considering that in all markets in Treatment 4, the Bayesian benchmark is close to the true value of the dividend. Our conjecture is in line with an increase in the dispersion of the price efficiency when introducing the public signal in Treatment 2. In fact, Figure 6(b) shows that most of deviations are around 0.2, which confirms our conjecture. In some markets the price efficiency lies between 0.4 and 0.8. These are cases where the public signal is wrong when predicting the true dividend value, but the private information in the market is sufficient for the traders to recognize such mistake and just partially correct for it. Even when the private signals are of a high quality, the traders need some time to discover and (partially) correct the mistakes of the public signal. Extrapolating such a behavior, we might infer that the traders can achieve a much higher price efficiency, probably close to that in Treatment 2. What we would like to stress here is that it seems quite a slow learning process for the traders to decipher the contemporaneous presence of public and private signals and incorporating such information into prices.

When the quality of the private signal is low, from Figure 6(a) we confirm that, although the informational efficiency does not suffer from introducing a public signal (see Result 3), price efficiency is significantly reduced. Figure 7(a) can give us a clearer picture of this phenomenon. Instead of price efficiency we introduce a measure of how close the price is to the true dividend value, i.e. the market efficiency measure:

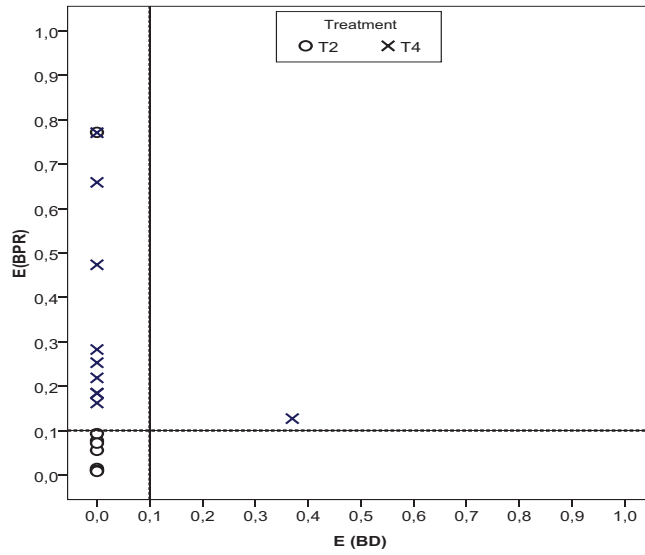
$$E_{DPR} = \frac{1}{60} \sum_{t=120}^{180} \frac{|PR_t - D|}{10}, \quad (17)$$

where PR_t is the market price, D is the dividend and t denotes the seconds in a trading period. From Figure 7(a) we can observe that the market efficiency measure fluctuates either around 0.2 or 0.8 in Treatment 3, whereas in Treatment 1 fluctuates around 0.5. This finding confirms our intuition that traders tend to follow the public signal, which might be wrong. With a low quality private signal it is hard to see whether traders can recognize and correct the mistakes of the public information.

We can summarize our main findings as follows:

