The Speed of Information Revelation and Eventual Price Quality in Markets with Insiders: Comparing Two Theories

Abstract

Two theoretical literatures, one on strategic revelation of private information, and the other on noisy rational expectations equilibrium (NREE), both provide a foundation for understanding how private information is impounded into asset prices, yet some of their predictions are conflicting. Here, we compare for the first time the two theories using data from carefully controlled laboratory asset markets. In the dynamics, we find strong evidence for strategic revelation theory, while final prices support the static predictions of the NREE theory. Price volatility increases when information is being impounded in prices.

1. Introduction

What is the speed at which private information is incorporated into the market price of a security? Is the outcome of the price discovery process affected by the number of informed traders in an economy, or will the same information eventually be revealed in prices, irrespective of the number of informed agents in the economy? These and other questions have been closely examined in two separate theoretical literatures: one using Bayesian Nash equilibirum (Kyle (1985); Holden and Subrahmanyam (1992)) and the other using noisy rational expectations equilibrium (REE) (Grossman and Stiglitz (1980); Hellwig (1980); Diamond and Verrecchia (1981); Brennan and Cao (1996)). Results from the parallel literatures show similarities, but a critical difference involves the relationship between the number of informed agents and the informational efficiency of the final market price.

On the one hand, a strategic trading environment should induce competition among insiders, resulting in brisk trading and an equilibrium governed by eventual full information revelation. In a strategic environment with imperfect competition, each trader has the ability to impact the price through his own individual trading. Hence, equilibrium in this environment requires that all traders respond optimally to each other, which will result in traders competing any informational rents to zero, and thus full information revelation. A rational expectations equilibrium, on the other hand, is rooted in the assumption that traders engage in perfect competition, and as such, do not have the ability to impact the market price through their trading. A rational expectations equilibrium may not entail fully revealing prices, as traders may not be able to fully invert prices to infer information due to exogenous noise in the environment. Although both the noisy rational expectations equilibrium and the Bayesian Nash Equilbrium (BNE) are richly developed theories that produce precise predictions of informational efficiency, empirical tests of each theory have yet to be as successful (Biais et al. (2009)). These tests are necessary if we are to have a better understanding of the predictive power of each theory in explaining trading patterns and prices in markets with asymmetric information. An inherent difficulty in performing such tests is the inability of the researcher to identify who holds information at what time. To sidestep this difficulty we design an experiment to test how well each theory can describe data from carefully controlled laboratory asset markets.

Our experimental treatments allow us to examine the relationship between eventual price quality and the proportion of informed traders in an economy. In particular, we vary the number of traders in our experimental asset market that receive inside information regarding the liquidating dividend of a risky security, which allows us to quantitatively identify the amount of information that is not revealed to the market by the end of trading. Moreover, our markets are run in a continuous double auction institution that provides us with time series data to study statistical properties of prices and volatility that we find to be associated with the information structure in the economy. We find that both the final price quality and speed of information transmission are associated with the number of informed agents, empirical facts that are predicted by REE and BNE theory, respectively.

Our experimental design follows in the footsteps of Plott and Sunder (1988), and hence, is informed by asset pricing theory. This contrasts with other recent work in experimental finance on the impact of insiders, notably that of Schnitzlein (2002), where the design is rooted in market microstructure theory, and hence, game theory. There, control of common knowledge is key (Aumann (1976)), in contrast with asset pricing theory, where mere knowledge of prices (and good forecasting of future price paths) is needed (Radner (1972)). Nevertheless, we demonstrate here that BNE theory does make valid predictions when agents do not have common knowledge about the underlying structure of the economy. One of the contributions of our work, therefore, is to establish that the essence of the dynamics in a standard experimental asset pricing setting continues to be well captured by game-theoretic inspired models like Holden and Subrahmanyam (1992), even when the assumption of common knowledge is not satisfied. As a result, we are the first to empirically establish, within a common setting, a link between market microstructure theory and asset pricing theory. The need to so had first been articulated in O'Hara (2003). Specifically, our main result ties together the two strands of theoretical literature, as our data support the dynamics of the BNE theories (Holden and Subrahmanyam (1992)), and the final market price predicted by the noisy REE theory (Grossman and Stiglitz (1980)).

