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Federal Reserve Bank of New York  
Staff Reports

# Estimating a Structural Model of Herd Behavior in Financial Markets

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Staff Report No. 561  
May 2012



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## **Estimating a Structural Model of Herd Behavior in Financial Markets**

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### **Abstract**

We develop a new methodology for estimating the importance of herd behavior in financial markets. Specifically, we build a structural model of informational herding that can be estimated with financial transaction data. In the model, rational herding arises because of information-event uncertainty. We estimate the model using 1995 stock market data for Ashland Inc., a company listed on the New York Stock Exchange. Herding occurs often and is particularly pervasive on certain days. In an information-event day, on average, 2 percent (4 percent) of informed traders herd-buy (sell). In 7 percent (11 percent) of information-event days, the proportion of informed traders who herd-buy (sell) is greater than 10 percent. Herding causes important informational inefficiencies, amounting, on average, to 4 percent of the asset's expected value.

Key words: herd behavior, market microstructure, structural estimation

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# 1 Introduction

In recent years there has been much interest in herd behavior in financial markets. This interest has led researchers to look for theoretical explanations and empirical evidence of herding. There has been, however, a substantial disconnect between the empirical and theoretical literatures: the theoretical work has identified motives for herding in abstract models that cannot easily be brought to the data; the empirical literature has mainly looked for atheoretical, statistical evidence of trade clustering, which is interpreted as herding.

This paper takes a novel approach: we develop a theoretical model of herding in financial markets that can be estimated with financial markets transaction data. This methodology allows us to measure the quantitative importance of herding, to identify when it happens, and to assess the informational inefficiency that it generates.

The theoretical work on herd behavior started with the seminal papers of Banerjee (1992), Bikhchandani et al. (1992), and Welch (1992).<sup>1</sup> These papers model herd behavior in an abstract environment in which agents with private information make their decisions in sequence. They show that, after a finite number of agents have chosen the same action, all following agents disregard their own private information and imitate their predecessors. More recently, a number of papers (see, among others, Avery and Zemsky, 1998; Lee, 1998; Cipriani and Guarino, 2008) have focused on herd behavior in financial markets. In particular, these studies analyze a market where informed and uninformed traders sequentially trade a security of unknown value. The price of the security is set by a market maker according to the order flow. The presence of a price mechanism makes it more difficult for herding to arise. Nevertheless, there are cases in which it occurs. In Avery and Zemsky (1998), for instance, herd behavior can occur when there is uncertainty not only about the value of the asset but also about the occurrence of an information event or about the model parameters.

As mentioned above, whereas the theoretical research has tried to identify the mechanisms through which herd behavior can arise, the empirical litera-

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<sup>1</sup>We only study informational herding. Therefore, we do not discuss herd behavior due to reputational concerns or payoff externalities. For an early critical assessment of the literature on herd behavior see Gale (1996). For recent surveys of herding in financial markets see Bikhchandani and Sharma (2001), Vives (2008) and Hirshleifer and Teoh (2009).

ture has followed a different track. The existing work (see, e.g., Lakonishok et al., 1992; Grinblatt et al., 1995; and Wermers, 1999) does not test the theoretical herding models directly, but analyzes the presence of herding in financial markets through statistical measures of clustering.<sup>2</sup> These papers find that, in some markets, fund managers tend to cluster their investment decisions more than would be expected if they acted independently. This empirical research on herding is important, as it sheds light on the behavior of financial market participants and in particular on whether they act in a coordinated fashion. As the authors themselves emphasize, however, decision clustering may or may not be due to herding (for instance, it may be the result of a common reaction to public announcements). These papers cannot distinguish spurious herding from true herd behavior, that is, the decision to disregard one's private information to follow the behavior of others (see Bikhchandani and Sharma, 2001; and Hirshleifer and Teoh, 2009).

Testing models of informational herd behavior is difficult. In such models, a trader herds if he trades against his own private information. The problem that empiricists face is that there are no data on the private information available to traders and, therefore, it is difficult to know when traders decide not to follow it. Our purpose in this paper is to present a methodology to overcome this problem. We develop a theoretical model of herding and estimate it using financial market transaction data. We are able to identify the periods in the trading day in which traders act as herders and to measure the informational inefficiency that this generates. This is the first paper on informational herding that, instead of using a statistical, atheoretical approach, brings a theoretical social learning model to the field data.<sup>3</sup>

Our theoretical analysis builds on the work of Avery and Zemsky (1998), who use a sequential trading model à la Glosten and Milgrom (1985) to study herding in financial markets. Avery and Zemsky (1998) show that, in financial markets, the fact that the price continuously adjusts to the order flow makes herding more difficult to arise. However, they also show that herding does arise if there is "event uncertainty," in the market, that is, uncertainty on whether an information event (i.e., a shock to the asset value, on which informed traders receive a signal) has occurred. Since event uncertainty

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<sup>2</sup>See also the recent paper by Dasgupta et al. (2011), who study the effect of institutional herding on long-term returns, and the literature cited therein.

<sup>3</sup>Whereas there are no direct empirical tests of herding models, there is experimental work that tests these models in the laboratory (see, e.g., Cipriani and Guarino, 2005 and 2009; and Drehmann, Oechssler, and Rider, 2005).

is a typical assumption of sequential trading market microstructure models (starting from Easley and O’Hara, 1992), it is a natural way of generating herd behavior in a financial economy.<sup>4</sup>

In our model, herding arises for a mechanism similar to that exposed by Avery and Zemsky (1998). However, whereas they were interested in providing theoretical examples of herding, our aim is to provide an empirical methodology to gauge the importance of herding in actual financial markets. For this purpose, we build a model of herding that can be estimated with financial market transaction data. In the model, an asset is traded over many days; at the beginning of each day, an informational event may occur, which causes the fundamental asset value to change with respect to the previous day. If an informational event has occurred, some traders receive private information on the new asset value.<sup>5</sup> These traders trade the asset to exploit their informational advantage over the market maker. If no event has occurred, all traders in the market are noise traders, that is, they trade for non-information reasons only (liquidity or hedging motives). Whereas the informed traders know that they are in a market with private information (since they themselves are informed), the market maker does not. This asymmetry of information between traders and the market maker implies that the market maker moves the price too “slowly” in order to take into account the possibility that the asset value may have not changed (in which case all trading activity is due to non-informational motives). As a result, after, for instance, a history of buys, a trader, even with a bad signal, may value the asset more than the market maker does. He will, therefore, trade against his own private information and herd-buy.

We estimate the model with stock market transaction data via maximum likelihood, using a strategy first proposed by Easley et al. (1997) to estimate the parameters of the Glosten and Milgrom (1985) model. There is an important difference, however, between Easley et al.’s (1997) methodology and ours. In their set up, informed traders are perfectly informed about the value of the asset; as a result, their decisions are never affected by the decisions of previous traders, and they never herd. Therefore, only the total *number* of buys, sells and no trades in each day matters; *the sequence* in which these

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<sup>4</sup>A similar mechanism is also present in Gervais (1997). Recently, Park and Sabourian (2011) have illustrated the necessary and sufficient conditions on private information for the occurrence of herding.

<sup>5</sup>The event is called informational precisely because some traders in the market receive private information on it.

trades arrive is irrelevant. In contrast, in our framework, the precision of private information is one of the parameters that we estimate. This opens the possibility that informed traders may receive noisy signals, and that they may find it optimal to ignore them and engage in herd behavior. In this circumstance, the sequence by which trades arrive in the market does matter: in contrast to Easley et al. (1997), we cannot estimate our model using only the number of buy or sell orders in a given day, but we must consider the whole history of trading activity in each day of trading.

As an illustration of the methodology, we estimate the model using transaction data for a NYSE stock (Ashland Inc.) during 1995. The restriction that private signals are always correct (as in Easley et al., 1997) is rejected by the data, which implies both that herd behavior arises in equilibrium and that there is information content in the sequence of trades.

Note that in each day of trading there is always high heterogeneity in trading decisions (i.e., even in days when the fundamental value has increased, we observe many sell orders, and vice versa). If private information were perfectly precise, the only way to account for it would be to have a high proportion of noise traders in the market (indeed, Easley et al. (1997) estimate that the proportion of noise traders is 83 percent). The advantage of our methodology is that it accounts for the heterogeneity in trading decisions not only through the the presence of noise traders, but also by allowing informed traders to receive the wrong piece of information. As one may expect, our estimate of the proportion of informed traders increases substantially with respect to Easley et al. (1997); according to our estimates, however, informed traders have a relatively imprecise signal, incorrect 40 percent of the time. In a nutshell, we partially explain the apparent noise in the data as the result of the rational behavior of imperfectly informed traders, as opposed to assuming that it all comes from randomly acting noise traders.

Allowing for an imperfectly precise signal has important consequences for estimates of trading informativeness. A large literature has studied the information content of trading activity using a measure (usually called the PIN, an acronym for **P**rivate **I**Nformation-based trading) based on the Easley et al. (1997) methodology (i.e., assuming that all informed traders receive the correct information). Using that methodology, the measure of information-based activity in our sample would be 9 percent. Using our methodology, instead, we obtain 19 percent. The difference is due to the fact that in the previous literature incorrect trades (e.g., selling in a good-event day) can only be due to exogenous, non-informative (e.g., liquidity) reasons, whereas in our

setup we do not exclude the possibility that they may be due to informed traders who either receive incorrect information or herd.<sup>6</sup>

Given our estimated parameters, we study how traders' beliefs evolve during each day of trading. By comparing these beliefs to the prices, we are able to identify periods of the trading day in which traders herd. In most of the trading periods, a positive (albeit small) measure of informed traders herd. In an information-event day, on average, between 2 percent (4 percent) of informed traders herd-buy (sell).

Herd behavior generates serial dependence in trading patterns, a phenomenon documented in the empirical literature. Herding also causes informational inefficiencies in the market. On average, the misalignment between the price we observe and the price we would observe in the absence of herding is equal to 4 percent of the asset's unconditional fundamental value.