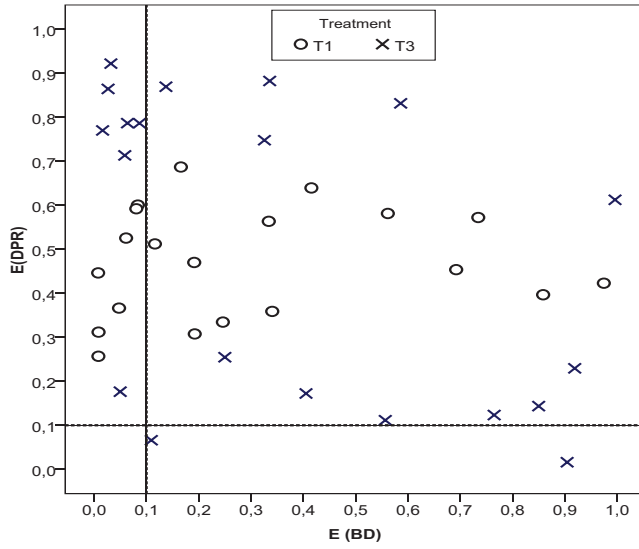


(a) Private signal $p = 0.6$

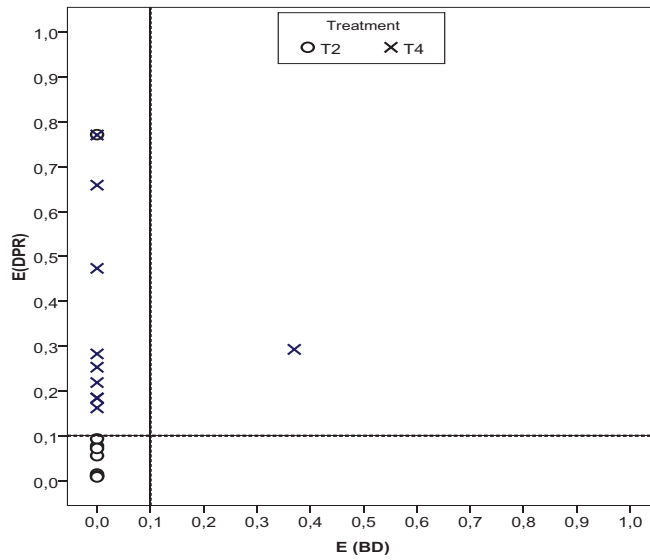


(b) Private signal $p = 0.8$

Figure 6: Price convergence to the Bayesian benchmark.



(a) Private signal $p = 0.6$



(b) Private signal $p = 0.8$

Figure 7: Price convergence to the dividend value.

Result 6: *The introduction of a public signal keeps constant the market efficiency but worsens the price efficiency due to the interplay between private and public information on the mechanism of incorporating information into prices.*

6 Conclusion

Inspired by the debate around the role that rating agencies and, in general, financial market key-players have played into the recent financial turmoil, we have used a laboratory experiments to investigate the role of public and private information in a financial market. We were motivated by the intuition that the introduction of a public information, in a setting where individuals are endowed with the possibility of purchase private information, can discipline the market in promoting the aggregation of subjects' private information into prices.

We have shown a quite natural and well-know result, i.e. the increase of *private information* into the markets favors the efficiency of prices in aggregating information. When introducing a public signal, such trivial picture becomes much more intriguing. The public signal, in fact, strongly perturbs both, the information acquisition process and the mechanism of incorporating information into prices.

Our experimental analysis shows three major results: i) the presence of a public signal creates a crowding-out effect on the private signals; ii) the public information counterbalances the reduced quantity of private information, therefore, leaving invariant the informational efficiency of markets; iii) the presence of a public signal affects negatively the efficiency of prices in incorporating and transmitting information.

As a final conclusion of our experimental test, we observe that if the private information is not of good quality, the public information dominates the market in the sense of driving the price. If this market regime might be beneficial in the case of correct release of public information, the case of an incorrect public signal might lead the market towards a price disconnect to the true fundamentals. Using the words of Taleb [2007], the market is fragile and not robust against the *black swan*, a very rare case that might resalable the recent financial crisis.

Appendix A: Information Purchased per Treatment

Market Session 1	N	n	$N - n$	D
1	15	9	7	10
2	16	7	9	0
3	19	11	8	0
4	27	10	17	0
5	22	17	5	10
6	16	7	9	10
7	14	4	10	0
8	24	14	10	10
9	25	6	19	0
10	19	7	12	0

Market Session 2	N	n	$N - n$	D
1	12	8	4	10
2	14	5	9	10
3	13	7	6	0
4	14	5	9	0
5	17	4	13	10
6	22	13	9	10
7	24	16	8	10
8	24	18	6	10
9	27	13	14	0
10	30	12	18	0

Table 3: Information purchased in Treatment 1.

Market Session 1	N	n	$N - n$	D
1	34	8	26	0
2	33	10	23	0
3	31	8	23	0
4	29	6	23	0
5	29	21	8	10
6	22	5	17	0
7	26	19	7	10
8	23	5	18	0
9	21	3	18	0
10	18	3	15	0

Table 4: Information purchased in Treatment 2.

