The Role of Public and Private Information in a Laboratory Financial Market*

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Abstract

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 (EMH), 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. However, the EMH does not say anything on the information gathering mechanism and the impact of different sources of information on traders behavior, since it treats information as exogenously given to the traders. Does a heterogeneous spectrum of information sources affect the traders' effort in gathering information? Does it have an impact on the traders participation in the market? Is the market efficiency reduced or enhanced by having access to different sources of information?

After the recent financial turmoil, academics and regulators started to debate on the role that the main rating agencies played in the global diffusion of financial instability. It seems that their optimistic recommendations have been aprioristically followed by the vast majority of investors, while revealing being misleading. Many governmental commissions and research groups world-wide have proposed various reforms of the financial system, among which an increase in the number of rating agencies, considering their small number a source of possible collusive behavior. However, why have financial investors passively followed recommendations of rating agencies? Did they search for independent and alternative sources of information in evaluating financial products? Might it be that the information provided by the rating agencies has produced a reduction in the information gathering activity of investors? It is clear that the rating agency oligopoly is just one of the determinant factors that have triggered the recent financial crisis.

Inspired by the debate on inadequacy of rating agencies, in our paper we will experimentally investigate the impact of the introduction of an imperfect, public and costless signal into a financial market where the participants have access to independent sources of costly and imperfect private information about the future prospect of a financial asset. The main focus of the paper is, on the one hand, the analysis of the efficiency of prices in aggregating and disseminating information, studying in particular whether and under which conditions the contemporaneous presence of private and public information enhances or reduce market efficiency. On the other hand, the investigation of the traders effort in gathering information as a function of the relative precision of the public signal with respect to noisiness and the cost of private information. In a market with these characteristics, using the words of Morris and Shin [2002] "public and private information (might) end up being substitute rather than being cumulative". In particular, Morris and Shin [2002] show that in a game-theoretical beauty contest, this substitution effect can significantly decrease the information content in the system and, depending on the noisiness of public information, resulting in a welfare loss.

In our paper we want to study a laboratory financial market where public and private information coexist. Their interaction have never been tested in experimental literature on financial markets. We can categorize previous experimental studies into two groups[1], 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.

As a representative example of the first category, we can mention the seminal paper of Plott and Sunder [1982], where they 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 uniformed traders are able to decipher the true state of the world by simply observing market price.[2] The review of different experimental studies on information aggregation and dissemination in a setting where *imperfect* information is distributed at no cost suggests that aggregation depends crucially on market features such as common knowledge, information distribution, subjects' experience.[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]).

A market for information parallel to an asset market is As an example of a representative paper of the second category we can mention Sunder [1992], who 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 in fixed (i.e. a given number of perfect signal where auctioned off). In a second experimental setting, the price

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

[2] Watts [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.

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

of information is fixed, whereas the number of informed traders is endogenous (and not known by traders). A series of experimental studies using different settings inspired by Sunder [1992] conclude that when the distribution of (perfectly) informed traders in 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 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 traders prefer short-term rather than long-term information. However, the experimental assets markets are 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. In this respect, there is little agreement on the theoretical literature on the effects of public information.[5] When evaluating the effects of public and private information in the market performance, two main issues require further investigation: the relative precision of the private and public signals and the relative weight that traders attach to these signals: the higher the weight that agents attach to public signals, the more likely does an imprecise public signal reduce market.

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

[4]See Copeland and Friedman [1991, 1992] or Camerer and Weigelt [1991], among others.
[5]See Amato and Shin [2004], Angeletos and Pavan [2004] or Hellwig [2005], among others.

in which true firm values are certified by screening agents whose payoffs 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.[6]

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. Using a game theoretic model, they predict that introducing a rating agency to a market that otherwise would have the unique equilibrium, can bring about multiple equilibria.

Our paper aims at contributing to this debate by analyzing whether the presence of public information (e.g. information provided by a rating agency or a central bank) 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 15 subjects. At the beginning of each trading period, each subject is endowed with $M = 1000$ units of experimental currency and $m = 10$ units of an unspecified asset that pays a dividend d at the end of the trading period. Apart from the dividend paid out at the end of each trading period, assets are worthless at the end of the 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 any moment within a given trading period, subjects can buy a private signal paying a cost $c = 4$ 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 subjects in the market. Such signal is made public before the trading period starts. Both (private and public) signals are partially but not totally informative as to the true state of the world.

Both, private and public signals are presented to the subjects taking the value 1 or 0

[6] However, Millon and Thakor [1985] assume perfect knowledge by the information gathering agency about the underlying risk of the borrower.

depending on the true dividend value. The subjects are explained 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 equal to 1 (0), he/she 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.

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 setting, 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 information. However, this difference does not change the nature of the solution to the model (see Section 4) as agents are 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 and the number of sessions conducted are displayed in table 1:

Treatment	p	P	♯ of sessions
1	0.6	-	2
2	0.8	-	1
3	0.6	0.8	2
4	0.8	0.8	1

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.

From table 1 we see the public signal (when available) is at least as good as a single private signal. It makes sense to assume that the rating agency or the public authority are endowed with and invest more resources in collecting and processing information compared to a private trader. An illustrative example might be the National Central Bank, for which there is no uncertainty on the future monetary policy to be applied.

Indeed, Romer and Romer [2000] find empirical evidence on favor of this assumption by comparing the errors in the inflation forecast of the Federal Reserve Bank to the private commercial forecast and demonstrate that Federal Reserve has more information about inflation compared to what is known to commercial forecasters. This makes sense, since they have uncertainty on the current monetary policy. However, whereas a single public signal is at least as accurate as a single private signal, the information market implemented in our experimental design allows for a private trader to invest in several private signals that, in aggregate, can make private information to be more accurate that the public signal for that particular trader. In addition, all signals are independent realizations of a given distribution.

Another important characteristic is that public information is freely revealed to all traders in the market while private information has a cost. This feature stresses the fact that the public institution is endowed with more resources for collecting and processing information compared to the private trader. Therefore, we assume that the production of a public signal has lower cost for the public institution that for the private trader.

The experiment was programmed using the Z-Tree software (Fischbacher [2007]). When the subjects arrived to the laboratory the instructions were distributed and explained aloud using a Power Point presentation and questions where answered. This was followed by 3 practice periods for subjects to get familiar with the software and the trading mechanism. The briefing period lasted some 40 minutes.

Each subject could only participate in one session. Each session consisted of 10 independent trading periods (markets) lasting 3 minutes each. At the beginning of each trading period the dividend was randomly determined by the experimenter and paid out at the end of the period.[7] 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, but every subject could handle so much as desired as long as he had enough cash or assets (no short sale was allowed). Parallel to the asset market, there is an information market where subjects can purchase as many private signals as he/she wanted during a given trading period, as long as he had enough cash.

After each 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

[7] The true dividend value was unknown to the subjects until the end of the trading period.

per private signal purchased). The subjects' final payoff was computed as the accumulated profit in the 10 trading periods, and paid to them in cash.[8] The average payoff was about 20 € and each session lasted around 90 minutes.[9]

3 The 'Do Nothing' Equilibrium

Let us try in this section to provide for an equilibrium which might help to analyze the experimental data. Since our experimental design share the main characteristics with that of Hey and Morone [2004]. The theoretical predictions of their model applies as well to our treatments 1 and 2 where only private information is available to the traders. They conclude with two simple predictions:[10] First, the market price *should* converge to the true value of the dividend if the market correctly aggregates the costly information available to the agents.[11] However, this leaves unexplained the question of on the price convergence process.[12] Concerning this issue, Hey and Morone [2004] identify one possible equilibrium in which no agent does anything. Later on **?** generalize this result to a market with private and private information, showing that 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.[13]

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

[8] One experimental currency unit is equivalent to 2 cents of euro.