The rest of the paper is organized as follows. Section 2 describes the theoretical model. Section 3 presents the likelihood function. Section 4 describes the data. Section 5 presents the results. Section 6 concludes. An Addendum available upon request contains the proofs and other supplementary material.

## 2 The Model

Following Easley and O'Hara (1987), we generalize the original Glosten and Milgrom (1985) model to an economy where trading happens over many days.

An asset is traded by a sequence of traders who interact with a market maker. Trading days are indexed by  $d = 1, 2, 3, \dots$ . Time within each day is discrete and indexed by  $t = 1, 2, 3, \dots$

### *The asset*

We denote the fundamental value of the asset in day  $d$  by  $V_d$ . The asset value does not change during the day, but can change from one day to the next. At the beginning of the day, with probability  $1 - \alpha$  the asset value remains the same as in the previous day ( $V_d = v_{d-1}$ ), and with probability  $\alpha$  it changes.<sup>7</sup> In the latter case, since as we will see, there are informed

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<sup>6</sup>As we explain later, in the context of our analysis, the PIN that one would estimate in the standard way (i.e., as in Easley et al., 1996) does not measure the proportion of informed trading activity in the market, but rather the proportion of trading activity stemming from informed traders with the *correct signal*.

<sup>7</sup>Note that  $v_{d-1}$  is the realization of the random variable  $V_{d-1}$ . Throughout the text, we will denote random variables with capital letters and their realizations with lower case



traders in the market, we say that an information event has occurred. If an information event occurs, with probability  $1 - \delta$  the asset value decreases to  $v_{d-1} - \lambda^L$  (“bad informational event”), and with probability  $\delta$  it increases to  $v_{d-1} + \lambda^H$  (“good informational event”), where  $\lambda^L > 0$  and  $\lambda^H > 0$ . Informational events are independently distributed over the days of trading. To simplify the notation, we define  $v_d^H := v_{d-1} + \lambda^H$  and  $v_d^L := v_{d-1} - \lambda^L$ . Finally, we assume that  $(1 - \delta)\lambda^L = \delta\lambda^H$ , which, as will become clear later, guarantees that the closing price is a martingale.

*The market*

The asset is exchanged in a specialist market. Its price is set by a market maker who interacts with a sequence of traders. At any time  $t = 1, 2, 3, \dots$  during the day a trader is randomly chosen to act and can buy, sell or decide not to trade. Each trade consists of the exchange of one unit of the asset for cash. The trader’s action space is, therefore,  $\mathcal{A} = \{buy, sell, no\ trade\}$ . We denote the action of the trader at time  $t$  in day  $d$  by  $X_t^d$ , and the history of trades and prices until time  $t - 1$  of day  $d$  by  $H_t^d$ .

*The market maker*

At any time  $t$  of day  $d$ , the market maker sets the prices at which a trader can buy or sell the asset. When posting these prices, he must take into account the possibility of trading with traders who (as we shall see) have some private information on the asset value. He will set different prices for buying and for selling, that is, there will be a bid-ask spread (Glosten and Milgrom, 1985). We denote the ask price (the price at which a trader can buy) at time  $t$  by  $a_t^d$  and the bid price (the price at which a trader can sell) by  $b_t^d$ .

Due to (unmodeled) potential competition, the market maker makes zero expected profits by setting the ask and bid prices equal to the expected value of the asset conditional on the information available at time  $t$  and on the chosen action, that is,

$$\begin{aligned} a_t^d &= E(V_d | h_t^d, X_t^d = buy, a_t^d, b_t^d), \\ b_t^d &= E(V_d | h_t^d, X_t^d = sell, a_t^d, b_t^d). \end{aligned}$$

Following Avery and Zemsky (1998), we will sometime refer to the market maker’s expectation conditional on the history of trades only as the “price”

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letters.

of the asset, and we will denote it by  $p_t^d = E(V^d|h_t)$ .<sup>8</sup>

*The traders*

There are a countable number of traders. Traders act in an exogenous sequential order. Each trader is chosen to take an action only once, at time  $t$  of day  $d$ . Traders are of two types, informed and noise. The trader's own type is private information.

In no-event days, all traders in the market are noise traders. In information-event days, at any time  $t$  an informed trader is chosen to trade with probability  $\mu$  and a noise trader with probability  $1 - \mu$ , with  $\mu \in (0, 1)$ .

Noise traders trade for unmodeled (e.g., liquidity) reasons: they buy with probability  $\frac{\varepsilon}{2}$ , sell with probability  $\frac{\varepsilon}{2}$  and do not trade with probability  $1 - \varepsilon$  (with  $0 < \varepsilon < 1$ ). Informed traders have private information on the asset value. They receive a private signal on the new asset value and observe the previous history of trades and prices, and the current prices. The private signal  $S_t^d$  has the following value-contingent densities:

$$g^H(s_t^d|v_d^H) = 1 + \tau(2s_t^d - 1),$$

$$g^L(s_t^d|v_d^L) = 1 - \tau(2s_t^d - 1),$$

with  $\tau \in (0, \infty)$ . (See Figure 1.)

For  $\tau \in (0, 1]$ , the support of the densities is  $[0, 1]$ . In contrast, for  $\tau > 1$ , the support shrinks to  $[\frac{\tau-1}{2\tau}, \frac{\tau-1+2\sqrt{\tau}}{2\tau}]$  for  $g^H$  and to  $[\frac{\tau+1-2\sqrt{\tau}}{2\tau}, \frac{\tau+1}{2\tau}]$  for  $g^L$  (in order for the density functions to integrate to one). Note that, given the value of the asset, the signals  $S_t^d$  are i.i.d. The signals satisfy the monotone likelihood ratio property. At each time  $t$ , the likelihood ratio after receiving the signal,  $\frac{\Pr(V_d=v_d^H|h_t^d, s_t^d)}{\Pr(V_d=v_d^L|h_t^d, s_t^d)} = \frac{g^H(s_t^d|v_d^H)}{g^L(s_t^d|v_d^L)} \frac{\Pr(V_d=v_d^H|h_t^d)}{\Pr(V_d=v_d^L|h_t^d)}$ , is higher than that before receiving the signal if  $s_t^d > 0.5$ , and lower if  $s_t^d < 0.5$ . For this reason we refer to a signal larger than 0.5 as a “good signal” and to a signal smaller than 0.5 as a “bad signal.”

The parameter  $\tau$  measures the informativeness of the signals. When  $\tau \rightarrow 0$ , the densities are uniform and the signals are completely uninformative. As  $\tau$  increases, the signals become more and more informative. For  $\tau \in [0, 1)$ , the support of the distribution of the likelihood ratio is bounded away from 0 and infinity, while for  $\tau \geq 1$  it is not. Following Smith and Sørensen (2000), in the first case we say that beliefs are bounded, and in the second case,

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<sup>8</sup>Standard arguments show that  $b_t^d \leq p_t^d \leq a_t^d$  (see Glosten and Milgrom, 1985).

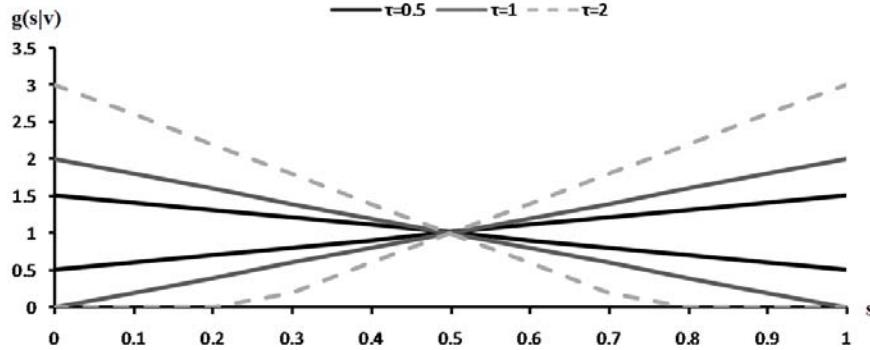


Figure 1: The signal. Signal state-contingent density functions for different values of  $\tau$ .

that they are unbounded. With bounded beliefs, no signal realizations (even the most extreme ones) reveal the asset value with probability one. With unbounded beliefs, in contrast, some high (low) signal realizations are only possible when the asset value is high (low), and therefore, the signal can be perfectly informative.<sup>9</sup> As  $\tau$  tends to infinity, the measure of perfectly informative signals tends to one.

An informed trader knows that an information event has occurred, and that as a result, the asset value has changed with respect to the previous day. Moreover, his signal is informative on whether the event is good or bad. Nevertheless, according to the signal realization that he receives and the precision  $\tau$ , he may not be completely sure of the effect of the event on the asset value. For instance, he may know that there has been a change in the investment strategy of a company, but not be sure whether this change will affect the asset value in a positive or negative way. The parameter  $\tau$  can be interpreted as measuring the precision of the information that the trader receives, or the ability of the trader to process such private information. Finally, note that, given our signal structure, informed traders are heterogenous, since they receive signal realizations with different degrees of informativeness about the asset's fundamental value.

In addition to capturing heterogeneity of information in the market, a

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<sup>9</sup>In particular, any signal greater than or equal to  $\frac{\tau+1}{2\tau}$  reveals that the asset value is  $v_d^H$ , whereas a signal lower than or equal to  $\frac{\tau-1}{2\tau}$  reveals that the asset value is  $v_d^L$ .