Market	Session 1	N	n	$N - n$	D	Public signal
1		15	11	4	0	10
2		14	7	7	0	0
3		15	8	7	0	0
4		14	6	8	0	0
5		13	9	4	0	0
6		12	10	2	10	0
7		18	10	8	10	0
8		14	8	6	0	0
9		23	15	8	10	0
10		23	13	10	10	0

Market	Session 2	N	n	$N - n$	D	Public signal
1		2	1	1	10	0
2		3	0	3	0	0
3		9	5	4	10	10
4		4	0	4	0	0
5		8	3	5	0	10
6		5	0	5	10	10
7		6	3	3	0	0
8		1	0	1	0	0
9		3	1	2	10	0
10		4	1	3	0	0

Table 5: Information purchased in Treatment 3.

Market	N	n	$N - n$	D	Public signal
1	9	9	0	10	10
2	25	4	21	0	0
3	20	17	3	10	0
4	23	6	17	0	0
5	16	3	13	0	10
6	19	14	5	10	10
7	24	2	22	0	0
8	32	3	29	0	0
9	18	8	10	0	10
10	12	10	2	10	10

Table 6: Information purchased in Treatment 4.

Appendix B: Market Trading Activity per Treatment

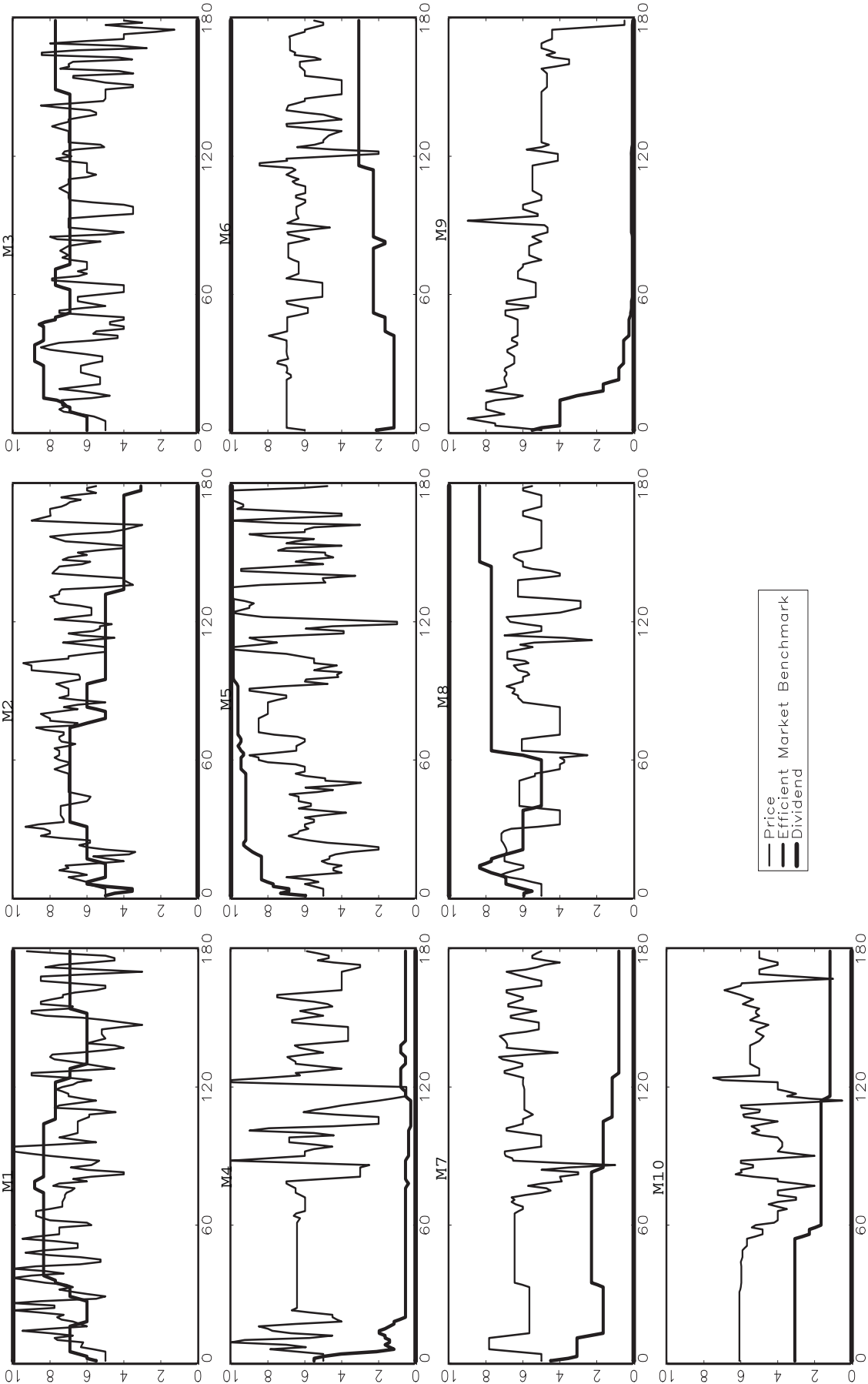


Figure 8: Private signal with $p = 0.6$ (Treatment 1, Session 1).