2. Theory

Asset pricing theory under asymmetric information has relied extensively on two competing notions of equilibrium behavior: Rational Expectations Equilibrium (REE) and Bayesian Nash Equilibrium (BNE). For the purpose of microstructure analysis, the critical difference between the two equilibrium concepts involves the impact that each agent can have on the price. In particular, the REE model does not allow the individual agent to impact the price; agents are competitive and take the price function as given when formulating demands for securities. In contrast, BNE is used to model strategic situations where individual agents can be "large" and are allowed to impact the price function given their demand schedules, but they take others' actions as given. In this section, we highlight the relevant aspects of both well-developed theories and ultimately produce testable hypotheses to determine the aspects of each theory that can best predict the results from our controlled experimental markets.

Noisy Rational Expectation Equilibrium

Under the Noisy REE framework (Grossman and Stiglitz (1980); Hellwig (1980); Diamond and Verrecchia (1981)) prices partially reveal inside information to the rest of the market. In what follows, we focus on the theory of Grossman and Stiglitz (1980) as our experimental design examines information *revelation* where each insider is endowed with the same piece of information[1], as opposed to information *aggregation* where signals of the underlying state of the

[1] In the original Grossman-Stiglitz (1980) model, inside information is acquired endogenously, at a fixed cost. In our design, insiders are exogenously endowed with information for simplicity.

economy are dispersed (Hellwig (1980); Diamond and Verrecchia (1981)). Moreover, while there are dynamic models of REE, they will not apply in our setting as our experiments do not involve intermediate consumption, nor do they involve the dissemination of new information or noise over time (Grundy and McNichols (1989); Wang (1994); He and Wang (1995); Brennan and Cao (1996)).

In the Grossman and Stiglitz (1980) model, uninformed traders infer inside information from the market price, which, in equilibrium, is determined by a convex combination of the demands of the uniformed and informed segments of the market. The equilibrium weight placed on the informed agents' demand increases with the proportion of informed agents in the market. This ultimately leads the price to be more responsive to the insiders' signal in a market with a higher proportion of informed agents. Hence, the theory predicts that *ceteris paribus,* markets with a higher proportion of informed agents (with homogenous signals) will have a more informative price at all times, where we define *informativeness* by

$$\frac{1}{|p_t - \theta|}$$

where p_t denotes the price at time t and θ denotes the signal the insider receives before the start of trading.

Because the NREE theory makes quantitative predictions about the equilibrium price efficiency as a function of the proportion of the economy that is informed, it is important to have sufficient exogenous variation in this variable in order to obtain powerful statistical tests of this theory. We therefore vary the proportion of the informed agents in our markets over a wide parameter range (0 to 0.75). This element of our design contrasts with Schnitzlein (2002) who uses markets with 0, 1, or 2 informed traders because the focus of that paper is on the BNE theory. As we describe in the next section, BNE predicts that strategic competition among any N>1 insiders should give rise to the same level informational efficiency as reflected in the final market price; hence, the design in Schnitzlein (2002) is not concerned with quantitatively assessing the role that the marginal insider plays in impounding information into asset prices. To put it another way, our design is aimed at testing different concentrations of oligopolistic competition, whereas Schnitzlein (2002) is concerned with testing between monopolistic and duopolistic competition.

Bayesian Nash Equilibrium

The Bayesian Nash Equilibrium (BNE) concept allows traders' orders to impact the market price, in contrast to the price-taking assumption of the noisy REE model. Hence, the BNE concept gives rise to strategic interaction among traders where insiders may have an incentive to slowly reveal their private information over time. The seminal analysis of insider trading using BNE was done in Kyle (1985) where it is shown that an information monopolist will reveal his private information gradually over time to the market by submitting market orders. Holden and Subrahmanyam (1992) (henceforth HS) extend this to competition of long-lived private information between multiple insiders. This extension represents the type of imperfect competition that we envisaged in our experiments.

HS study a multi-period asset market with a single risky asset that pays a liquidating dividend, v, at the end of N periods. The dividend value is normally distributed and only the informed agents in the economy see the realized value of the liquidating dividend before the first trading period. Hence, there are only two types of agents, the informed and the uninformed, and each informed agent has identical information (a more general setup allowing for correlated signals across insiders is examined in Foster and Viswanathan (1996)). HS show that several market variables, including the informational efficiency of price is a function of the number of insiders in the market. In particular, they find that as the number of informed agents increases so does the informational efficiency of the price, as measured by the conditional variance of the equilibrium market price at each trading period. See Figure 1, which is reproduced from HS. Intuitively, competition causes insiders to be more aggressive early on, for fear of others stealing their information rents. In the limit, as the number of insiders approaches infinity, all information is incorporated into the market price in the first trade.