[9] Note that subjects 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. No subject earned a negative final payoff in any session.

[10] See [Hey and Morone, 2004, p. 664]

[11] 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.

[12] To describe the price convergence process we could rely on the literature on informational cascades in a non-market context introduced by Banerjee [1992] and Bikhchandani et al. [1992].

[13] See [Hey and Morone, 2004, p. 643] for an explanation of the no trade as equilibrium when traders have different beliefs or different risk attitudes.

$I_T = \{i_1, i_2, ...i_t, ..., i_T\}$. 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:

$$Pr(I_T) = Pr(I_T|D = 10) \cdot Pr(D = 10) + Pr(I_T|D = 0) \cdot Pr(D = 0). \quad (2)$$

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:

$$Pr(D = 0|I_T) = 1 - Pr(D = 10|I_T) \ , \quad (3)$$

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:

$$Pr(I_T|D = 10) = p^n \cdot q^{N-n} \ , \quad (4)$$

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:

$$Pr(D = 10) = Pr(D = 0) = \frac{1}{2} \; . \tag{5}$$

The marginal probability in eq. (2) takes then form:

$$Pr(I_T) = \frac{1}{2}p^n \cdot q^{N-n} + \frac{1}{2}p^{N-n} \cdot q^n \; . \tag{6}$$

Putting together eqs. (1), (4), (5) and (6), we obtain:

$$Pr(D = 10|I_T) = \frac{p^n \cdot q^{N-n}}{p^n \cdot q^{N-n} + p^{N-n} \cdot q^n} = \frac{1}{1 + \left(\frac{q}{p}\right)^{2n-N}} \; . \tag{7}$$

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

$$\eta_T = \sum_{t=1}^{T} i_t = 2n_T - N_T \; , \tag{8}$$

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

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

and

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

According to eq. (9), 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, $Pr(D = 10|I_T) = 0.5$. This is obviously the case at the beginning of the trading period 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 equations 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 a setting with 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 $P \geq p$.[14] 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. (4) is then modified as follows:

$$Pr(I_T, S = 1 | D = 10) = P \cdot \left[p^n \cdot q^{N-n}\right] \ , \tag{11}$$

and

$$Pr(I_T, S = -1 | D = 10) = Q \cdot \left[p^n \cdot q^{N-n}\right] \ . \tag{12}$$

Using eqs. (11) and (12), we can easily modify eq. (9) in order to take into account the public signal:

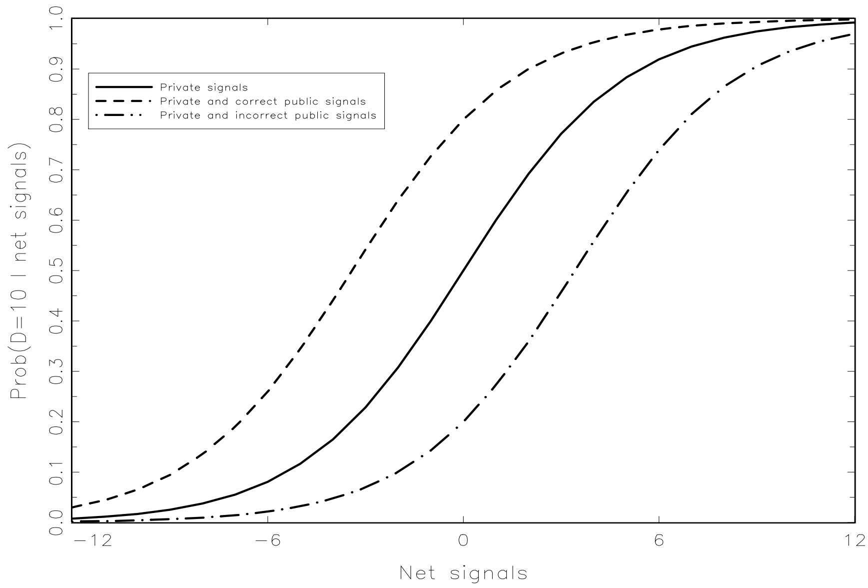
$$Pr(D = 10 | I_T, S) = \left[1 + \left(\frac{Q}{P}\right)^S \left(\frac{q}{p}\right)^{\eta_T}\right]^{-1} \ . \tag{13}$$

In order to illustrate eq. (13) 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 available information is the public signal. Therefore, $\eta_T = \eta_0 = 0$ and $Pr(D = 10 | I_T, S = 1) = 0.8$ or $Pr(D = 10 | I_T, S = -1) = 0.2$ depending on the value of the public signal being 1 or -1, respectively. 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.

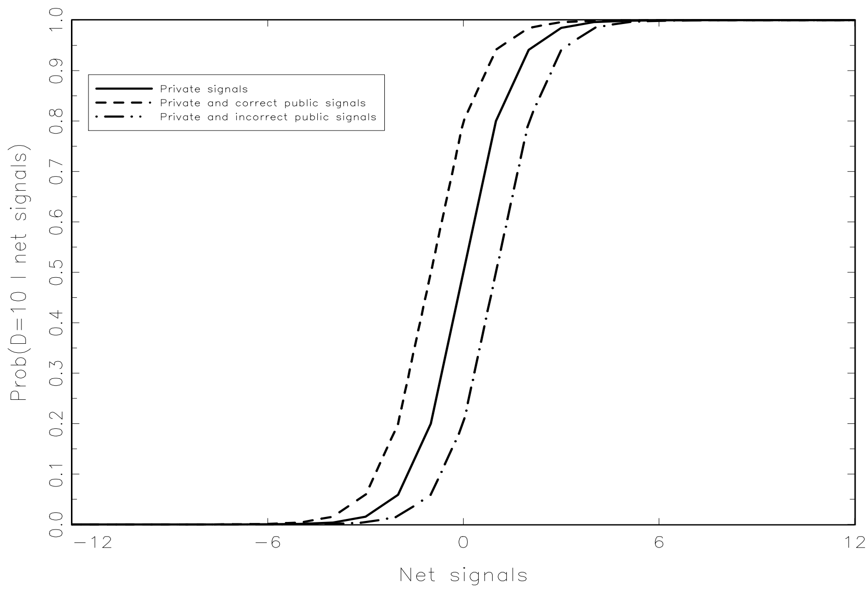
As a further illustrative example of eq. (13), in Figure 1(b) we plot the probability of observing a dividend $D = 10$ as a function of the net information η_T present in the market at time T, for different qualities of the private signals[15]. Additionally, we can observe the influence of a correct 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. Note that in the case of a quality of the private 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

[14]The quality of a signal is defined according to the probability of being correct.

[15]Without 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 with only private information and presence of correct or incorrect public signal, respectively.

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 used by traders includes all information purchased by the traders, I_T. The equilibrium price, under risk neutrality assumption, is given by:

$$B_t = 10 \cdot Pr(D = 10|I_T) + 0 \cdot Pr(D = 0|I_T) = 10 \left[1 + \left(\frac{q}{p} \right)^{\eta_T} \right]^{-1} . \qquad (14)$$

In the presence of a public signal S eq. (14) can be re-written as:

$$B_t = 10 \cdot Pr(D = 10|I_T, S) + 0 \cdot Pr(D = 0|I_T, S) = 10 \left[1 + \left(\frac{Q}{P} \right)^{S} \left(\frac{q}{p} \right)^{\eta_T} \right]^{-1} . \qquad (15)$$

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. Eqs. (14) and (15) represent a situation where, when a subject buys a signal, this information is incorporated into the price correctly and instantaneously as if such information would be available to all subjects in the market.