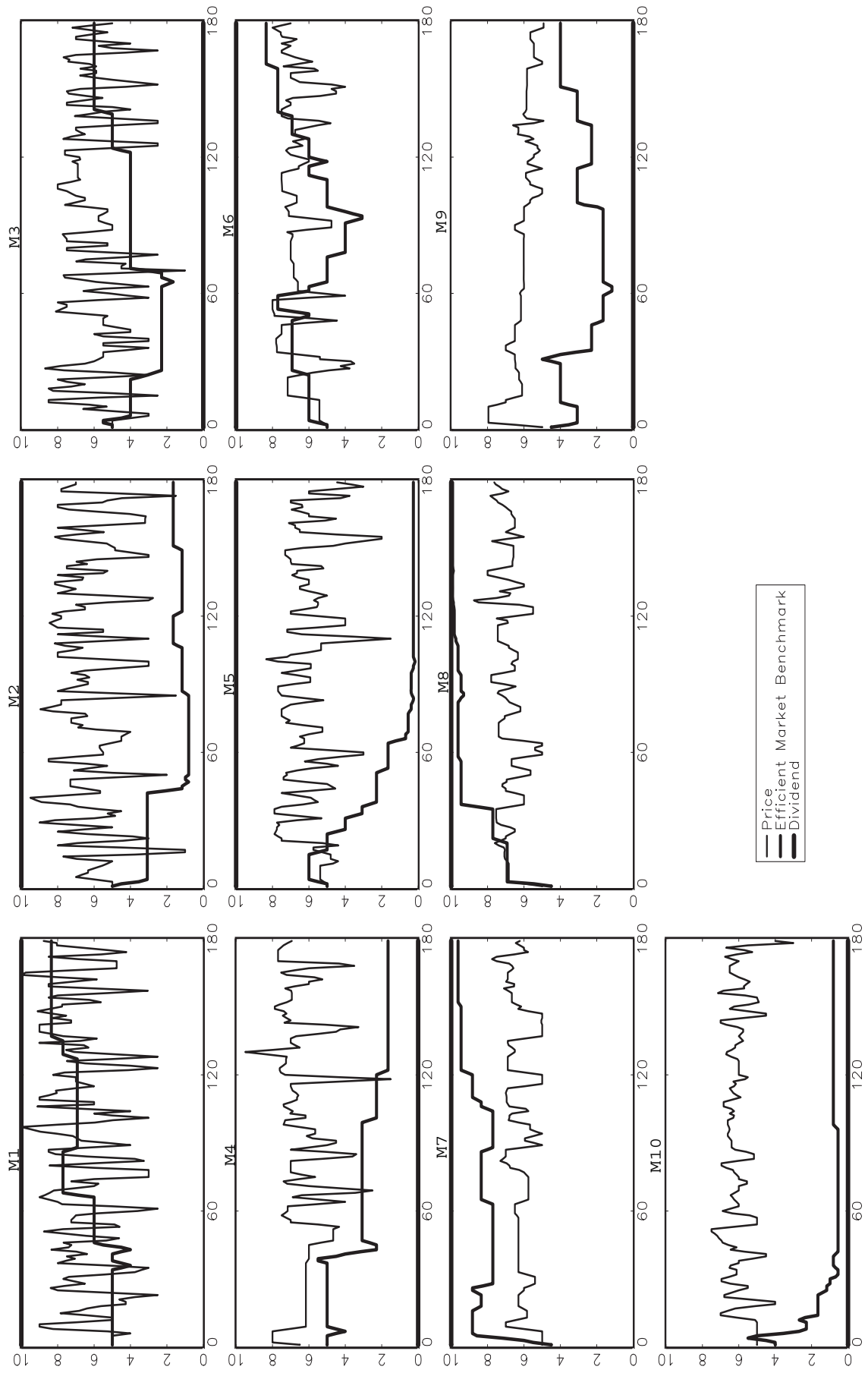


Figure 9: Private signal with $p = 0.6$ (Treatment 1, Session 2).