However, although HS find that information is revealed at different speeds as a function of the number of insiders, they also conclude that the *"*informational advantage in financial markets is competed away extremely rapidly even in the case of just two informed traders*"* [p. 257 of Holden and Subrahmanyam (1992)]. By the last period of trade, all inside information is incorporated into the price. The predictions of HS contrast with those from Bertrand competition. Under Bertrand competition, from the moment there are two insiders with enough financial clout to potentially buy or sell the entire supply of securities at hand, all inside information is revealed instantaneously.

Prior experimental work (Schnitzlein (2002)) has shown that when the assumption in HS of common knowledge of the number of insiders in the market is violated, the dynamics of the HS framework are not achieved. However, the experimental design in Schnitzlein (2002) is of a very different nature from ours. Like the HS theory, it is heavily rooted in game theory, and hence common knowledge (and relaxation thereof) is crucial. Our design is inspired by asset pricing theory, which builds on knowledge of prices and accurate ("rational") expectations of future prices[2], and hence *does not invoke* common knowledge in order to arrive at equilibrium pricing. Interestingly, our experimental results

[2] Motives for trade in our experiment are explicitly based on risk aversion. Moreover, there is no aggregate risk in the economy, which means that asset pricing theory predicts prices will behave "as if" every subject is risk neutral. This allows us to interpret prices without concern for (unobservable) levels of individual risk aversion.

imply that several of HS' predictions are robust to the paucity of common knowledge[3].

In our experimental markets, we exogenously manipulate the amount of private information in the economy by endowing a different proportion of 20 traders with private information across different periods. This simple treatment technique allows us to formulate testable hypotheses based on the previously discussed theories:

> Hypothesis 1a (BNE): Under the Bayesian Nash Equilibrium model, the speed at which the price converges to the underlying fundamental is positively correlated with the proportion of informed agents in the market.
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> Hypothesis 1b (BNE): Under the Bayesian Nash Equilibrium model, although the speed of information transmission varies with the proportion of insiders in the market, all private information is eventually incorporated into the market price.
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> Hypothesis 2 (Bertrand): Under Bertrand competition, we expect insiders to immediately compete away any informational profits and the price will instantaneously reflect all inside information.

[3] One potential reason for the different effect of common knowledge in our design compared with that of Schnitzlein (2002), is that in our design, the focus is on uncertainty over the number of insiders within an oligopoly information structure. In the Schnitzlein (2002) design, there is uncertainty over the *type* of information structure: monopoly, duopoly, or oligopoly.

Hypothesis 3 (Noisy REE): Following Conjecture 1 from Grossman and Stiglitz (1980) [p. 394], *"The more individuals who are informed, the more informative is the price system."* However, the equilibrium price is never fully revealing.

Because our experimental setting does not include intermediate consumption or the introduction of new information or noise over the course of a trading period, the dynamic NREE models do not apply in our setting. Hence, we refrain from making any predictions regarding the dynamics of pricing from the NREE model. It would be interesting to develop a model of dynamic NREE that corresponds to our experimental setting, but we leave that for future research.

Price Volatility and Information Transmission

Key to the theory of asset pricing under asymmetric information is the ability of uninformed traders to infer private information from the market price; that is, uninformed traders are assumed to be able to invert the price function, even if only imperfectly. Much of the theory on information transmission and revelation takes the ability of the uninformed to do this as given, and voluminous experimental research, starting with Plott and Sunder (1988), has repeatedly shown that even novice traders are quite capable of correctly reading information from prices (Lundholm (1991); Ackert (2008)). A recent neuroeconomic study (Bruguier et al. (2010)) showed that, during replay of markets with insiders, uninformed traders engage theory of mind, an innate human capacity to detect and track intentionality in their environment. Theory of mind is thought to rely on pattern recognition, but it is unknown what these patterns (statistical properties of price dynamics) are in the case of markets with insiders that allow the uninformed to track the information of the informed. Bruguier et al. (2010) provide preliminary evidence that the trading decisions of insiders generate excess volatility, which uninformed market participants could use to ascertain their presence. Likewise, in field data, price volatility is higher during trading than when markets are closed, a finding that is generally attributed to the presence of insiders, who of course have to rely on trade (and hence, open markets) to profit from their informational advantage (French and Roll (1986)). See also Ederington and Lee (1993), who show that an increase in volatility is often a signal that private information is entering the market.

These findings prompt us to conjecture the following about the link between insider information and volatility[4]:

> Hypothesis 4: Volatility is highest at the beginning of the period when the information asymmetry is strongest, and it decreases over time as information is incorporated into the market price

[4] The equilibrium volatility is difficult to compute analytically under the HS theory. Furthermore, our conjectures about volatility are inherently dynamic, and hence are not predicted by the static NREE theory. It follows that our conjectures are not necessarily rooted in either the HS or NREE theory, but instead are meant as exploratory hypotheses about the mechanism through which the uninformed can infer information from statistical regularities in pricing.