5 Results

Probably the easiest way to summarize the results of our experiments is to display the trading activity in all the markets for the 4 treatments implemented. 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 (in seconds) at which the trade took place. The 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 dotted line indicates the Bayesian price, i.e the price computed using eq. (14) or eq. (15), without or with a public signal, respectively. The squares indicate the public signal (either on 10 or 0), available to the subjects at the beginning of the trading period.

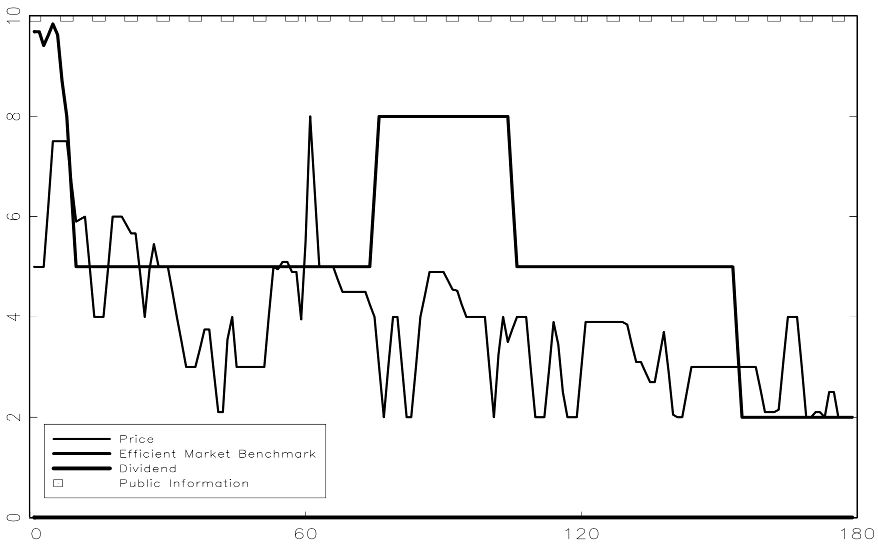


Figure 2: The figure shows the graph of T4M9 as an illustrative example.

A simple inspection of these figures shows that the "do nothing" equilibrium is not a meaningful description of the trading behavior of the subjects in any of the implemented treatments, since subjects purchase private information[16] as well as post bids and asks in the market.

In order to analyze the market dynamics we will focus attention on two aspects of the experiment: the information demand, the market informativeness and the aggregation of information into market prices.

5.1 Information Market Demand

A crucial aspect of our experimental design is that the quantity of information available in the market is endogenous. More precisely, the private information supply is perfectly elastic, that is, subjects can buy as many signals as they want at a fixed price.

We analyze whether or under which conditions the information available to the traders in the market is sufficient to discover the true state of the world. In particular, we will focus attention on the role that have on the information acquisition process the private information quality and the availability of public information.

[16] See Appendix 6 for a detailed description of the information purchased by traders per market.

5.1.1 Quality of the private signal

As a first step we analyze the number of private signals as a function of its quality. Figure 3 shows the distribution of the private signals purchased across treatments. It is apparent from the figure that, given the information cost, an increase in the quality of the private signal increases the traders' willingness to invest in the acquisition of private information and, as a consequence, traders possess not only more accurate information but also more information. Indeed, the number of purchased signals is *significantly* higher in Treatment 2 ($p = 0.8$) as compared to Treatment 1 ($p = 0.6$).[17] Moreover, this picture does not change with the introduction of a public signal, since the same pattern is confirmed as shown in Figure 3 when comparing Treatments 3 ($P = 0.8$, $p = 0.6$) and 4 ($P = 0.8$, $p = 0.8$).[18] We can conclude that:

Result 1: *Subjects purchase more signals the higher their quality and therefore, the quantity and quality of information present in the market increases.*

5.1.2 The Availability of Public Information

Another interesting finding relates to the impact that the presence of a free public signal has on the traders' behavior in the information market, that is, how the acquisition of private signals is affected by the presence of a free public signal of the same or better quality that a single private signal.

Fixing the quality of the private signal, we observe that the introduction of a public signal *significantly* reduces the number of private signals purchased by traders. Figure 3 illustrates this effect. This phenomenon is observed for both, low and high quality private signals. However, when the quality of the public signal is higher than a single private signal (comparing Treatment 1 to Treatment 3) the reduction on the number of signals purchased is more pronounced that in the situation where the public signal released in the market has the same accuracy that a single private signal (comparing Treatment 2 to Treatment 4). 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

[17] A Mann-Whitney test rejects the null hypothesis of equal mean at a 1% significance level.

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

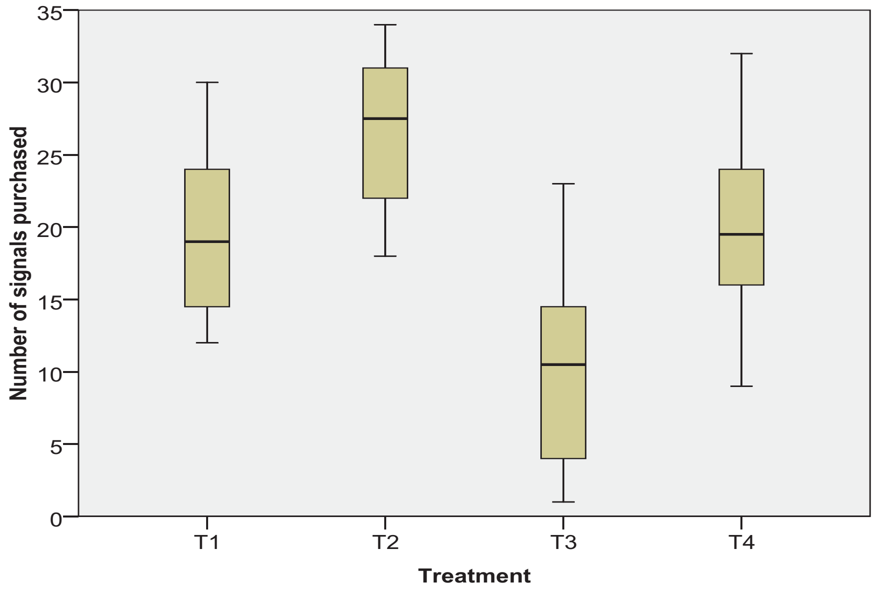


Figure 3: Number of private signals purchased per treatment.

of a *public* information and it is inversely related to the relative quality of both sources of information. We can summarize our findings as follows:

Result 2: *The access to public information has a crowding-out effect on the traders' effort to acquire additional private information.*

However, it remains an open question whether the presence of a public signal compensates for the missing information due to this crowding-out effect and its effect on 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 the Bayesian prince (B_t) computed in eqs. (14) or (15) 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 all 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:

$$E_{BD} = \frac{1}{60} \sum_{t=120}^{180} \frac{|B_t - D|}{10} \,, \tag{16}$$

where B_t is the Bayesian price given in eq. (15), D is the dividend and t denotes the seconds in a trading period.[19]

Using eq. (16) we can evaluate whether the introduction of a public signal is beneficial for the overall information efficiency. Indeed, we observe that the introduction of the public signal compensates for the reduction on the acquisition of private signals due to the crowding-out effect.[20] This means that the introduction of a public signal does not alter 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 provided by the public signal is sufficient to counterbalance the reduction in the number of private signals present in the market, under the assumption of an efficient utilization of the information.