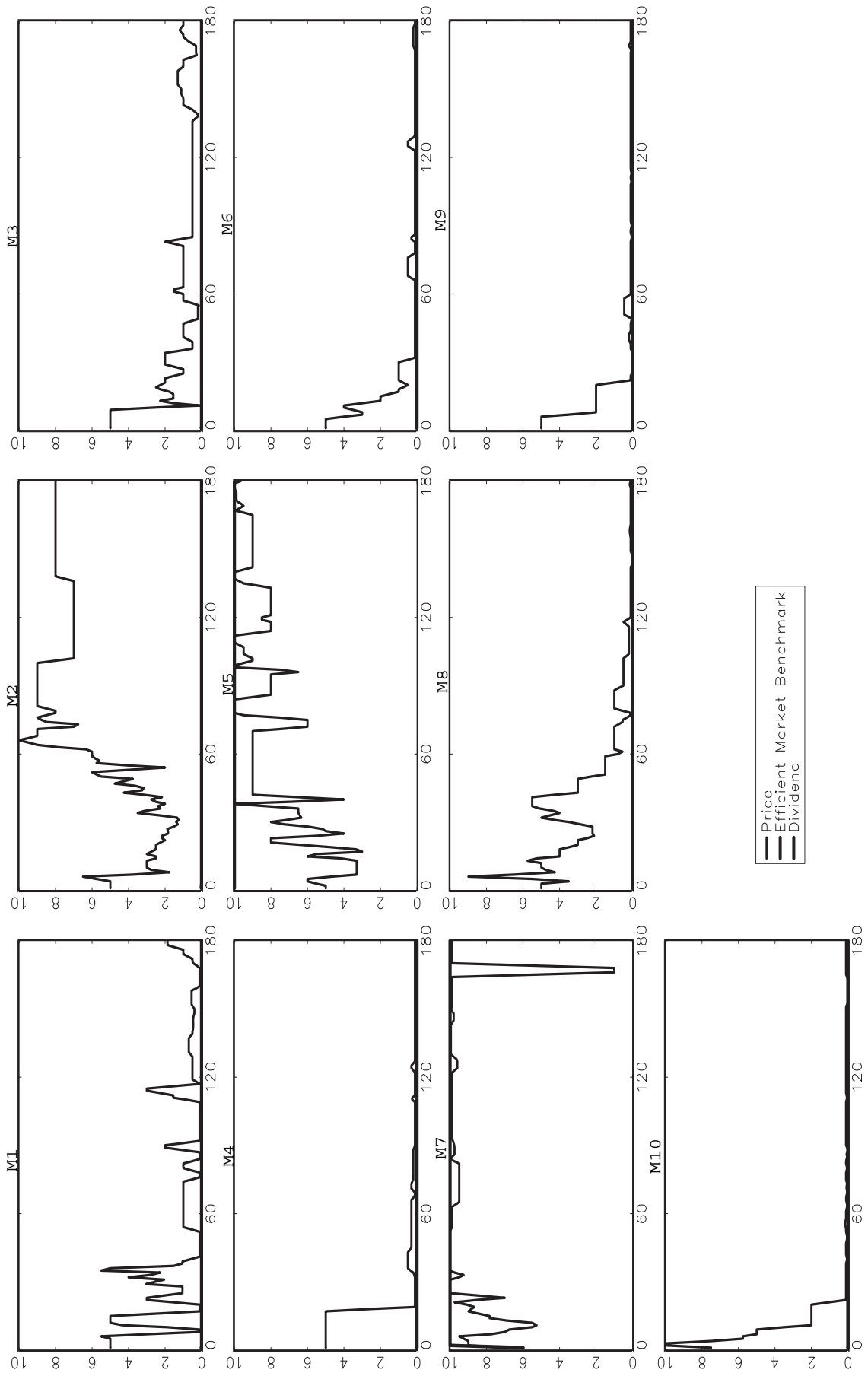


Figure 10: Private signal with $p = 0.8$ (Treatment 2).