Our reasoning is that at any point in time, the price in a market with fewer insiders is less informative, and hence there is more information yet to be incorporated into the price. In summary, we hypothesize that markets with insiders can be characterized by the time series of volatility, and furthermore, this time series may have power to reveal the proportion of the market participants that is informed.

3. Experimental Design

We ran a series of virtual stock markets using an anonymous, online platform, like Euronext and other electronic financial markets in the real world, which uses the continuous open book exchange mechanism. The platform is open-source and is fully described online at http://jmarkets.ssel.caltech.edu/. A screenshot of the trading interface and instructions which were read aloud to subjects while they followed along on the computer are located at: http://clef.caltech.edu/exp/info/.

A total of five *sessions* were run, each with twenty different subjects and each session consisting of thirteen independent *periods*[5]. The periods were five minutes long during which subjects were allowed to trade by submitting anonymous but publicly displayed orders.

[5] Hence, we use a between-subjects design so as to maximize exogenous variation in the number of insiders across the 65 periods.

Before trade started in each period, subjects were endowed with notes, cash, and two risky securities, all of which expired at the end of the period. The two risky securities (stock X & stock Z) paid complimentary dividends, and the notes always paid 50 cents. Denote the dividend paid by Stock X as *v*, so that stock Z always paid 50-*v* cents. Endowments were heterogeneous across subjects, but the aggregate supply of the two risky securities was always equal so that there was no aggregate risk. Theoretically, risk neutral pricing should obtain: prices should equal the expected payoff of the asset.

We appealed to risk (or ambiguity) aversion as an inducement for trade. We allowed trade only in X and the note, but *we closed market Z for trading.* As such, participants endowed with more units of X than Z could obtain a balanced (risk-free) portfolio only by selling X, while participants endowed with more of Z than X could balance their portfolio only by buying X. Because there were an equal number of participants in both categories, and because there was no *a priori* reason to expect that subjects in either category were more risk or ambiguity averse than the other, equal price pressure should obtain from the sell and buy side.

This design is a major departure from traditional experiments on asset pricing under asymmetric information, which either start everyone out with an equal endowment of a single risky security so that there is aggregate risk; e.g. the prediction markets of (Arrow et al. (2008)); or those which use differences in payoffs unknown to the participants; e.g., (Plott and Sunder (1988); Camerer and Weigelt (1991)). We prefer our approach because it induces trade without *a priori* imputing a (unknowable) bias in pricing due to the risk or ambiguity aversion that is inevitably present in experiments (Bossaerts and Plott (2004); Bossaerts et al. (2007); Bossaerts et al. (2010)).

In each session, two of the thirteen periods were designated as "control" periods, where no trader received any information regarding the final liquidating dividend of Stock X. The remaining 11 periods were designated "test" periods, where we exogenously manipulated the proportion of the market that was informed. There were exactly 20 subjects in each period, and the number of informed agents ranged from 2 to 15 traders. Table 1 displays the mapping between the number of insiders and the signal given to the insider for each of the 65 periods. In periods with insiders, all agents knew that there were insiders. However, in some periods, only insiders knew *how many* insiders there were, and in other periods, no traders knew the number of insiders.[6]

Insiders received a signal for the period that was drawn uniformly from an interval within 5 cents of the liquidating dividend of Stock X: $\theta \in [v - .05, v + .05]$.[7] All insiders in a period received the same signal. It is important to note that because insiders were endowed with an imperfect signal of the liquidating dividend, they too should engage in trading to hedge endowment risk.

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[6] This is the violation of common knowledge that we referred to above. Note that this feature of the design provides a strong test of the HS theory because if predictions from this theory are upheld without explicit common knowledge of the underlying structure of the economy, this would provide evidence for the robustness of the HS theory to certain informational properties of the economy.

[7] Signals were truncated to fall within the possible range of dividends. Eg, if the liquidating dividend was 0.49, then signals were drawn uniformly from [0.44, 0.5].