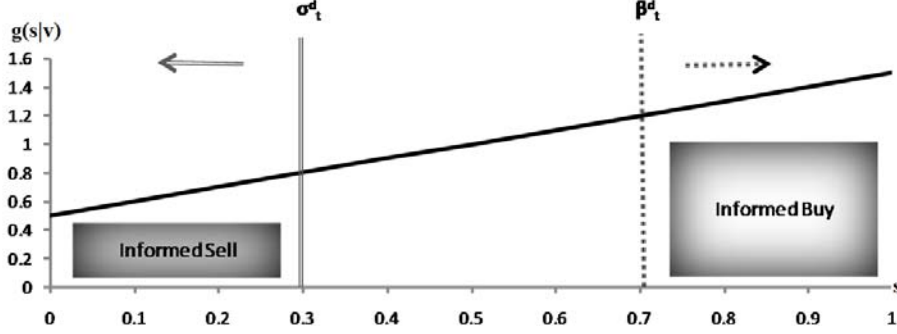


Figure 2: Informed trader's decision. The figure illustrates the signal realizations for which an informed trader decides to buy or sell when  $V_d = v_d^H$  (the signal density function is conditional on  $v_d^H$ ).

linear density function for the signal makes it possible to compute the traders' strategies and the market maker's posted prices analytically. As a result, we obtain a simple and tractable likelihood function. Moreover, in contrast to other specifications such as a discrete signal (e.g., a noisy binary signal), our choice avoids creating a discontinuity in the likelihood function, which would make estimation problematic.

An informed trader's payoff function,  $U : \{v_d^L, v_d^H\} \times \mathcal{A} \times [v_d^L, v_d^H]^2 \rightarrow \mathbf{R}^+$ , is defined as

$$U(v_d, X_t^d, a_t^d, b_t^d) = \begin{cases} v_d - a_t^d & \text{if } X_t^d = \text{buy}, \\ 0 & \text{if } X_t^d = \text{no trade}, \\ b_t^d - v_d & \text{if } X_t^d = \text{sell}. \end{cases}$$

An informed trader chooses  $X_t^d$  to maximize  $E(U(V_d, X_t^d, a_t^d, b_t^d) | h_t^d, s_t^d)$  (i.e., he is risk neutral). Therefore, he finds it optimal to buy whenever  $E(V_d | h_t^d, s_t^d) \geq a_t^d$ , and sell whenever  $E(V_d | h_t^d, s_t^d) \leq b_t^d$ . He chooses not to trade when  $b_t^d < E(V_d | h_t^d, s_t^d) < a_t^d$ .

Note that at each time  $t$ , the trading decision of an informed trader can be simply characterized by two thresholds,  $\sigma_t^d$  and  $\beta_t^d$ , satisfying the equalities

$$E[V_t^d | h_t^d, \sigma_t^d] = b_t^d$$

and

$$E[V_t^d | h_t^d, \beta_t^d] = a_t^d.$$

An informed trader will sell for any signal realization smaller than  $\sigma_t^d$  and buy for any signal realization greater than  $\beta_t^d$ . Obviously, the thresholds at each time  $t$  depend on the history of trades until that time and on the parameter values.<sup>10</sup>

Figure 2 (drawn for the case of a good informational event) illustrates the decision of informed traders. An informed trader buys the asset with a signal higher than the threshold value  $\beta_t^d$ , sells it with a signal lower than  $\sigma_t^d$ , and does not trade otherwise. The measure of informed traders buying or selling is equal to the areas (labelled as “Informed Buy” and “Informed Sell”) below the line representing the signal density function.

## Herd Behavior

To discuss herd behavior, let us start by introducing some formal definitions.

**Definition 1** An informed trader engages in herd-buying at time  $t$  of day  $d$  if 1) he buys upon receiving a bad signal, that is,

$$E(V_d|h_t^d, s_t^d) > a_t^d \text{ for } s_t^d < 0.5,$$

and 2) the price of the asset is higher than at time 1, that is,

$$p_t^d = E(V^d|h_t^d) > p_1^d = v_{d-1}.$$

Similarly, an informed trader engages in herd-selling at time  $t$  of day  $d$  if 1) he sells upon receiving a good signal, that is,

$$E(V_d|h_t^d, s_t^d) < b_t^d \text{ for } s_t^d > 0.5,$$

and 2) the price of the asset is lower than at time 1, that is,

$$p_t^d = E(V^d|h_t^d) < p_1^d = v_{d-1}.$$

In other words, a trader herds when he trades against his own private information in order to conform to the information contained in the history of trades, that is, to buy after the price has risen or to sell after the price has fallen.

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<sup>10</sup>Since noise traders buy and sell with probabilities bounded away from zero, standard arguments prove that both the bid and ask prices, and the informed traders' signal thresholds exist and are unique.

Since traders in our model receive different signals, it may well be (and typically will be the case) that, at a given point in time, traders with less informative signals (i.e., close to 0.5) will herd, whereas traders with more informative signals (close to the extremes of the support) will not. We are interested in periods of the trading day in which traders engage in herd behavior for at least some signal realizations. At any given time  $t$ , we can detect whether an informed trader herds for a positive measure of signals by comparing the two thresholds  $\sigma_t^d$  and  $\beta_t^d$  to 0.5. Since a trader engages in herd-buying behavior if he buys despite a bad signal ( $s_t^d < 0.5$ ), there is a positive measure of herd-buyers whenever  $\beta_t^d < 0.5$ .<sup>11</sup> Similarly for herd sellers. Note that, as we will discuss below, condition 2 in the definition of herding is always satisfied when condition 1 is. Therefore, we formally define herd behavior as follows:

**Definition 2** There is herd behavior at time  $t$  of day  $d$  when there is a positive measure of signal realizations for which an informed trader either herd-buys or herd-sells, that is, when

$$\beta_t^d < 0.5 \text{ or } \sigma_t^d > 0.5.$$

Figures 3 and 4 show an example of herd-buy and herd-sell, respectively, in a day with a good information event. The areas below the signal density function and between the thresholds and 0.5 represent the measures of informed traders who herd-buy and herd-sell.

The reason why herd behavior arises is that prices move “too slowly” as buy and sell orders arrive in the market. Suppose that, at the beginning of an information-event day, there is a sequence of buy orders. Informed traders, knowing that there has been an information event, attach a certain probability to the fact that these orders come from informed traders with good signals. The market maker, however, attaches a lower probability to this event, as he takes into account the possibility that there was no information event, and that all the buys came from noise traders. Therefore, after a sequence of buys, he will update the prices upwards, but by less than the movement in traders’ expectations. Because traders and the market maker interpret the history of trades differently, the expectation of a trader with

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<sup>11</sup>We identify an informed trader with the signal he receives: thus, “a positive measure of herd-buyers” means “a positive measure of signal realizations for which an informed trader herd-buys.”

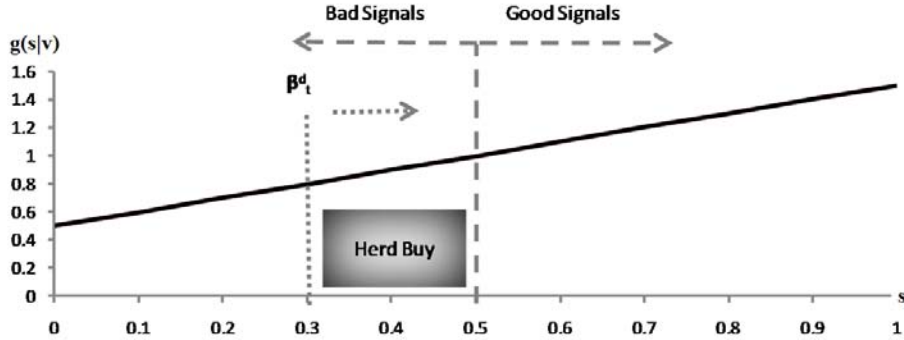


Figure 3: Herd-buy. In the figure, an informed trader buys even upon receiving a bad signal (higher than 0.3).

a bad signal may be higher than the ask price, in which case he herd-buys (obviously, traders who receive signals close to 0.5 will be more likely to herd, since the history of trades has more weight in forming their beliefs).

We state this result in the next proposition (the proof is in the Addendum available on request):

**Proposition 1** For any finite  $\tau$ , herd behavior arises with positive probability. Furthermore, herd behavior can be misdirected, that is, an informed trader can engage in herd-buy (herd-sell) in a day of bad (good) information event.

Avery and Zemsky (1998) have shown how herding can arise because of uncertainty on whether an information event has occurred (see their IS2 information setup). In our model herding arises for the same reason. Our contribution is to embed this theoretical reason to herd in a model that is suitable to empirical analysis.

Note that in our model (similarly to Avery and Zemsky’s IS2 information setup), traders trade against their own private information (i.e., buy after a bad signal or sell after a good one) only to conform to the past trading pattern, and never to go against it. Using the language of the social learning literature, in our model agents go against their private information only to herd, and never to act as contrarians. This means that whenever condition 1 in Definition 1 is satisfied, so is condition 2. That is, condition 2 is redundant. For instance, an informed trader with, e.g., a bad signal never buys

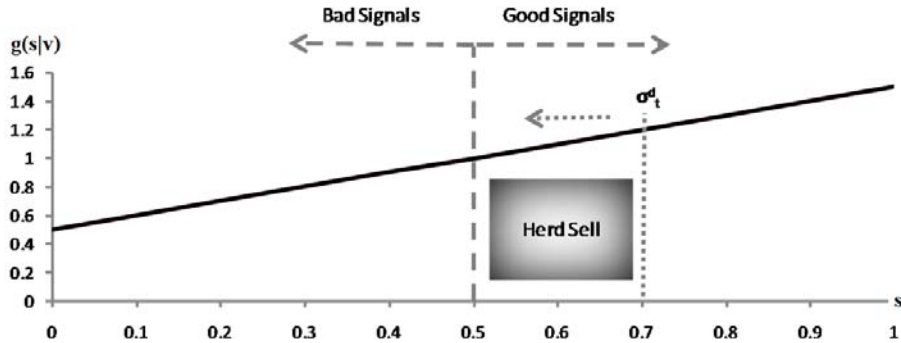


Figure 4: Herd sell. In the figure, an informed trader sells even upon receiving a good signal (lower than 0.7).

after a history of trades have pushed the price downward with respect to the beginning of the day. Indeed, his expected value after the price has decreased is lower than that of the market maker (because he attaches a higher probability to the event that the sell orders come from informed traders).<sup>12</sup>

When  $\tau > 1$ , extreme signals reveal the true value of the asset, and traders receiving them never herd. In the limit case of  $\tau$  tending to infinity, all signal realizations become perfectly informative, with the result that no informed trader herds. Therefore, while our model allows for herd behavior, it also allows for the possibility that some traders (when  $\tau > 1$ ) or all traders (when  $\tau \rightarrow \infty$ ) only rely on their private information and never herd.