Result 3: *The information conveyed by the public information compensates for the crowding-out effect on the private information: the impact of the public information turns out to be neutral on the markets information efficiency.*

5.1.3 The Market Information Efficiency

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, i.e. the market information efficiency of each treatment. 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?

[19]The choice of averaging over the last trading minute is a compromise between having good statistics for 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.

[20]A 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).

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. (16). In principle, setting a threshold value on eq. (16), we can compute the minimum net private signal (η_T in eq. (8)) 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 dividend.[21] In Table 2 we give the minimum values of the net private signal which guarantees aggregation at 1% (10%) confidence level across the implemented treatments, that is, $E_{BD} \leq 0.01$ ($E_{BD} \leq 0.1$).[22]. These sort of critical values can be visualized from casual inspection of Figures 1(a) and 1(b).

	Minimum η_T with:		
	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 η_T in order to identify the true dividend value in the different cases of our experimental setting, at 1% (10%) confidence level.

In Figure 4 we plot 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 traders and evaluate the impact of an increase in the quality of the private signals. In the majority of cases[23] 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

[21]In 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.

[22]We 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).

[23]The 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.

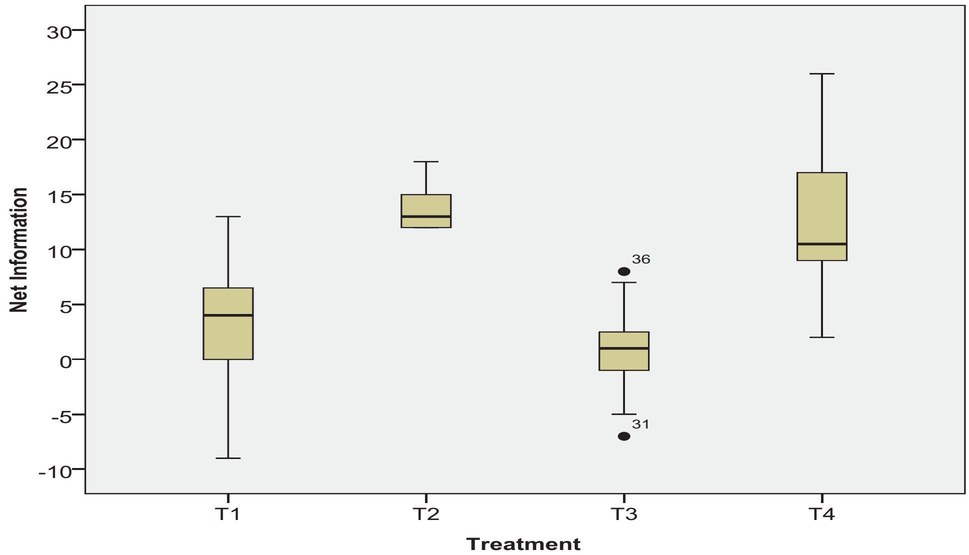


Figure 4: Net private signal (η_T) per treatment.

minimum net signal of 6 given a confidence level of 10% (see first column in Table 2 if $p = 0.6$). 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 first column in Table 2 if $p = 0.8$), and, in fact, all markets can potentially discover the value of the dividend both at 1% confidence levels. From Table 2 and Figure 4 we conclude that when the quality of information is low, traders 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.

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 (.[24] 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, where the quantity and quality of the private information is higher, the subjects are still over-informed since the net private signal is almost always above the

[24]The 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. See second and third columns in Table 2 if $p = 0.6$. The individual markets can be easily identified in the Figures included at the end of the paper.

critical level.[25]

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 on the release of public information.*

Therefore we can conclude that despite the crowding-out effect, the release of public information is not responsible for the market information inefficiency when the quality of the private signal is low. In the same way, the release of a public signal when traders have access to high quality costly private signals, the release of public information helps to reduce the excess of private signals present in the market. In this sense, we can say that public information positively influences the private information market when the quality of privata signals is high, whereas it enhances the under-information phenomenon in those markets where traders have access to low quality signals.

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:

$$E_{BPR} = \frac{1}{60} \sum_{t=120}^{180} \frac{|B_t - PR_t|}{10} \,, \tag{17}$$

where B_t is the Bayesian price given in eq. (15), PR_t is the market price and t denotes the seconds in a trading period (See footnote 19). With this measure we can easily quantify the deviation from what the traders could have achieved using efficiently all 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. $E_{BP} < 0.1$.[26]

[25] The net private signal is above the minimum required level at both 1% or 10% confidence level in all cases but one (T4M9). See second and third columns in Table 2 if $p = 0.8$.

[26] We 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].

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 quantity (and quality) 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 introduction of a public signal *significantly* reduces price efficiency[27], 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 present in the market is compensated by the public signal. This implies that the introduction of the public information does not affect the informational efficiency of the markets, that is, the traders' potential to discover the true value of the dividend. 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. Recall that $E_{BD} \leq 0.1$ represents a situation where the information present in the market, if efficiently used, allows traders to discover the true dividend value, whereas $E_{BPR} \leq 0.1$ means that traders do efficiently used the information present in the market, that is, the observed prices are close to the market Bayesian benchmark.

Let us start from Figure 6(b). In this markets traders have access to high quality

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

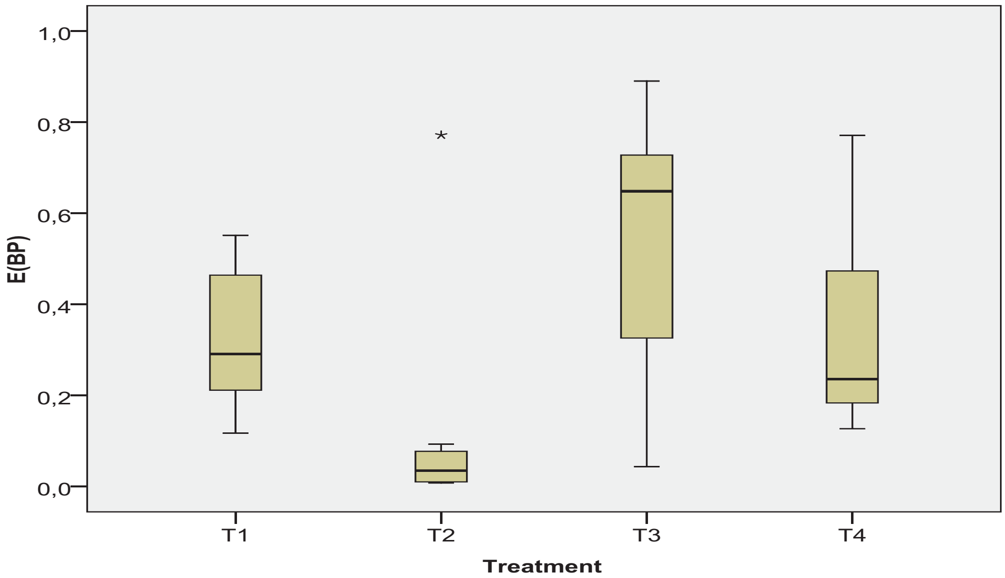


Figure 5: Time average of absolute difference between Bayesian and market price.

private signals. In almost all markets, if information is efficiently used, traders should discover the true dividend value. Indeed, 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 in all but one markets observed prices[28] are below the confidence level of 10%, i.e. observed prices follow the Bayesian benchmark. For a better visualization of the price behavior see Figure 10. From Result 3 we know that the 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, since prices deviate from the Bayesian bechmark in all markets. This means that even if the information present in the market should be enough for the traders to decipher the true dividend value, they do not.