Short selling was allowed, and subjects were instructed that the liquidating value of their short position would be deducted from their earnings at the end of the period. Period earnings were equal to the sum of final cash holdings plus any dividends paid for units of stock and notes held (or subtracted for units of stock and notes sold short). We also imposed a bankruptcy constraint that banned the submission of orders that, if executed, could lead to a negative portfolio value for at least one possible value of the liquidating dividend. For insiders, the bankruptcy constraint was evaluated only for those possible values of the liquidating dividend that were consistent with their signal (e.g., if their signal was 0.20, then the bankruptcy constraint was evaluated only for dividend values equal to 0.15, 0.16,…, 0.25). Additionally, this bankruptcy constraint took into account any open orders, so that subjects could not place orders that could lead to bankruptcy conditional on open orders being executed.

Earnings were cumulative across periods, and final payouts included a $10 show-up reward. All sessions were ran at Caltech's Social Sciences Experimental Laboratory, drawing participants from a pool of mostly graduate and undergraduate students, and a few postdoctoral fellows as well as staff. Each session lasted just over two hours, of which one hour was devoted to instructions and training in using the trading interface. Instructions are located at http://clef.caltech.edu/exp/info/. Total earnings varied from $35-$75 for a session.

Note that we do not explicitly impose all assumptions of the Kyle and HS models. In particular, we do not model noise traders that submit normally distributed orders, nor do we model the market maker who sets the price equal to the expectation of the liquidating dividend conditional on the price history. Moreover, we allow uninformed liquidity traders to enter orders at their own discretion, which gives rise to the possibility that informed traders and liquidity traders exhibit trading activity that is concentrated during specific time intervals (Admati and Pfleiderer (1988)). We abstract from several of these assumptions as our aim is to test whether theories invoking BNE or NREE have predictive power in a standard trading mechanism, namely, the continuous double auction. They should, if the theories capture the essence of the situation at hand.

4. Results

A. Eventual price quality

In this section we report results from all 65 periods (thirteen periods in five sessions). Periods are differentiated by the number of insiders and the signal that the insiders received, if applicable. Terminal market prices, along with the signal and number of insiders for each period are shown in Table 1. The average (standard error) of the difference between the insider's signal and the final market price was \$0.035 (\$0.004), indicating that the final market price was statistically different from the insider signal ($p<0.001$). This is consistent with results from Schnitzlein (2002) who finds that the mean price error in the final twenty seconds of trading is different from the insider's signal, but is inconsistent with BNE theory as outlined in Hypothesis 1B.

Figure 2 aggregates the sessions by number of insiders, and displays a measure of the mean price error at different points within the period[8]. The mean price error is defined as the absolute value of the difference in the market price p_t and the insider signal θ, $|p_t - \theta|$, averaged across all periods with the same number of insiders. Our first main result is that, unconditional on the number of insiders, price quality monotonically increases over time. This immediately rejects Hypothesis 2, the Bertrand Hypothesis, which claims that prices should immediately reflect the insider information.

As a control, we ran ten periods with no insiders, where we define the signal as the unconditional expected dividend, equal to $0.25. Note that the control periods are similar to the treatment where all traders are informed (which we did not run), in the sense that all traders have symmetric information;[9] this is why the figure suggests a similarity between the treatment with fifteen insiders (where so many traders are informed that their information is inevitably revealed in prices) and the control sessions with zero insiders. Because we set out to examine price patterns as a function of the number of insiders, all subsequent analyses use *only* periods where there are at least two insiders.

Our second main result is that the market price quality at the end of a period is correlated with the number of informed agents in the economy. This is clear from Figure 2, which shows that the mean price error at the end of the period (turquoise bars)

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[8] For all subsequent analyses, we pool data from the treatments with 14 and 15 insiders because there are no significant differences between these treatments, and it increases statistical power for our tests across the remaining treatments.

[9] While all traders have symmetric information in the control periods and in the treatment where all traders are informed, the difference is in the *precision* of the information. In the control period, there is little precision because conditional on the subject's information set, there is uniform probability that the liquidating dividend is in the range of [0, 0.5]. In the treatment where all traders are informed, there is much greater precision as there is uniform probability that the liquidating dividend is in the range $[\theta - 0.05, \theta + 0.05]$.

decreases monotonically with the number of insiders. We estimate an OLS regression of the price error on the number of insiders and the informativeness of the signal using the 55 periods where at least 2 insiders were informed[10]:

$$\left|p_{final} - \theta\right| = \alpha + \beta_1 Insiders + \beta_2 |0.25 - \theta| + \varepsilon$$

We find that $\beta_1 = -0.007$ which is significantly negative (p<0.001); this indicates that increasing the proportion of the market that is informed by 5% (1 trader out of a total of 20) leads to an increase in eventual price quality of 0.007 cents, or, relative to the total price range of 0 to 50 cents, a 1.4% increase in price efficiency. We also find that $\beta_1 = 0.398$ which is significantly positive (p<0.001). This indicates that a more informative signal (one that is drawn near the extremes of the range [0, 0.5] also leads to an increase in eventual price quality. One potential reason for this is because it may be easier for uninformed traders to learn from the market price when the signal is "far" from their *ex-ante* expectation of the liquidating dividend: 0.25. Moreover, using only these two regressors, we find the r-squared from the regression to be 0.55 suggesting that this simple bivariate linear model has substantial predictive power.