The probability of herding depends on the parameter values. To take an extreme example, when  $\alpha$  (the probability of an information event) is arbitrarily close to zero, the market maker has a very strong prior that there is no information event. He barely updates the prices as trades arrive in the market, and herding arises as soon as there is an imbalance in the order flow, as happens in the seminal model of Bikhchandani et al. (1992). In contrast, if  $\alpha$  is close to 1, the market maker and the informed traders update their beliefs in very similar manners, and herding rarely occurs.

Herding is important also for the informational efficiency of the market. During periods of herd behavior, private information is aggregated less efficiently by the price as informed traders with good and bad signals may take the same action. The most extreme case is when traders herd for all

<sup>12</sup>The formal proof of the result is contained in an Addendum available on request.



signal realizations (e.g., traders herd-buy even for  $s_t^d = 0$ ). In such a case, the market maker is unable to make any inference on the signal realization from the trades. The market maker, however, updates his belief on the asset value, since the action remains informative on whether an information event has occurred.<sup>13</sup> Since the market maker never stops learning, he gradually starts interpreting the history of past trades more and more similarly to the traders and, as a result, the measure of herders shrinks.

During an information-event day, the measure of herders changes with the sequence of trades, and can become positive more than once at different times of the day. Given that information always flows to the market, however, the bid and ask prices converge to the asset value almost surely.<sup>14</sup> Eventually the market maker learns whether a good event, a bad event, or no event occurred.<sup>15 16</sup>

### 3 The Likelihood Function

To estimate the herding model presented above, we have to specify its likelihood function. Let us denote the history of trades at the end of a trading day by  $h^d := h_{T_d}^d$ , where  $T_d$  is the number of trading times in day  $d$ . We denote the likelihood function by

$$\mathcal{L}(\Phi; \{h^d\}_{d=1}^D) = \Pr(\{h^d\}_{d=1}^D | \Phi),$$

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<sup>13</sup>The market maker learns since in periods of herding, the proportion of buys and sells is different from that in an uninformed day. Essentially, whereas in our model there is herd behavior, there is never an informational cascade.

<sup>14</sup>The proof of convergence is standard and we omit it.

<sup>15</sup>Recall that we have assumed that  $(1 - \delta)\lambda^L = \delta\lambda^H$ . This implies that  $E(V_{d+1}|V_d = v_d) = v_d$ . Since the price converges to the fundamental value almost surely, this guarantees that the martingale property of prices is satisfied. (We return on this point at the end of Section 4.)

<sup>16</sup>Of course, with a finite number of trades, learning the true value of the fundamental is not guaranteed. An implicit assumption of the literature is that even in those days in which there is not enough trading activity, the market maker learns the true value of the asset by the end of the day—i.e., before the following trading day starts—e.g., because public information is revealed during the night. In any event, in our dataset there is enough trading activity that learning during the day occurs most of the time: the end-of-day market maker’s belief that an event has occurred is either above 0.9 or below 0.1 in 87 percent of days (i.e., in 87 percent of days the market maker has learned whether there was an event or not with 90 percent confidence).

where  $\Phi := \{\alpha, \delta, \mu, \tau, \varepsilon\}$  is the vector of parameters.

Note that we write the likelihood function for the history of trades only, disregarding bid and ask prices. In our model there is no public information: for this reason, there is a one-to-one mapping from trades to prices, and adding prices would be redundant.

The one-to-one mapping from trades to prices breaks down in the presence of public information, since price changes may be the result of public information arrival (as opposed to being only determined by the order flow). Nevertheless, our likelihood function for the history of trades would still be correctly specified. The reason is that the probability of any given trade only depends on whether the trader is informed, and, in such a case, on whether his belief is higher or lower than the market maker's; neither event is affected by the arrival of public information (since this would affect traders' and market maker's beliefs in the same way, shifting all beliefs by the same amount).

Remember that information events are assumed to be independent. Moreover, as we mentioned in the previous section, before the market opens, market participants have learned the realization of the previous day's asset value. Because of this, the probability of the sequence of trades in a day only depends on the value of the asset that day. Therefore, the likelihood of a history of trades over multiple days can be written as the product of the likelihoods of the histories of trades for each day:

$$\mathcal{L}(\Phi; \{h^d\}_{d=1}^D) = \Pr(\{h^d\}_{d=1}^D | \Phi) = \prod_{d=1}^D \Pr(h^d | \Phi).$$

Let us focus on the probability of a history of trades in a single day. As we have written, the *sequence* of trades, and not just the *number* of trades, conveys information. Having many buy orders at the beginning of the day is not equivalent to having the same number of buy orders spread out during the day. In fact, a particular sequence of buy or sell orders may create herd behavior: in periods of herding, the probability of a trade depends on the measure of informed traders who herd and is different from the probability in the absence of herding. Therefore, we have to compute the probability of a history of trades recursively, that is,

$$\Pr(h_t^d | \Phi) = \prod_{s=1}^t \Pr(x_s^d | h_s^d, \Phi),$$

where the probability of an action at time  $t$  of day  $d$ ,  $\Pr(x_t^d | h_t^d, \Phi)$ , depends on the measure of informed traders who buy, sell or do not trade after a given history of trades  $h_t^d$ .

Using the law of total probability, at each time  $t$ , we compute  $\Pr(x_t^d|h_t^d, \Phi)$  in the following way:

$$\Pr(x_t^d|h_t^d, \Phi) = \Pr(x_t^d|h_t^d, v_d^H, \Phi) \Pr(V_d = v_d^H|h_t^d, \Phi) + \Pr(x_t^d|h_t^d, v_d^L, \Phi) \Pr(v_d^L|h_t^d, \Phi) + \Pr(x_t^d|h_t^d, v_{d-1}, \Phi) \Pr(v_{d-1}|h_t^d, \Phi).$$

To show how to compute these probabilities, let us consider, first, the probability of an action conditional on a good-event day. For the sake of exposition, let us focus on the case in which the action is a buy order. As illustrated above, at each time  $t$ , in equilibrium there is a signal threshold  $\beta_t^d$  such that an informed trader buys for any signal realization greater than  $\beta_t^d$ , that is,

$$E(V_d|h_t^d, \beta_t^d) = a_t^d = E(V_d|h_t^d, X_t^d = \text{buy}, a_t^d, b_t^d),$$

which can be written as

$$v_{d-1} + \lambda^H \Pr(v_d^H|h_t^d, \beta_t^d) - \lambda^L \Pr(v_d^L|h_t^d, \beta_t^d) = v_{d-1} + \lambda^H \Pr(v_d^H|h_t^d, \text{buy}_t^d) - \lambda^L \Pr(v_d^L|h_t^d, \text{buy}_t^d),$$

or, after some manipulations, as<sup>17</sup>

$$\Pr(v_d^H|h_t^d, \beta_t^d) - \Pr(v_d^H|h_t^d, \text{buy}_t^d) = \frac{\delta}{1 - \delta} (\Pr(v_d^L|h_t^d, \beta_t^d) - \Pr(v_d^L|h_t^d, \text{buy}_t^d)). \quad (1)$$

The probabilities in this equation can easily be expressed as a function of the traders' and market maker's beliefs a time  $t - 1$  and of the parameters. Specifically, the probability that an informed trader receiving signal  $\beta_t^d$  attaches to the good event is

$$\Pr(v_d^H|h_t^d, \beta_t^d) = \frac{g^H(\beta_t^d|v_d^H) \Pr(v_d^H|h_t^d, V_d \neq v_{d-1})}{g^H(\beta_t^d|v_d^H) \Pr(v_d^H|h_t^d, V_d \neq v_{d-1}) + g^L(\beta_t^d|v_d^L) \Pr(v_d^H|h_t^d, V_d \neq v_{d-1})} =$$

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<sup>17</sup>Note that for simplicity's sake in the probabilities to compute the ask we have omitted  $a_t^d$  and  $b_t^d$  in the conditioning. More importantly, note that the magnitude of the shocks that buffet the asset's value ( $\lambda^L$  and  $\lambda^H$ ) do not appear in this equation, since they cancel out. This is important, since it implies that we do not need to estimate them.