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

[28] In 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.

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 is 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:

$$E_{DPR} = \frac{1}{60} \sum_{t=120}^{180} \frac{|PR_t - D|}{10} , \tag{18}$$

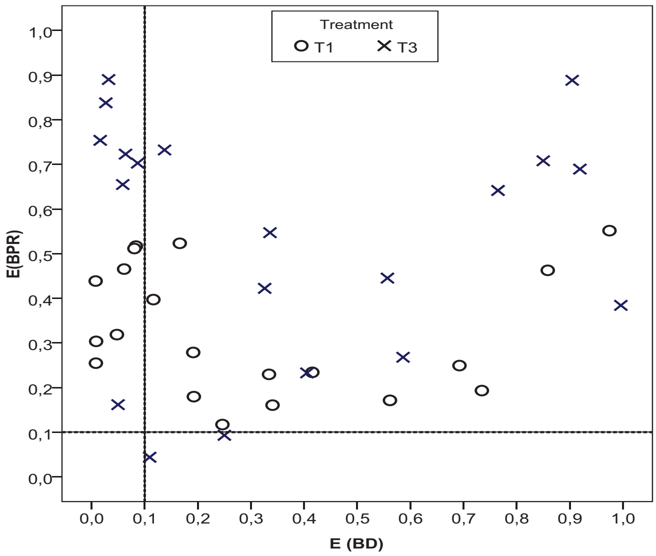
where PR_t is the market price, D is the dividend and t denotes the seconds in a trading period. From Figure 7(a) we can observe that the market efficiency measure fluctuates either around 0.2 or 0.8 in Treatment 3, whereas in Treatment 1 fluctuates around 0.5. This finding confirms our intuition that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

We can summarize our main findings as follows:

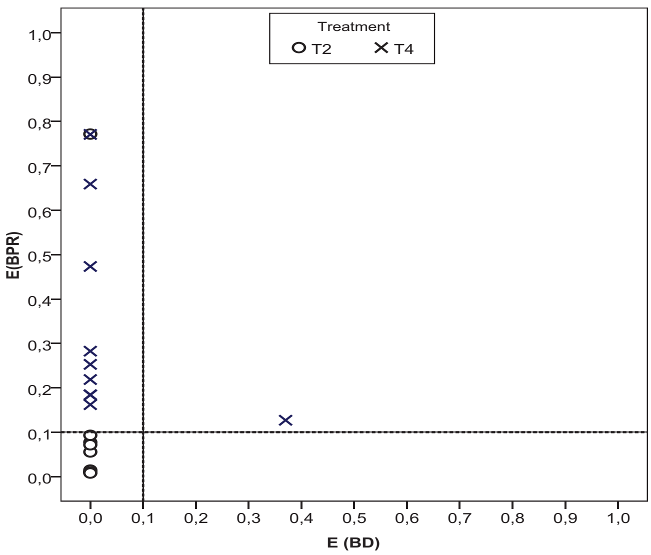
Result 6: *The introduction of a public signal keeps constant the market efficiency but worsens the price efficiency due to the interplay between private and public information on the mechanism of incorporating information into prices.*

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

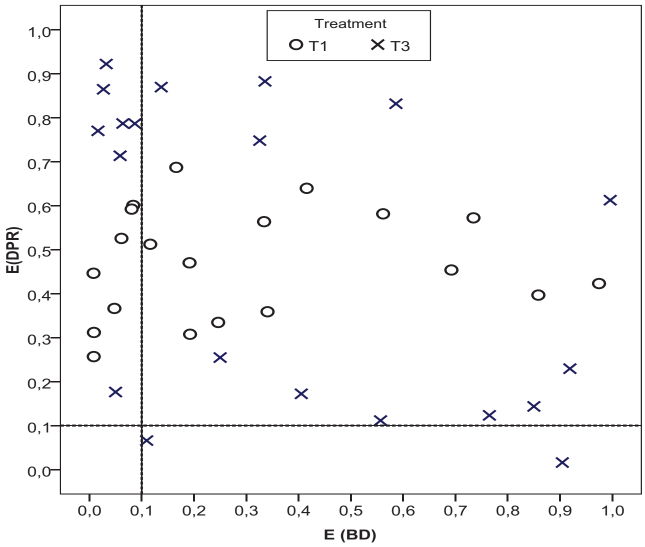


(a) Private signal $p = 0.6$

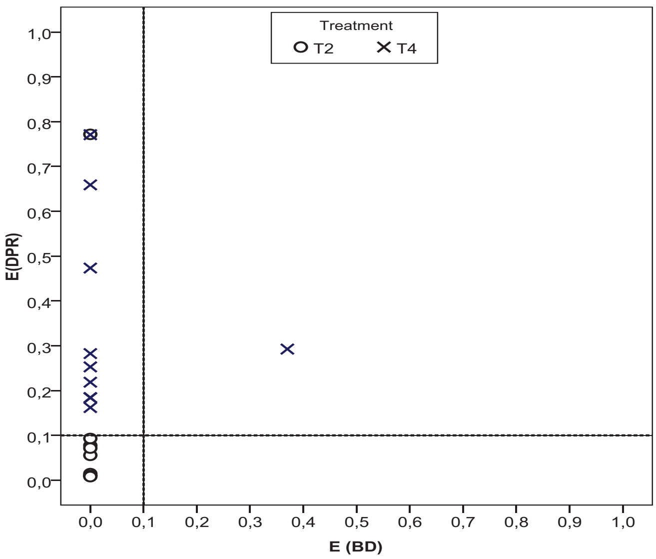


(b) Private signal $p = 0.8$

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.

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 counter-balances 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