Our second main result supports the noisy REE hypothesis (Hypothesis 3), originally put forth in Grossman and Stiglitz (1980). Conversely, this result rejects the notion that competition between insiders should drive prices (immediately) towards the fully revealing equilibrium via Bertrand pricing (Hypothesis 2). Because the final market price, on average, *does not reach* the fully revealing price, we also reject Hypothesis 1b, which states that all information will eventually be reflected in prices, regardless of the number of insiders.

[10] Each period was treated as an independent observation.

An important question given our results is, what is the source of the end-of-period mispricing? We conjecture that there are two possible mechanisms that can prevent prices from being fully efficient in our setting. The first possibility is a stochastic aggregate supply of risky asset shares, which is precisely the source of the mispricing in the original Grossman and Stiglitz (1980) model. While the aggregate supply of shares of the risky stock in our experiment is a fixed parameter at the beginning of each period by the experimenter, it is unknown to every subject. Hence, in the tradition of Bayesian analysis within each subject's information set, the aggregate supply is in fact a random variable, and thus the mispricing may be driven by this stochasticity.

Another potential mechanism that could drive the final mispricing is subject error. Because the size of the mispricing is highly correlated with the number of informed traders, it is likely the case that if the source of mispricing is due to subject error, it is on behalf of the informed trader subjects, who effectively "leave money on the table" at the end of the period. This is consistent with past experimental work showing that subjects may not always compete prices down to cost in a Bertrand setting, which can be driven by a small probability of some subjects setting prices irrationally (Dufwenberg and Gneezy (2000)). While we speculate that the mispricing is driven by either stochastic aggregate supply or subject errors, our data do not allow us to identify which of the two are in fact driving the wedge between final prices and the insider signal[11].

We conclude that the noisy REE theory explains final price quality of our asset markets with asymmetric information better than either the BNE concept or Bertrand competition.

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[11] Future work would be able to test the noisy aggregate supply hypothesis by exogenously varying the uncertainty of the aggregate supply from the subject's point of view.

B. Speed of information revelation

Our third main result concerns the speed at which private information is transmitted to the market. Figure 2 shows a significant difference in the amount of information transmitted to the market within 30 seconds, between the case of 15 insiders and 2 insiders. With two insiders, the market has yet to incorporate nearly any information in the price: the market price is 14 cents away from the insider signal. In contrast, with fifteen insiders, nearly all information is reflected in the price: the market price is a mere 2 cents away from the insider signal.

This suggests that, with more insiders, the price adjustment process is more rapid. Indeed, the speed of price adjustment within the first 30 seconds (measured as the difference in the market price and the conditional expected dividend at 30 seconds) is correlated with the number of insiders ($p<0.001$) as theorized by HS (see Figure 1, reproduced from their article), and encapsulated in our Hypothesis 1a.

While our data qualitatively support the dynamics of H&S, the speed with which information is revealed through trading is substantially slower in our experiments than in the theory. Figure 1 suggests that nearly all information should be incorporated in the price within the first 1/3 of the trading period. Our data (see Figure 2) do not support this: with 2 or 6 insiders, price quality improves significantly during the latter 2/3 of the trading period [$p<0.001$, under the null that price quality improvement is absent; tobit model corrected for left-censoring at 0].

We also cast doubt on the prediction of the HS theory that the prices should converge to the fundamental by the end of the period, independent of the number of insiders (Hypothesis 1b). As we pointed out before, the eventual price quality in our experiments significantly depended on the number of insiders ($p<0.001$). Altogether, while the data support the hypothesis that the speed of information revelation is a function of the number of informed agents in the market, eventual pricing is not as "informationally efficient" as predicted in HS.

C. Volatility

Information aggregation experiments have repeatedly confirmed the ability of uninformed traders, even novices, to readily detect insider trading. Building on preliminary evidence from Bruguier et al. (2010), we conjectured that patterns in volatility reveal not only the presence but also the number of insiders (Hypothesis 4).

We divided each period into several sub-periods, and used the range of transaction prices as our measure of volatility.[12] Figures 3 and 4 document the relationship between volatility and the number of insiders, when partitioning each period into 3 and 10 equal sub-periods, respectively.