The probability that the market maker attaches to the good event can, instead, be computed as<sup>18</sup>

$$\Pr(v_d^H | h_t^d, buy_t^d) = \frac{\Pr(buy_t^d | v_d^H, h_t^d) \Pr(v_d^H | h_t^d)}{\Pr(buy_t^d | v_d^H, h_t^d) \Pr(v_d^H | h_t^d) + \Pr(buy_t^d | v_{d-1}, h_t^d) \Pr(v_{d-1} | h_t^d) + \Pr(buy_t^d | v_d^L, h_t^d) \Pr(v_d^L | h_t^d)}.$$

By substituting these expressions into (1) we can compute  $\beta_t^d$ . Two comments are in order. First, the above expressions themselves contain the probabilities of a buy order by an informed trader in a good, bad and no-event day; all these probabilities obviously depend on the threshold  $\beta_t^d$  itself (as illustrated below). That is, the threshold  $\beta_t^d$  is a fixed point. Second, at time  $t = 1$ , the prior beliefs of the traders and of the market maker are a function of the parameters only. Therefore, we can compute  $\beta_1^d$  as the solution to equation (1), and, from  $\beta_1^d$ , the probability of a buy order at time 1. After observing  $x_1^d$ , we update the market maker's and traders' beliefs, repeat the same procedure for time 2, compute  $\beta_2^d$  and the probability  $\Pr(buy_2^d | x_1^d, V_d = v_d^H, \Phi)$ . We do so recursively for each time  $t$ , always conditioning on the previous history of trades. Note that in order to maximize the likelihood function the thresholds  $\beta_t^d$  (and the analogous threshold  $\sigma_t^d$ ) have to be computed for each trading time in each day of trading, for each set of parameter values

Once we have solved for  $\beta_t^d$ , we can compute the probability of a buy order in a good-event day. Let us focus on the case in which  $\tau \in [0, 1)$ , that is, let us concentrate on the case of bounded beliefs. In this case:

$$\begin{aligned} \Pr(buy_t^d | h_t^d, v_d^H) &= \\ \mu \int_{\beta_t^d}^1 (1 + \tau(2s_t^d - 1)) ds_t^d + (1 - \mu) \left(\frac{\varepsilon}{2}\right) &= \\ \left( \left( \tau(1 - \beta_t^{d2}) + (1 - \tau)(1 - \beta_t^d) \right) \mu + (1 - \mu) \left(\frac{\varepsilon}{2}\right) \right). \end{aligned}$$

By following an analogous procedure, we compute  $\sigma_1^d$  and the probability of a sell order in a good event day, that is,

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<sup>18</sup>For simplicity, in the conditioning of the probability of a trade we omit that it also depends on the vector of parameters  $\Phi$ .

$$\begin{aligned} \Pr(\text{sell}^d | h_t^d, V_d = v_d^H, \Phi) = \\ \mu \int_0^{\sigma_t^d} (1 + \tau(2s_t^d - 1)) ds_t^d + (1 - \mu) \left(\frac{\varepsilon}{2}\right) = \\ \left( \left( (1 - \tau)\sigma_t^d + \tau\sigma_t^{d^2} \right) \mu + (1 - \mu) \left(\frac{\varepsilon}{2}\right) \right). \end{aligned}$$

The probability of a no-trade is just the complementary to the probabilities of a buy and of a sell.

The analysis for the case of a bad information event ( $V_d = v_d^L$ ) follows the same steps. The case of a no-event day ( $V_d = v_{d-1}$ ) is easier, since the probabilities of a buy or sell is  $\frac{\varepsilon}{2}$  and the probability of a no-trade is  $1 - \varepsilon$ . Also the case of unbounded beliefs, where  $\tau \geq 1$ , can be dealt with in a similar manner. The only change are the extremes of integration when computing the probability of a trade.

Finally, to compute  $\Pr(x_t^d | h_t^d, \Phi)$ , we need the conditional probabilities of  $V_d$  given the history until time  $t$ , that is,  $\Pr(V_d = v | h_t^d, \Phi)$  for  $v = v_d^L, v_{d-1}, v_d^H$ . These can also be computed recursively by using Bayes's rule.

To conclude, let us provide some intuition regarding the model's identification. For simplicity's sake let us consider only the number of buys, sells, and no trades in each day.<sup>19</sup> Similarly to analogous structural models of market microstructure, our model classifies days into high-volume days with a prevalence of buys ("good event" days), high-volume days with a prevalence of sells ("bad event" days) and low-volume days ("no event" days). The parameter  $\alpha$  defines the probability that there is an event at the beginning of a trading day. We use data over many days of trading to identify it. The imbalance between buys and sells in event days identifies  $\delta$ . No-event days allow us to identify  $\varepsilon$ , since in no-event days only noise traders trade. Finally, in good event days, the ratio between buys and sells is determined by the proportion of traders who trade in the right direction (i.e., buy when there is a good event), which depends on  $\mu$  and  $\tau$ . An analogous argument holds for bad-event days. To any given estimate of  $\mu$  and  $\tau$  corresponds only one predicted ratio between buys and sells in the two types of days.<sup>20</sup>

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<sup>19</sup>In our estimation we use much more information than that, since we take into account the entire sequence of trades when constructing the likelihood function.

<sup>20</sup>For a further argument for identification, see footnote 27.

## 4 Data

Our purpose is to carry out a structural estimation of herding based on a market microstructure model. We perform our empirical analysis on a stock, Ashland Inc., traded in the New York Stock Exchange and already used in the seminal paper by Easley et al. (1997).<sup>21 22</sup>

We obtained the data from the TAQ (Trades and Quotes) dataset.<sup>23</sup> The dataset contains the posted bid and ask prices (the “quotes”), the prices at which the transactions occurred (the “trades”), and the time when the quotes were posted and when the transactions occurred. We used transactions data on Ashland Inc. in 1995, for a total of 252 trading days. The data refer to trading in the New York Stock Exchange, the American Stock Exchanges, and the consolidated regional exchanges.

The TAQ dataset does not sign the trades, that is, it does not report whether a transaction was a sale or a purchase. To classify a trade as a sell or a buy order, we used the standard algorithm proposed by Lee and Ready (1991). We compared the transaction price with the quotes that were posted just before a trade occurred.<sup>24</sup> Every trade above the midpoint was classified as a buy order, and every trade below the midpoint was classified as a sell order; trades at the midpoint were classified as buy or sell orders according to whether the transaction price had increased (uptick) or decreased (downtick) with respect to the previous one. If there was no change in the transaction price, we looked at the previous price movement, and so on.<sup>25</sup>

TAQ data do not contain any direct information on no trades. We used the established convention of inserting no-trades between two transactions if the elapsed time between them exceeded a particular time interval (see, e.g., Easley et al., 1997). We obtained this interval by computing the ratio

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<sup>21</sup>The name of the stock is slightly different, since the company changed name in 1995, and Easley et al. (1997) use 1990 data.

<sup>22</sup>We performed our analysis also using other stocks. The results, reported in an Addendum available on request, are broadly in line with those we illustrate in the paper for Ashland Inc.

<sup>23</sup>Hasbrouck (2004) provides a detailed description of this dataset.

<sup>24</sup>Given that transaction prices are reported with a delay, we followed Lee and Ready’s (1991) suggestion of moving each quote ahead in time of five seconds. Moreover, following Hasbrouck (1991, p. 581), we ignore quotes posted by the regional exchanges.

<sup>25</sup>We classified all trades, with the exception of the opening trades, since these trades result from a trade mechanism (an auction) substantially different from the mechanism of trade during the day (which is the focus of our analysis).

between the total trading time in a day and the average number of buy and sell trades over the 252 days (see, e.g., Chung et al., 2005). In our 252 trading day window, the average number of trades per day was 90.2. We divided the total daily trading time (390 minutes) by 90.2, and obtained a unit-time interval of 259 seconds (i.e., on average, a trade occurred every 259 seconds). If there was no trading activity for 259 seconds or more, we inserted one or more no-trades to the sequence of buy and sell orders. The number of no-trades that we inserted between two consecutive transactions was equal to the number of 259-second time intervals between them. To check the robustness of our results, we also replicated the analysis for other no-trade time intervals (2, 3, 4, 5, 6 and 7 minutes).

Our sample of 252 trading days contained on average 149 decisions (buy, sell, or no-trade) per day. The sample was balanced, with 30 percent of buys, 31 percent of sells and 40 percent of no trades.

Finally, remember that in our theoretical model, we assume that the closing price is a martingale. For the case of Ashland Inc. during 1995, this hypothesis is indeed supported by the data: the autocorrelogram of price changes is not significantly different from zero at all lags and at all significance levels.<sup>26</sup>

## 5 Results

We first present the estimates of the model parameters, and then illustrate the importance of herd behavior in the trading activity of Ashland Inc. during 1995.

### 5.1 Estimates

We estimated the parameters through maximum likelihood, using both a direct search method (Nelder-Mead simplex) and the Genetic Algorithm.<sup>27</sup> The two methods converged to the same parameter values. Table 1 presents the estimates and the standard deviations for the five parameters of the

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<sup>26</sup>We report the autocorrelogram in an Addendum available on request.

<sup>27</sup>We also simulated the theoretical model and verified that we could recover the model's parameters. Both methods converged to the true parameter values, which provides further evidence in favor of identification.

model.<sup>28</sup>

Parameter	Estimate	S.D.
$\alpha$	0.28	0.03
$\delta$	0.62	0.06
$\mu$	0.42	0.01
$\tau$	0.45	0.02
$\varepsilon$	0.57	0.002

Table 1: Estimation Results.

The table shows the estimates for the five parameters of the model and their standard deviations.

Information events are relatively frequent: from the estimate of  $\alpha$ , we infer that the probability of an information event is 28 percent, that is, in almost a third of trading days, trading activity is motivated by private information. There is a small imbalance between good and bad-event days: the probability of a good information event is 62 percent (although the parameter  $\delta$  has a relatively high standard deviation).<sup>29</sup> During event days, the proportion of traders with private information is 42 percent. The remaining trading activity comes from noise traders, who trade 57 percent of the time. Moreover, private information is noisy (that is, it is not perfectly informative). The estimate for  $\tau$  is 0.45, which means that the probability of receiving an “incorrect signal” — i.e., a signal below 0.5 when we are in a good-information event day or a signal above 0.5 when we are in a bad-information event day — is 39 percent.<sup>30</sup>

As explained above, we constructed our dataset adding a no-trade after each 259 seconds of trading inactivity. As a robustness check, we repeated the estimation on several other datasets, where we added a no trade for different intervals of trading inactivity. We report these estimates in Table 2.

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<sup>28</sup>Standard deviations are computed numerically with the BHHH estimator.

<sup>29</sup>Note that  $\delta$  is greater than 0.5, although in the sample the number of buys and sells is essentially balanced. This happens because among the days with high trading volume (classified as event days), a higher number of days have a positive trade imbalance than a negative one. To see this, consider the posterior beliefs of  $\delta$  and  $\alpha$  at the end of each day. In 22 percent of days the posterior belief of both  $\alpha$  and  $\delta$  is above 0.5 (i.e., we are in an good-event day), whereas in only 12 percent of days the posterior belief of  $\alpha$  is above 0.5 and that of  $\delta$  is below 0.5 (i.e., we are in a bad-event day).