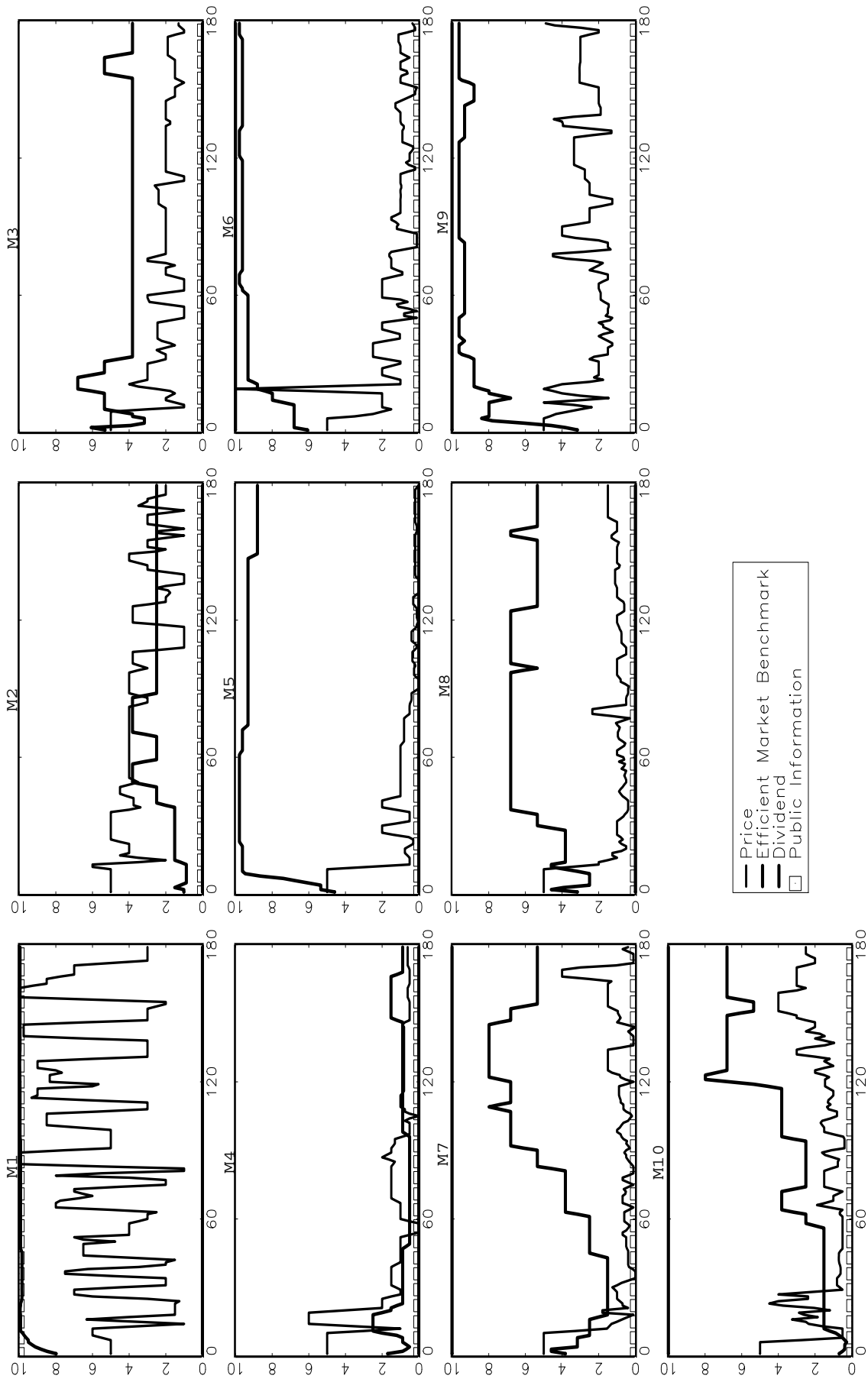


Figure 11: Private signal with $p = 0.6$ and public signal with $P = 0.8$ (Treatment 3, Session 1).