Figure 3 shows that all markets exhibit heteroskedasticity. In the first subperiod, volatility is highest in markets with 6 insiders. In the final subperiod, volatility is highest in markets with two insiders. This suggests that, with two insiders, substantial insider

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[12] We also studied the dynamics of volatility when measured as the standard deviation of the error term in second-by-second regressions of transaction prices on insider signal across all sessions with a given number of insiders. This produces qualitatively the same outcomes. The graphs can be obtained upon request.

trading may still be taking place near the end of the trading period. Overall, volatility is indeed negatively correlated with the number of insiders in the final sub-period (p=0.001), consistent with the results from Figure 2 on the speed of information revelation, which showed that markets with more insiders revealed information earlier. We also find that volatility in the middle sub-period is negatively correlated with the number of insiders (p=0.001).

Figure 4 illuminates the fact that volatility in asset markets with two insiders *increases* midway through the trading period, whereas markets with more insiders generally see monotonically decreasing volatility after the first minute (60s) of trading. Also note the similarity in the pattern of volatility between markets with no insiders and markets with fifteen insiders (when nearly all agents were informed).

D. Further details

Although the main focus of this paper is on price dynamics and informational efficiency of prices, our experiments produce a rich data set that can be used to examine other aspects of market microstructure theory. For example, Figure 5 shows the evolution of market and limit orders in an illustrative period with six insiders, stratified by submitter type (insider/uninformed). During this period, prices gradually declined to 9 cents, close to the insider signal of 5 cents (and within insiders' confidence interval).

Strikingly, insiders mostly submit limit (sell) orders (Bloomfield et al. (2005)). As such, insiders are actually providing liquidity, although one-sided. This contrasts with many formal models, including HS, where insiders are *assumed* to submit market orders, and where market makers provide liquidity. The ability of HS to shed light on our experimental data thus shows that the insights of the model do not depend on artificial order type restrictions imposed on market participants. In situations where insiders have the option to submit limit orders as well, thus providing liquidity, some of the main conclusions evidently continue to obtain. Also note that uninformed and informed market order flow seem to be concentrated in specific time intervals, consistent with results in Admati and Pfleiderer (1988).

We are not the first to observe that insiders use limit orders. Our observation is in line with Barner et al. (2005), who also noted that insiders tender limit order contracts. The focus in this paper is on price dynamics and price quality. We leave a study of the microstructure details to a future paper.

5. Conclusion

There are two classes of models that make predictions about price quality in markets with insiders. One comes out of the tradition of competitive analysis and general equilibrium theory, and is known as noisy REE. The second one emerged from a game-theoretic analysis of market microstructure, using the concept of Bayesian Nash Equilbrium. The two classes do not always make the same predictions. In particular, the noisy REE theory predicts that prices will not fully reveal all inside information in the economy, but instead the price will be masked by noise in proportion to the number of informed agents in the market. The market microstructure theory predicts that, by the end of trading, competition for informational rents will have driven the price to fully reveal all private information to the market.

Here, we discussed results from a series of markets experiments where we exogenously vary the number of insiders over a wide range of parameters in order to examine its effect on the informational efficiency of prices. We discovered that noisy REE better predicts the end-of-period price quality. Specifically, we found that price efficiency increased with the proportion of traders that held inside information. This stands in contrast to the prediction that BNE makes about the (static) final market price efficiency, namely, that final market prices should be fully efficient *unconditional* on the proportion of the economy that is informed. On the other hand, the BNE theory quite effectively captured features of price dynamics. In particular, the speed with which information becomes revealed in prices depends on the number of insiders, in accordance with HS. Our experiments also provide positive results in light of Schnitzlein (2002), since we find that even in a far more strategically complex environment than the game-theoretic framework in HS, the dynamics of the HS theory emerge, while the NREE theory is able to provide an explanation for the fact that not all informational rents are captured at the end of trading. This finding allows us to uncover an empirical connection between the literature on market mircrostructure and asset pricing (O'Hara (2003)).