<sup>30</sup>Given the signal density functions, the probability of an incorrect signal is given by  $0.5 - 0.25\tau$ .



	NT=120	S.D.	NT=180	S.D.	NT=240	S.D.
$\alpha$	0.20	0.02	0.25	0.02	0.27	0.02
$\delta$	0.72	0.02	0.67	0.04	0.61	0.01
$\mu$	0.26	0.01	0.36	0.01	0.41	0.01
$\tau$	0.44	0.01	0.40	0.03	0.44	0.02
$\varepsilon$	0.33	0.001	0.45	0.001	0.54	0.002
$\beta$	0.64		0.63		0.62	
$\Gamma$	0.32		0.33		0.34	
	NT=300	S.D.	NT=360	S.D.	NT=420	S.D.
$\alpha$	0.30	0.03	0.27	0.03	0.27	0.04
$\delta$	0.60	0.03	0.61	0.03	0.55	0.07
$\mu$	0.40	0.01	0.39	0.01	0.37	0.01
$\tau$	0.52	0.03	0.59	0.03	0.67	0.01
$\varepsilon$	0.62	0.002	0.69	0.002	0.74	0.002
$\beta$	0.62		0.62		0.62	
$\Gamma$	0.32		0.31		0.30	

Table 2: Robustness Checks for Different No-trade Intervals.

The table shows the estimates for various no-trade intervals, from 2 to 7 minutes.

The last two rows report two more statistics derived from the estimated parameters and explained in the text.

The estimates of the probability of an information event ( $\alpha$ ) and of a good event ( $\delta$ ) are fairly similar over the different no-trade intervals. The estimate of  $\varepsilon$  increases with the the no-trade interval: this is expected since the number of no-trades in the sample (and, therefore, also in the no-event days) becomes smaller and smaller. To have a characterization of trading activity in no-event days independent of the no-trade interval, following Easley et al. (1997), we computed the probability of observing at least one trade during a 5-minute interval in a no-event day:  $\beta = 1 - (1 - \varepsilon)^{\frac{300}{\text{Seconds}}}$  (where “Seconds” is the no-trade interval). Table 2 shows this probability to be independent of the choice of the no-trade interval.

The parameter  $\mu$  is quite stable across samples, whereas  $\tau$  increases. To understand this, it is useful to observe that if both  $\tau$  and  $\mu$  were constant, as  $\varepsilon$  increases the estimated proportion of trading activity due to traders not having correct information (either because they are noise or because their signal is incorrect) would increase. In contrast, this proportion should obviously be independent of our choice of no-trade interval. This is indeed

the case. To show this we computed the parameter

$$\Gamma = \frac{\mu(0.5 + 0.25\tau)}{(1 - \mu)\varepsilon + \mu},$$

which represents the proportion of correctly informed traders (e.g., informed traders with a signal greater than 0.5 in a good-event day) over the sum of all informed traders and the noise traders who trade. In other words,  $\Gamma$  is approximately equal to the fraction of trades coming from informed traders with the correct signal.<sup>31</sup> It is remarkable that  $\Gamma$ , which equals 0.34 when the no-trade interval is 259 seconds, is constant across all the different datasets that we used to estimate the model’s parameters. This shows the robustness of our results to the choice of the no-trade interval.

Let us now discuss how our results compare to different specifications of the model. A natural comparison is with a model in which the signal precision is not estimated, but is restricted to be perfectly informative (i.e.,  $\tau \rightarrow \infty$ ). This is the case studied by Easley et al. (1997). In this case, all informed traders follow their own private information, the sequence of trades has no informational content beyond the aggregate numbers of buys, sells and no trades, and herding never arises. As a result, the likelihood function does not need to be computed recursively (see Easley et al., 1997, for a detailed description). Table 3 presents the estimated parameters.

Parameter	Estimate	S.D.
$\alpha$	0.33	0.04
$\delta$	0.60	0.06
$\mu$	0.17	0.01
$\varepsilon$	0.58	0.002

Table 3: Parameter Estimates for the Easley, Kiefer, and O’Hara (1997) Model.

The table shows the estimates for the four parameter model of Easley, Kiefer, and O’Hara (1997), in which informed traders know the true asset value. The no-trade interval is 259 seconds.

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<sup>31</sup>The approximation is due to the fact that we are ignoring that, because of the bid-ask spread, a small measure of informed traders may not trade. Easley, Kiefer, and O’Hara (1997) report a similar composite parameter when analyzing their results for different no-trade intervals.

The estimates for  $\alpha$  and  $\delta$  are very close to those we obtained for our model. This shows that the classification of days is not affected by the specification of the signal structure. Similarly, the estimates for  $\varepsilon$  in the two models are almost the same. This is not surprising since  $\varepsilon$  captures the trading activity of noise traders, and is not affected by assumptions on the structure of private information. The parameter  $\mu$  is smaller in the restricted model, which is intuitive since this model imposes that all informed traders receive the correct signal (i.e., they know whether a good or a bad information event occurred).

The restriction in Easley et al. (1997) is not supported by the data. The likelihood ratio test overwhelmingly rejects the hypothesis of perfectly informative signals, with a LR statistic of 272.15 (and a p-value of zero).<sup>32</sup> This is important for our aims, since the fact that signals are not perfectly informative implies that the sequence in the order flow matters. In other words, the number of buys, sells and no-trades at the end of the day is not a sufficient statistic for the pattern of trading activity. Depending on the sequence, herd behavior by informed traders may occur in equilibrium.

In the market microstructure literature, a great deal of attention has been given to the PIN, a measure of the probability that a trade comes from an informed trader (see, among others, Easley et al., 1996, and the literature cited in Chung et al., 2005). This measure is given by  $\text{PIN} = \frac{\alpha\mu}{\alpha\mu + \varepsilon(1-\alpha\mu)}$ , where the numerator is the beginning-of-the-day probability that a trade is information based and the denominator is the probability that a trade occurs. With the estimated parameters of our model, the PIN equals 19 percent, whereas for the Easley et al. (1997) model it is only 9 percent.<sup>33</sup> The difference is due to the fact that, in the previous literature, incorrect trades (e.g., sell orders in a good-event day) can only be due to exogenous, non-informative (e.g., liquidity) reasons to trade, whereas in our setup we do not exclude that they may come from informed traders who either receive

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<sup>32</sup>A note of warning on the result of the test is needed here, since the null hypothesis is on the boundary of the parameter space (see Andrews, 2001).

<sup>33</sup>We compute the PIN for our model using the same formula as Easley et al. (1996). They interpret the PIN as the probability of a trade coming from an informed trader at the beginning of the day. In our model, since the signal is continuous, the interpretation is correct only if we ignore the bid-ask spread (otherwise, some informed traders may decide not to trade because their expectations fall inside the bid-ask spread.) We use this approximation for simplicity's sake and to keep comparability with the existing work on the PIN.

the incorrect information or herd. Because of this, the PIN computed for the Easley et al. (1997) model is lower than for our model.

If we adjust for the fact that in our model the information may not be correct (i.e., we multiply the PIN computed with our parameter estimates by the probability of a correct signal  $0.5 + 0.25\tau$ ), the proportion of trading activity stemming from traders with a *correct signal* becomes almost the same as the standard PIN in Easley et al.'s (1997) model. Since the null that the signal is perfectly precise is rejected by the data, our results suggest that the PIN computed from a model with signals that are always correct (that is, as computed in the literature) measures the proportion of informed-based trading coming from traders *receiving the correct information* and not the overall proportion of information-based trading (which is its usual interpretation).

Finally, note that a 99 percent confidence interval for  $\tau$  does not include 1.<sup>34</sup> This means that there is evidence in our sample that there are no realizations of the signal that reveal the true asset value with probability one. In the jargon of the social learning literature, signals are bounded.

## 5.2 Herd Behavior

The estimates of the parameters  $\alpha$  and  $\tau$  imply that herd behavior can occur in our sample. Since the estimate of  $\alpha$  is clearly lower than 1,<sup>35</sup> there is information uncertainty in the market, which is a necessary condition for the mechanism of herd behavior highlighted in Section II to work. Moreover, the estimate  $\tau = 0.44$  means that traders receive a signal that is noisy (i.e., not perfectly informative) and may decide to act against it (i.e., buy upon receiving a bad signal or sell upon receiving a good one).

### The Frequency of Herding

Recall that there is herd behavior at time  $t$  of day  $d$  when there is a positive measure of signal realizations for which an informed trader either herd-buys or herd-sells, that is, when, in equilibrium, either  $\beta_t^d < 0.5$  (herd-buy) or  $\sigma_t^d > 0.5$  (herd-sell). To gauge the frequency of herd behavior in our sample, for each trading day we computed the buy thresholds ( $\beta_t^d$ ) and the sell thresholds ( $\sigma_t^d$ ) given our parameter estimates. As an illustration, Figure

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<sup>34</sup>Since the parameter's standard deviation is 0.02, this is the case for any reasonable confidence interval.

<sup>35</sup>The parameter's standard deviation is 0.03. See the argument in the previous footnote.