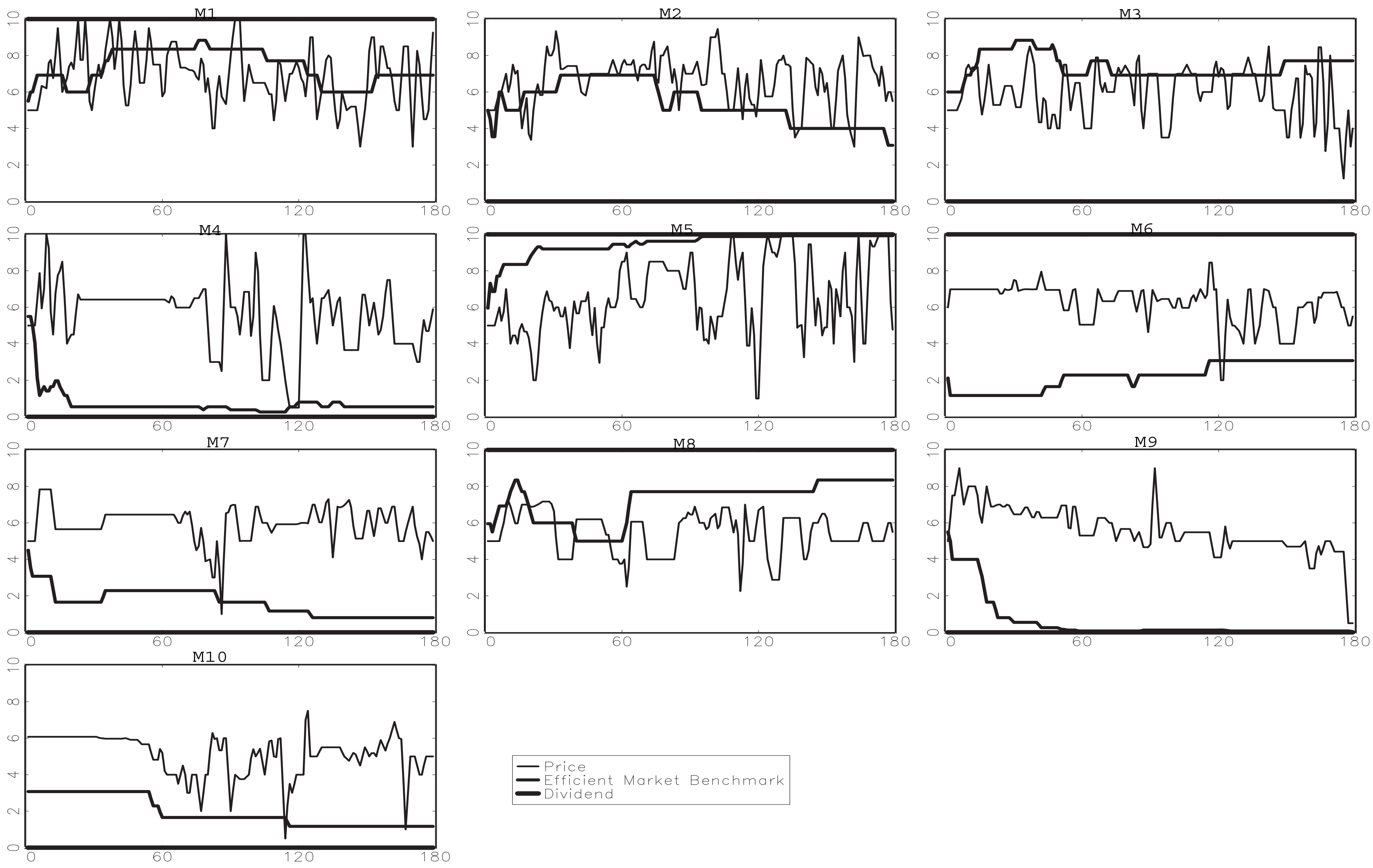


Figure 8: Private signal with $p = 0.6$ (Treatment 1, Session 1).

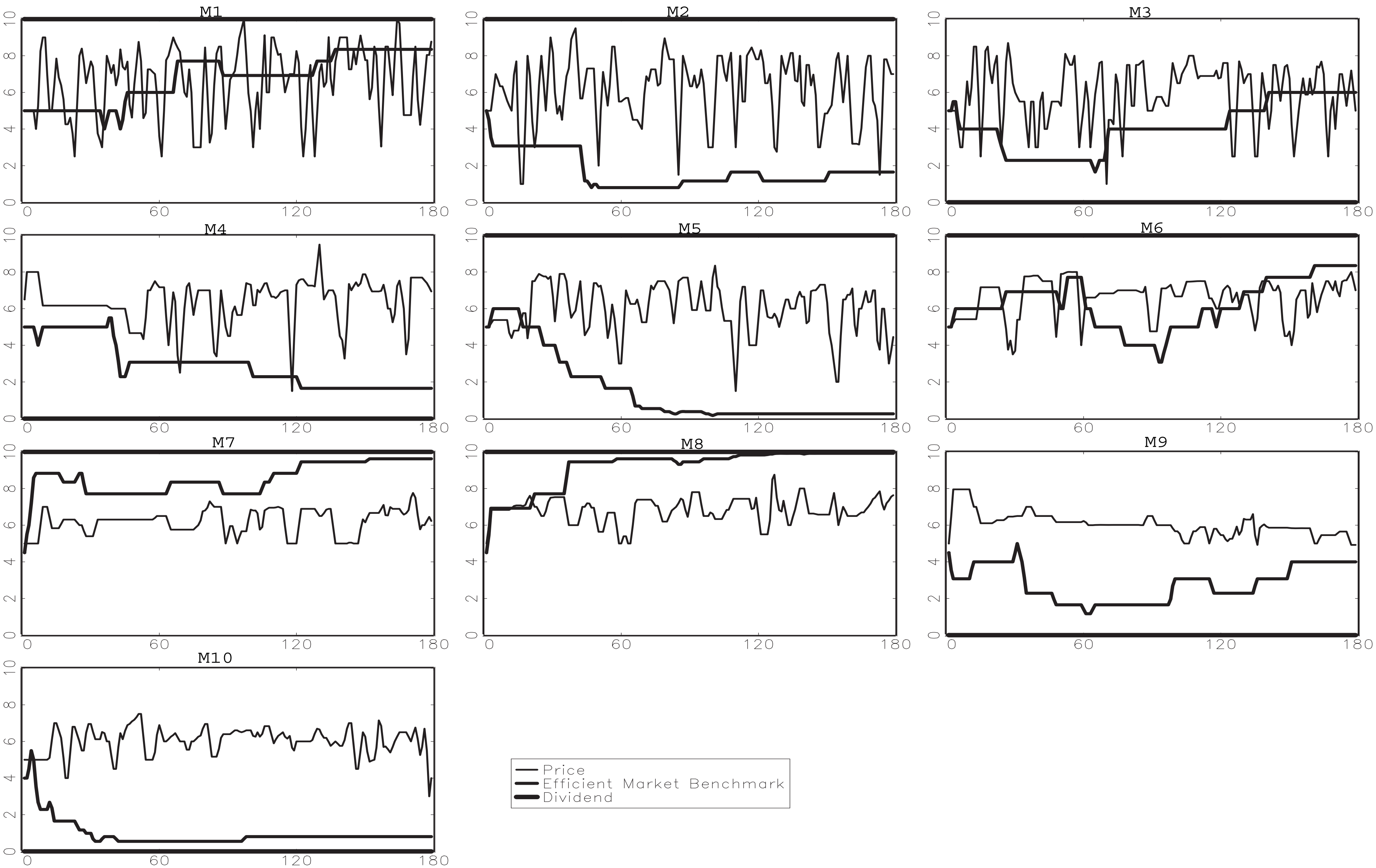


Figure 9: Private signal with $p = 0.6$ (Treatment 1, Session 2).