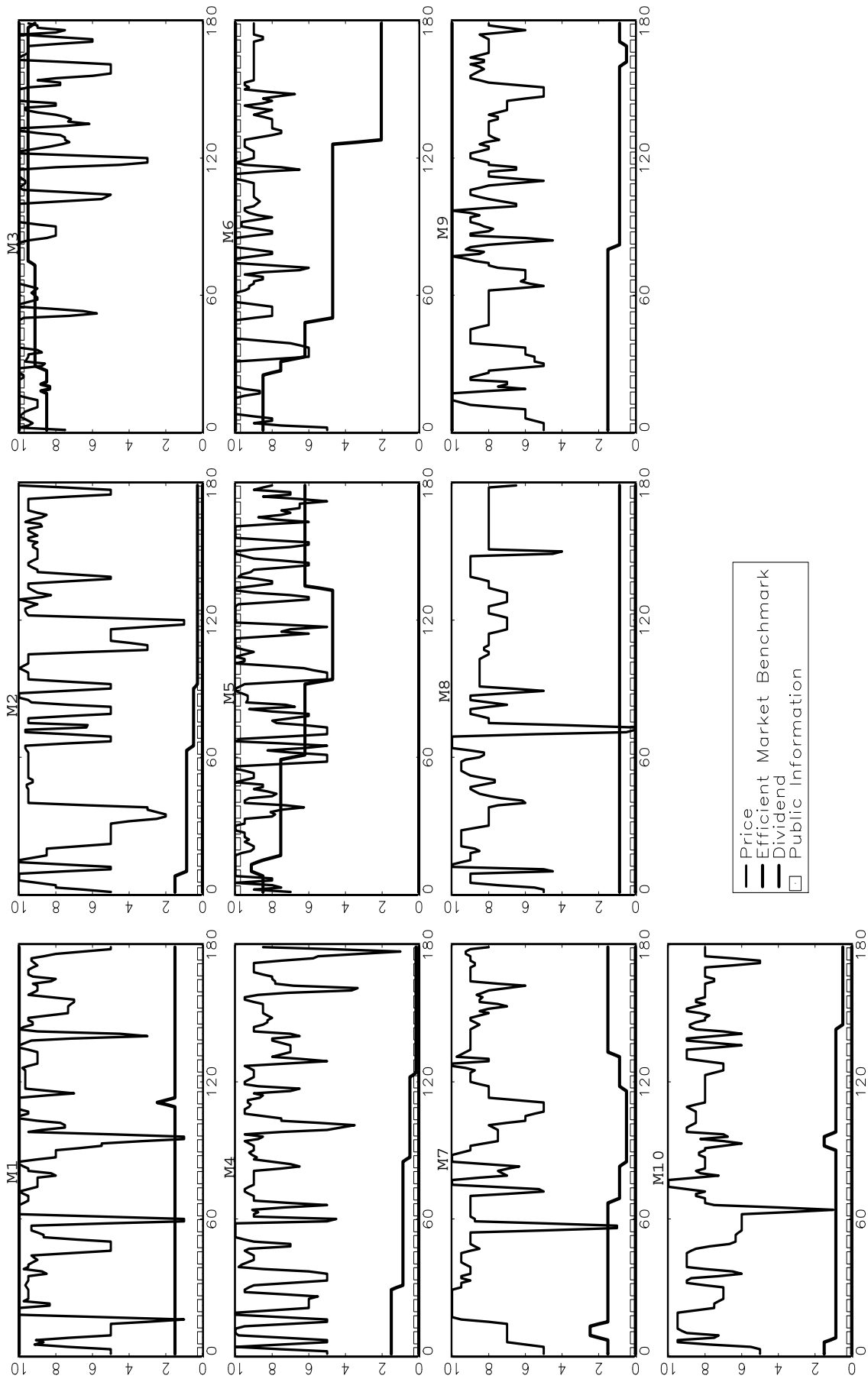


Figure 12: Private signal with $p = 0.6$ and public signal with $P = 0.8$ (Treatment 3, Session 2).