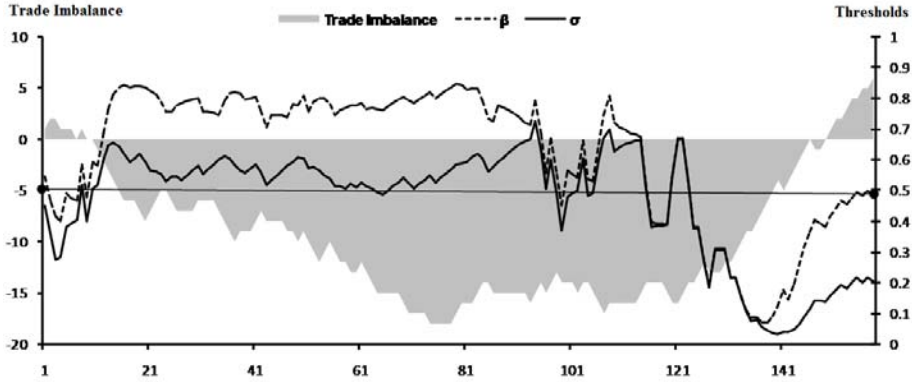


Figure 5: A day of trading. The figure reports the evolution of the trade imbalance (shaded line), buy threshold (dashed line) and sell threshold (solid line) in one day of trading. The thresholds are measured on the right vertical axis, and the trade imbalance on the left vertical axis. Herd-sell occurs when the solid line is above 0.5 (indicated by a horizontal line) and herd-buy when the dashed line falls below 0.5.

5 shows the thresholds (on the right vertical axis) for one day out of the 252 days in the sample. Whenever the buy threshold (dotted line) drops below 0.5 or the sell threshold (solid line) goes above 0.5, there is herd behavior. The shaded area (measured on the left vertical axis) represents the trade imbalance, that is, at each time  $t$ , the number of buys minus the number of sells arrived in the market from the beginning of the day until time  $t - 1$ . As one can see, herd-buying occurs at the beginning of trading activity, as the trade imbalance is positive, that is, as more buys than sells arrive in the market. This is followed by a long stretch of herd-sells, as sell orders arrive and the trade imbalance becomes negative. At the very end of the day, herd behavior effectively disappears.

To understand better the informed traders' behavior, it is useful to look at how the market maker changes his expectation and sets the prices during the day. Figure 6 reports the evolution of the price (i.e., the market maker's expectation) during the day and the probability that the market maker attaches to being in an event day. For the first 100 periods, the market maker's belief on the occurrence of an event fluctuates because, although the sell orders outnumber the buy orders, nevertheless there are many buy

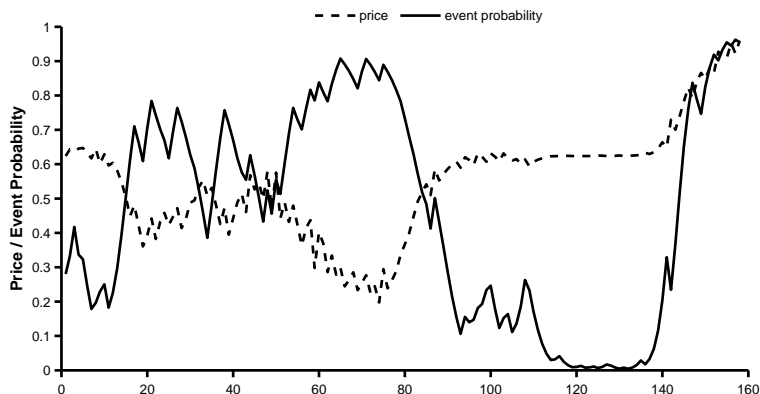


Figure 6: A day of trading. The figure reports the evolution of the price (dashed line) and of the probability that the market maker attaches to being in an event day (solid line) in one day of trading.

orders and several periods of inactivity. After trading time 90, the market maker is confident that there was no event, as his belief on the occurrence of an information event approaches zero.<sup>36</sup> As a result, he does not need to protect himself from adverse selection, and, as illustrated above, the buy and sell threshold become very close to each other. Finally, the sharp increase in the trade imbalance after period 100 leads the market maker to reassess (i.e., eventually, to increase) the probability he attaches to an information event, thus leading to a widening of the thresholds.<sup>37</sup>

In order to analyze the frequency of herding across all the days in our sample, we compute how often the buy threshold is below 0.5, or the sell threshold is above 0.5. It should be clear that this analysis is relevant both for event and no-event days. In both cases, the existence of signal realizations for which informed traders herd (if an information event has occurred, which neither the market maker nor an external observer knows at the moment of

<sup>36</sup>The sharp reduction in the probability that the market maker attaches to an information event between periods 80 and 100 is due to the fact that although we are in a period of herd sell, the trade imbalance is fairly constant.

<sup>37</sup>As one can observe in Figure 6, the price evolution is quite smooth, whereas the market maker's belief on the occurrence of an event swings considerably. This is due to the extreme asymmetry of information between traders and market makers on whether an event has occurred or not.

the trade) modifies the way the market maker updates the price, which, as we shall see, affects the market’s informational efficiency.

In our sample, herding happens quite frequently: over the 252 days of trading,  $\beta_t^d$  is below 0.5 in 30 percent of trading periods, and  $\sigma_t^d$  is above 0.5 in 37 percent of trading periods. Moreover, there are some days where herding is very pronounced. Table 4 reports the proportion of days in which the buy or sell thresholds (i.e.,  $\beta_t^d$  or  $\sigma_t^d$ ) cross 0.5 at least 10, 30, and 50 percent of the time. Herd-buying was observed in more than 50 percent of the trading times in 23 percent of the 252 days in our sample. Similarly, herd-selling was observed in more than 50 percent of the trading times in 35 percent of the 252 days in our sample.

	> 10%	> 30%	> 50%
Herd-Buy	0.79	0.47	0.23
Herd-Sell	0.83	0.58	0.35

Table 4: Days with High Frequency of Herd Behavior.

The table shows the proportion of days in which the percentage of trading periods with herd behavior was higher than 10, 30 or 50. For instance, in 23 percent of days, herd-buy periods were at least 50 percent of the total.

	Herd-Buy	Herd-Sell
Mean Time	60	61
Mean Length	9	10
Length S.D.	13	15
Max Length	99	120

Table 5: Time and Length of a Herd.

The first row of the table shows the mean trading period in which herd behavior occurred. The other rows show the mean, standard deviation and maximum for the number of consecutive trading periods in which there was herd behavior.

Table 5 reports the mean period of the day when we observed herding, that is, approximately the 60<sup>th</sup> trading period for both herd-buy and herd-sell (which, in clock time, is roughly after 2 hours and 36 minutes of trading).<sup>38</sup>

<sup>38</sup>On average there are 149 decisions in a day (390 minutes). Therefore, the average length of a trading period is 2.6 minutes.

It is also interesting to ask how long periods of herding last, that is, for how many trading periods after a herd starts we observe a positive measure of herders. Herd-buys last on average 9 trading periods (corresponding to about 24 minutes) and herd-sells last on average for 10 periods. There is, however, pronounced variability in the length of herds, with a standard deviation of 13 and 15 trading periods. The longest herd-buy lasted for 99 periods (about 257 minutes) and the longest herd-sell lasted 120 periods (312 minutes).

### Proportion of Herders

The previous analysis helps us gauge how often herding occurs in our sample. The fact that at a given time the buy (sell) threshold is lower (higher) than 0.5, however, does not tell us how likely it is for an informed trader to herd at that time. This is captured by the measure of signal realizations for which an informed trader herds. As we will discuss in detail in the next subsection, this measure is also very important for the informational efficiency of the market. The higher the measure of signal realizations for which traders herd, the lower the informational efficiency.

To compute the measure of herd-signal realizations, however, we need to know the distribution of signals on any given day. This, in turn, depends on whether the day of trading was a good-event or a bad-event day. To this purpose, we classified a day as a good-event day (bad-event day) if either  $\Pr(V_d = v^H | h_{T_d}) > 0.9$  (good-event day) or  $\Pr(V_d = v^L | h_{T_d}) > 0.9$  (bad-event day). That is, we classified a day as a good (bad) event day if at the end of the day, the posterior probability of the day being a good (bad) event day was higher than 0.9.<sup>39</sup>

We concentrated our analysis on the days classified as good-event or bad-event days. For each trading period, we computed the proportion of bad signals for which informed traders would herd-buy, and the proportion of good signals for which informed traders would herd-sell. Consider, for instance, a good-event day. On such a day, the signal is distributed according to  $g^H(s_t^d | v_d^H) = 1 + 0.44(2s_t^d - 1)$ . For each trading period in which  $\beta_t^d < 0.5$ , we computed the measure of signals between  $\beta_t^d$  and 0.5 (i.e., the measure of signals for which an informed trader herd-buys). We then divided this measure by the measure of signals between 0 and 0.5 (the measure of all bad

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<sup>39</sup>Of course, the 0.9 threshold is arbitrary. As a robustness check we repeated the calculations for 0.75, 0.8 and 0.85 and obtained very similar results. The results are available in an Addendum available on request.



signals, i.e., all signals for which the informed trader could potentially herd-buy). We refer to this ratio as the “proportion of herd-buyers,” since it is the proportion of informed traders with a bad signal who would nevertheless herd-buy were they to trade in that period. The proportion of herd-sellers was calculated in a similar way. We report the average results in Tables 6 and 7.

	Average	S.D.	Max
Herd-Buyers	2%	3%	11%
Herd-Sellers	4%	6%	29%

Table 6: Percentage of Herders.

The table shows the mean, the standard deviation and the maximum of the percentage of herd-buyers and herd-sellers.

	> 1%	> 5%	> 10%
Herd-Buyers	0.53	0.16	0.07
Herd-Sellers	0.55	0.22	0.11

Table 7: Event Days with a High Percentage of Herders.

The table shows the proportion of days in which the percentage of herd-buyers or herd-sellers was higher than 1, 5 or 10. For instance, in 11 percent of days, the percentage of herd-sellers was at least 10.

On average, across all event days, the proportion of herd-buyers was 2 percent and that of herd-sellers 4 percent. These proportions are, however, quite variable across days, reaching a maximum of 11 percent for herd-buy and 29 percent for herd-sell. Misdirected herding (i.e., herd-buying in a bad-event day and herd-selling in a good-event day) does occur: on average, in a bad-event day the proportion of herd-buyers was 1 percent; in a good-event day, the proportion of herd-sellers was 2 percent.