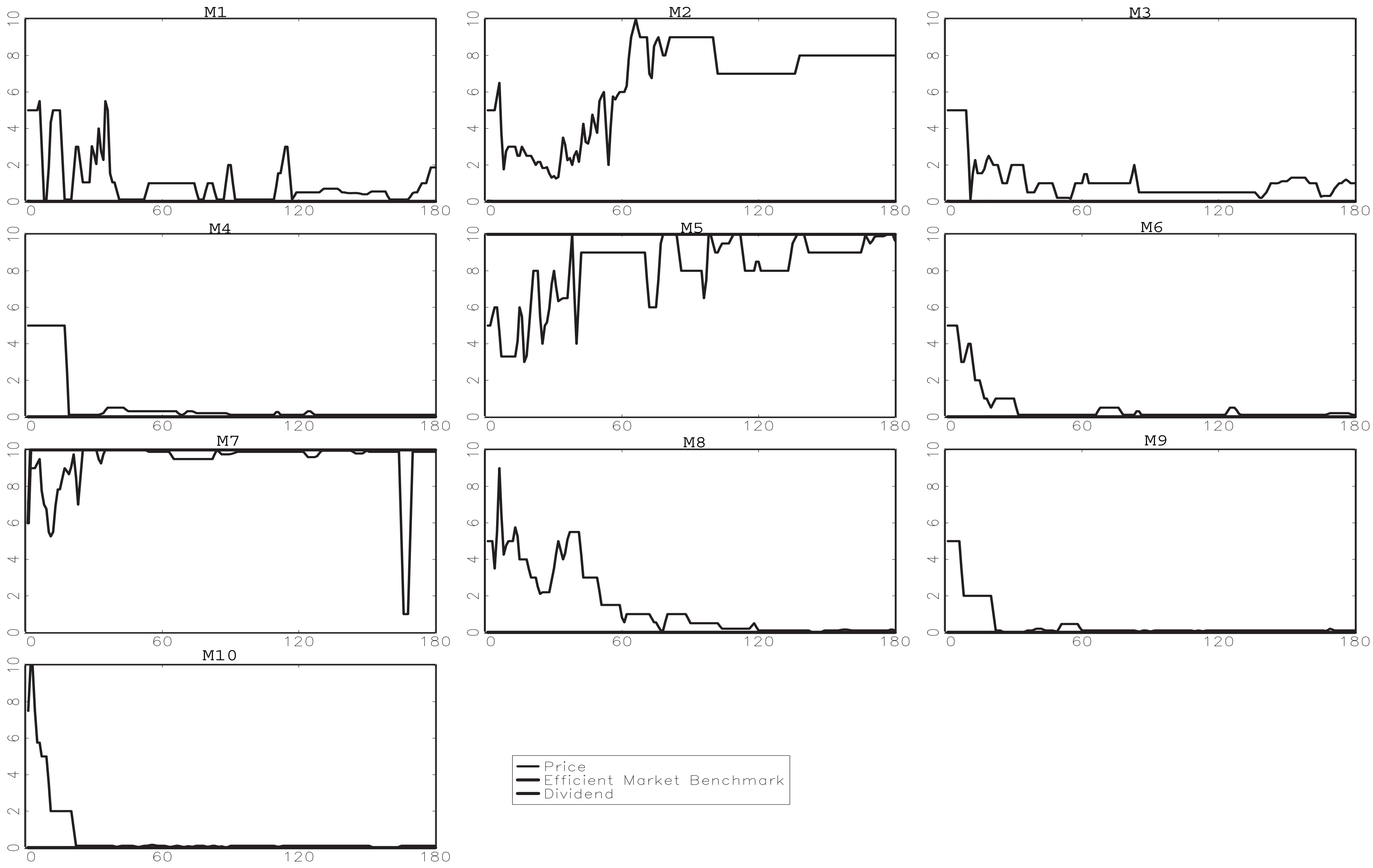


Figure 10: Private signal with $p = 0.8$ (Treatment 2).

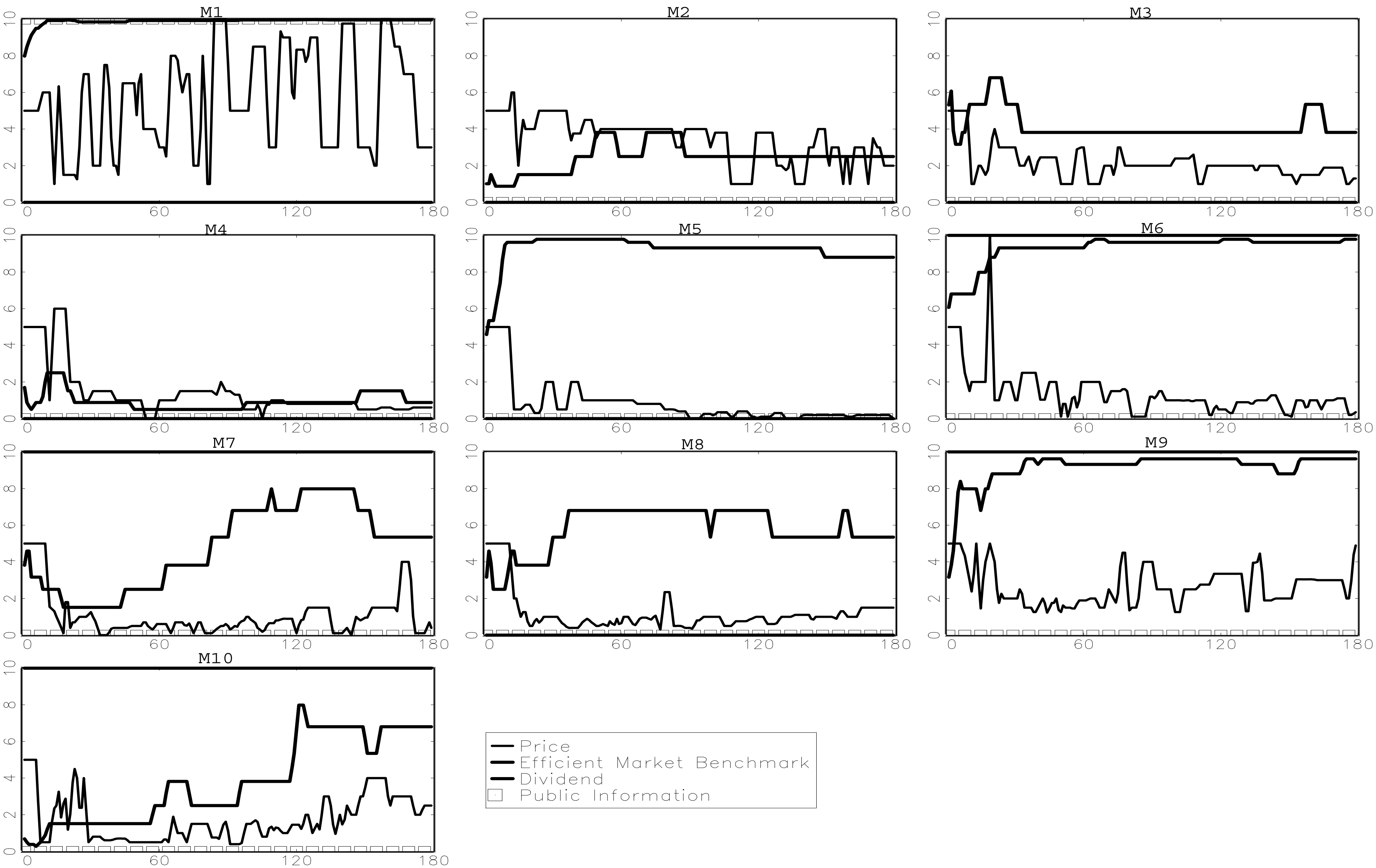


Figure 11: Private signal with $p = 0.6$ and public signal with $P = 0.8$ (Treatment 3, Session 1).