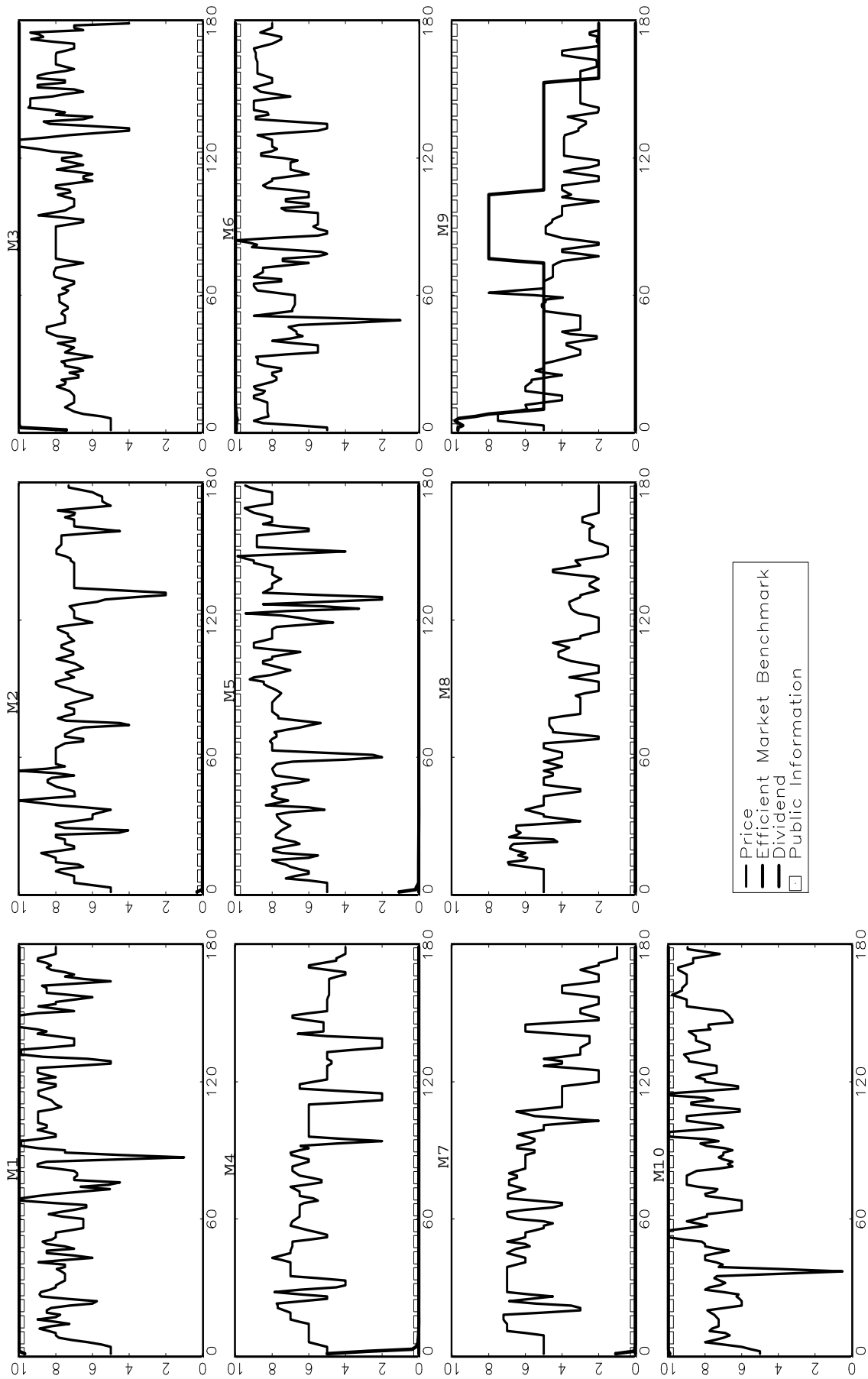


Figure 13: Private signal with $p = 0.8$ and public signal with $P = 0.8$ (Treatment 4).

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