As Table 7 shows, there are a substantial number of days where the percentage of herd-buyers or sellers is significant: for instance, in 7 percent of event days, the proportion of informed traders who herd-buy was higher than 10 percent; similarly, in 11 percent of event days, the proportion of informed traders who herd-sell was higher than 10 percent. This confirms the

result of the previous section that herding behavior seems to be particularly concentrated in some days of trading.

An important question is whether herding usually happens after buy or sell orders have accumulated in the market. Table 8 shows that this is actually the case. The first row of Table 8 reports the average level of the trade imbalance in periods of herd-buy (i.e., when  $\beta_t^d < 0.5$ ). The trade imbalance is on average positive both in good and in bad-event days. This means that herd-buy usually happens when there has been a preponderance of buys. Similarly, the second row of Table 8 shows that herd-selling usually occurs when there has been a preponderance of sells.

	Good-Event Days	Bad-Event Days
$\beta_t^d < 0.5$	9	3.5
$\sigma_t^d > 0.5$	-8.2	-12.9

Table 8: Trade Imbalance in Periods of Herding.

The table shows the average level of the trade imbalance in periods of herd-buy and herd-sell.

	Good-Event Days	Bad-Event Days
$\Pr(\text{buy} \beta_t^d < 0.5)$	0.48	0.31
$\Pr(\text{buy})$	0.43	0.26
$\Pr(\text{sell} \sigma_t^d > 0.5)$	0.39	0.48
$\Pr(\text{sell})$	0.27	0.45

Table 9: Proportion of Buys and Sells in Periods of Herding.

The table shows the proportion of buys and sells in periods of herd-buy, in periods of herd-sell and in the whole sample.

By definition, herd-buying increases the proportion of buys and herd-selling increases the proportion of sells. Table 9 illustrates this point, by showing the frequencies of buy orders and of sell orders that we observe in periods of herd-buying and herd-selling and contrasting them with the overall frequencies. In good-event days, for instance, the overall frequency of buy orders is 43 percent. This frequency goes up to 48 percent when there is herd-buying. Two comments are in order. First, the pattern shown in Table 8 is

inconsistent with models in which the signals are always correct (as in Easley et al., 1997). In this class of models, the probability of any action is constant as long as one conditions on the type of day (good event day, bad event day, or no information day). This is not true in the data, and is a deviation from the prediction of Easley et al. (1997) that our analysis captures (since, in our model, the probability of a given action changes with the whole sequence of trading activity, as the buy and the sell thresholds change). Second, the results of Tables 8 and 9 taken together imply that higher positive (negative) levels of the trade imbalance increase the probability of a buy (sell) order. That is, herd behavior generates serial dependence in the trading pattern during the day.<sup>40</sup>

As a final remark, let us observe that our analysis of herding bears little relation to the existing, statistical (i.e., a-theoretical) measures of herding. As we mentioned in the Introduction, these measures of herding (starting with the paper of Lakonishok et al., 1992, (LSV)) do not study herd behavior in the trading activity of a security (a stock). Instead, they focus on whether portfolio decisions by particular classes of fund managers are clustered. This action clustering, labelled “herding” by this literature, may derive from real imitation, but also from many other factors (e.g., common reaction to a public announcement). The comparison between the two types of analysis is difficult to carry out not only because the “traditional” measures cannot be used to measure herd behavior as it is defined in the theoretical herding literature, but also because they consider very different types of dataset, typically cross sections of holdings of fund managers at a quarterly or monthly frequency. As a result, it would be impossible to compute the LSV measure on our dataset, or to estimate our measure of herding on the LSV dataset.

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<sup>40</sup>In a related strand of literature, Hasbrouck (1991, 1991a) and Chung et al. (2005), among others, provide evidence of autocorrelation in trades. Easley et al. (1997a; 2008) recognize the importance of serial dependence in trading activity. To capture it, they allow for path dependence in noise trading due to unmodeled reasons. In contrast, in our model, the sequence of trading becomes important for reasons dictated by economic theory.

Nevertheless, one may wonder whether the presence of herding hinges on the assumption that the arrival of noise traders is an i.i.d. process; i.e., whether what we call herding is instead a time dependence in liquidity shocks that we assume away in our maximum likelihood estimation. This is not the case. In an Addendum available on request, we report the results of the estimation of alternative model specifications in which we allow for time-dependence in the behavior of noise traders. We find that, our estimate of the amount of herding in the market does not decrease; if something, depending of the specific form of time dependence, herding may slightly increase.

## Informational Inefficiency

In periods of herd behavior, a proportion of informed traders trade against their signals; as a result, information is aggregated less efficiently by the asset price. Indeed, It is easy to show that trades convey the maximum amount of information when informed traders buy upon receiving a good signal and sell upon receiving a bad one.<sup>41</sup> In periods of herding, in contrast, traders may buy even with a bad signal or sell even with a good one.

To quantify the informational inefficiency caused by herding, we proceeded in the following way. We simulated the history of trades and prices over many days for our theoretical model, using our estimates of the parameter values. We then compared the simulation results with two benchmarks that capture the price behavior in an informationally efficient market. In the first benchmark, we simulated the model forcing informed traders to buy (sell) upon a good (bad) signal. In other words, informed traders (irrationally) never herded and always followed their private information. As a second benchmark, we considered the case in which there is no information uncertainty, that is, the market maker knows whether there has been an informational event. As a result, he updates his beliefs (and prices) exactly as informed traders do, and, because of this, informed traders never herd. Essentially, in the first benchmark, the market is efficient because traders (irrationally) follow their signals; in the second benchmark, the market is efficient because the informational asymmetry between traders and market makers due to event uncertainty is eliminated. The difference between the two scenarios is caused by the bid-ask spread. When, in the first benchmark, we force informed traders to buy (sell) upon a good (bad) signal, we disregard the incentive not only to herd, but also to abstain from trading (because a trader's expectation may fall within the bid-ask spread).<sup>42</sup>

We simulated the price paths for 100,000 days of trading (with 149 trading periods per day) for our theoretical model and for the two benchmarks. Then, at each time  $t$  of any day  $d$ , we computed the distance (i.e., the absolute value of the difference) between the price  $E(V_d|h_t^d)$  in our model and that in the benchmark.

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<sup>41</sup>By this, we mean that the strategy  $X_t^d = -1$  for  $s_t^d < 0.5$  and  $X_t^d = 1$  for  $s_t^d > 0.5$  minimizes  $E[(E(V_d|h_t^d, x_t^d) - V_d)^2]$ . Note that, for simplicity's sake, we assume that traders cannot use no trades to reveal information, since in equilibrium they abstain from trading only when their expectation is inside the bid-ask spread.

<sup>42</sup>See previous footnote.

Table 10 presents the average distance taken over all trading periods as a percentage of the expected value of the asset. For the first benchmark, we present the average distance both over all days and over informed days only. For the second benchmark, by construction, only the average distance over event days is meaningful.

No-Herd Benchmark		No Event Uncertainty Benchmark
All Days	Event Days	Event Days
4%	10%	7%

Table 10: Informational Inefficiency

The table shows the average distance between the public belief in the model and that in the benchmarks as a percentage of the expected value of the asset.

Av. Distance	No-Herd Benchmark		No Event Uncertainty Benchmark
	All Days	Event Days	Event Days
$\geq 10\%$	0.13	0.37	0.21
$\geq 15\%$	0.07	0.20	0.11
$\geq 20\%$	0.04	0.11	0.06

Table 11: Days of High Informational Inefficiency

The table shows the proportion of days in which the average distance between the public belief in the model and that in the benchmarks is higher than 10, 15, or 20 percent of the expected asset value.

The average distance between the prices in our model and in the first benchmark over all days amounts to 4 percent of the asset expected value. If we focus our attention on event days, the distance is higher (10 percent), since the imbalance between buys and sells causes herding to arise more often. The average distance between the public beliefs using the second benchmark is similar, equal to 7 percent. In Table 11 we repeated these computations for days in which herding was more pronounced. In 7 percent of days (20 percent of event days) the distance between the price and the non-herding price is greater 15 percent. This suggests that there are days when intraday herding affects the informational properties of the price in a very significant manner.<sup>43 44</sup>

<sup>43</sup>In order to give the reader a point of reference, let us note that Ashland Inc.'s daily standard deviation in 1995 was one percent.

<sup>44</sup>Note that by construction any mispricing due to herding is corrected by the beginning

## 6 Conclusion

We developed a theoretical model of herd behavior in financial markets amenable to structural estimation with transaction data. We estimated the model using data for a NYSE stock (Ashland Inc.) in 1995, and identified the periods in each trading day when informed traders herd. We found that herding was present in the market and fairly pervasive on some trading days. Moreover, herding generated important informational inefficiencies.

The main contribution of this paper is methodological: it provides an empirical strategy to analyze herding within a structural estimation framework. This contrasts with existing empirical studies of herding, which are based on atheoretical, statistical measures of trade clustering.

In future research, we plan to use our methodology to investigate the importance of herding for a large number of stocks, by analyzing how herding changes with stock characteristics (e.g., large stocks versus small ones) and with the macroeconomic environment (e.g., crises versus tranquil periods). We also plan to contribute to the existing literature on information and asset pricing, both by studying whether our measure of market informativeness (which takes into account that information may not be perfectly precise) improves the performance of the information factor, and by testing whether herding itself is a risk factor priced in the market.

Finally, whereas our interest was in learning in financial markets, our methodology could be fruitfully used in fields other than financial economics. The voluminous and growing theoretical literature on social learning has been intensively tested in laboratory experiments. It is, however, generally acknowledged that these models cannot be easily studied with field data, because we lack data on private information. Our methodology shows how this problem can be overcome.

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of the following day (by which point the previous day's asset value is learned). This, however, does not lower the relevance of such mispricings. Trades are executed throughout the day at prices that are not the closing prices. In as much as there are deviations from the informationally efficient price, this will affect the welfare of the traders, including those who are not in the market for speculative reasons.

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