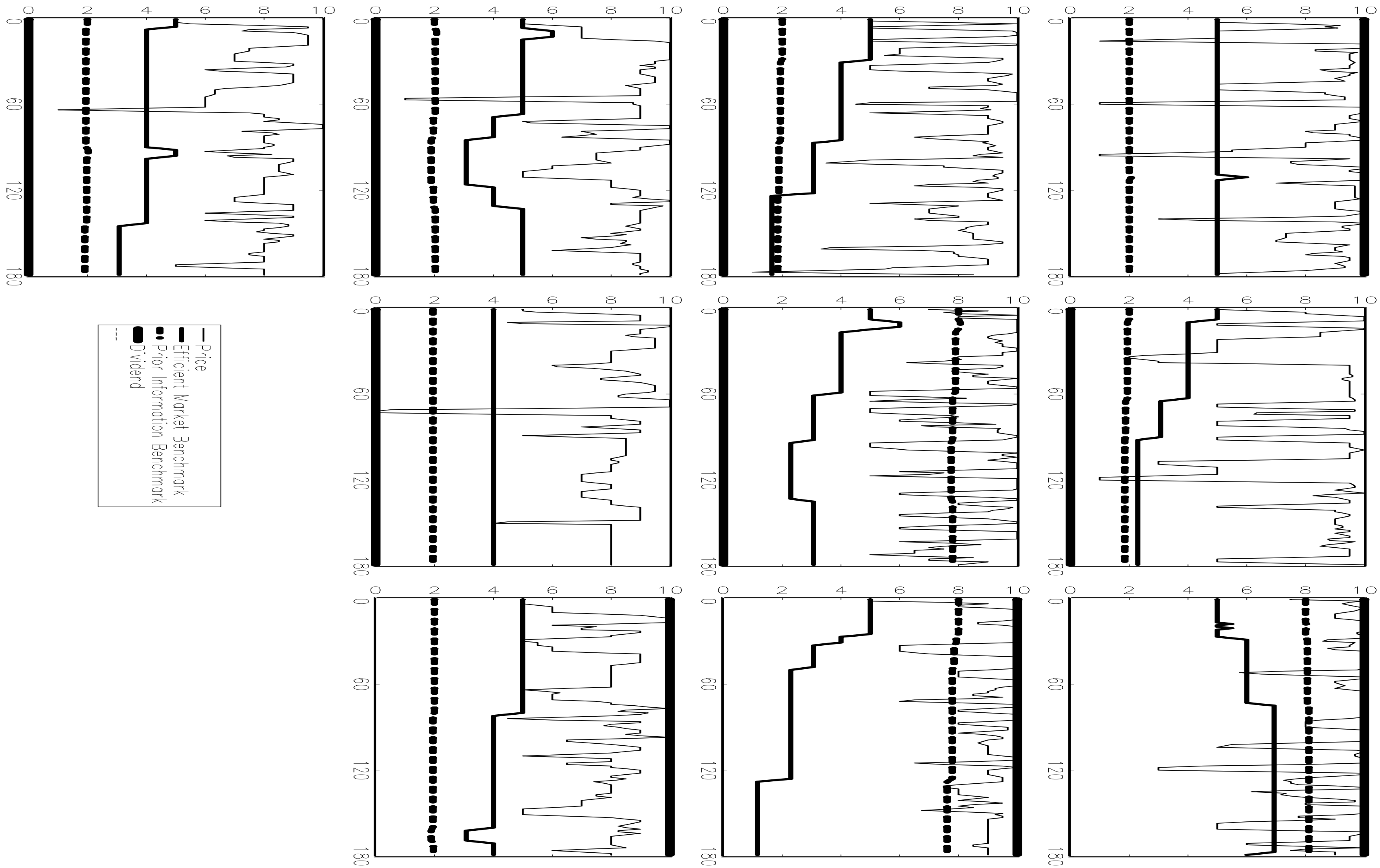


Figure 12: Private signal with $p = 0.6$ and public signal with $P = 0.8$ (Treatment 3, Session 2).

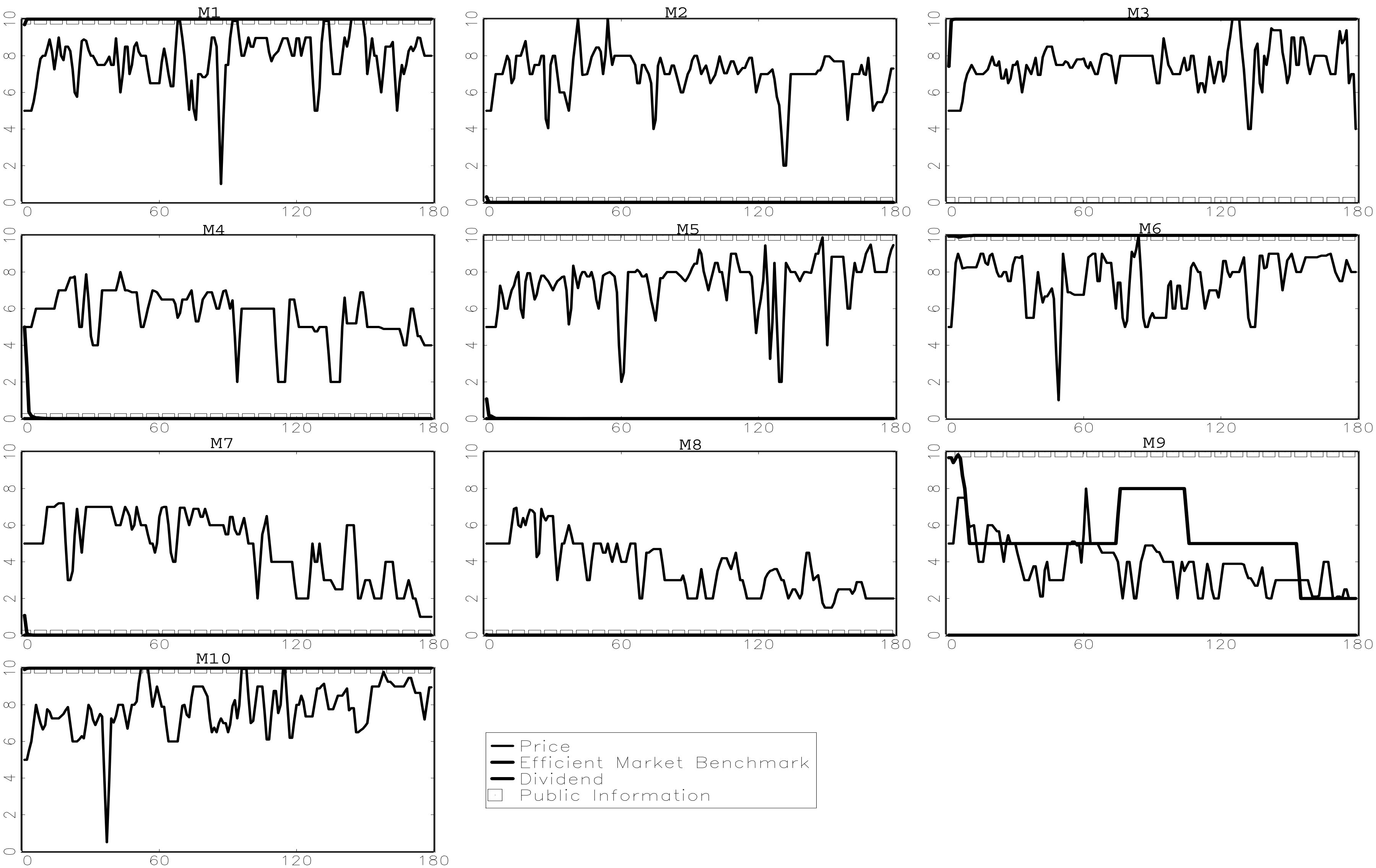


Figure 13: Private signal with $p = 0.8$ and public signal with $P = 0.8$ (Treatment 4).

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