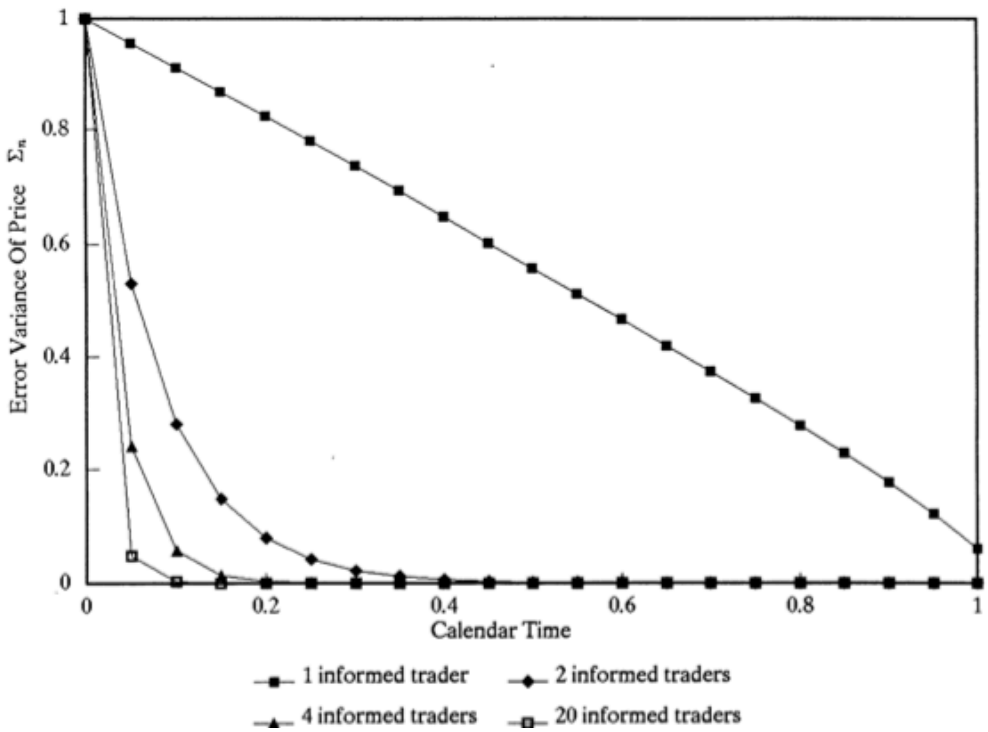
One potential reason why we do not see fully revealing final pricing as predicted by the HS theory is lack of common knowledge about the number of insiders. Although lack of common knowledge does not seem to affect the predictions of the dynamics of HS, it is possible that there may be an effect during the final trading round. As we alluded to above, there are other assumptions from the HS theory which we did not explicitly impose in our design. For example, we do not model noise traders as traders who submit normally distributed orders at each round. The insider's uncertainty about the uninformed traders' strategies may then affect the insider's equilibrium trading strategy. Another possible source for the absence of fully revealing prices is subject error. It may prove interesting for theorists to model the environment in HS, allowing for bounded rationality on behalf of the insiders in order to rigorously understand whether subject error can in fact induce this mispricing, and to look for other interesting theoretical predictions borne out by such a model.

We also discovered that insider trading generates heteroskedasticity that changes with the number of insiders. Consistent with a conjecture in Bruguier et al. (2010), uninformed traders therefore should be able to detect not only the presence, but also the number, of insiders from volatility patterns. Our findings provide support for the standard interpretation of heteroskedasticity in field data, namely, that it reflects incorporation of private information into pricing (French and Roll (1986); Ederington and Lee (1993)). Moreover, the connection we uncover between the number of insiders and the level of price volatility suggests an open avenue for future research on using measures of volatility to detect insider trading.

Our experimental design departs from the standard approach in experimental economics. In particular, we were careful to ensure that participants always had a reason to trade even if no insiders were present. We avoided aggregate risk in order to obtain pricing predictions unaffected by risk or ambiguity aversion. And by closing a market in the complementary asset, we assured that downward price pressure from traders eager to sell to avoid risk or ambiguity was offset exactly by upward price pressure from traders wanting to buy to avoid (the same) risk or ambiguity. It should be added that we never observed "information mirages" (whereby market prices seem to reflect precise insider information, but in fact get it completely wrong; (Camerer and Weigelt (1991); Barner et al. (2005)). It is an open question whether our design – conscious of ambiguity or risk aversion, aggregate risk, and deliberately avoiding no-trade theorems while staying within standard asset pricing theory – explains the absence of information mirages.

Our experiments generate a wealth of data that could be used in the future to study more detailed aspects of the microstructure of markets. It could shed light on, for instance, strategies of insiders when they can choose freely whether to submit limit or market orders. In this respect, we discovered that insiders predominantly trade through limit orders, and hence, provide liquidity (albeit one-sided), corroborating earlier evidence (Barner et al. (2005)), but in contrast with standard restrictions imposed on insiders in theoretical models, including HS.

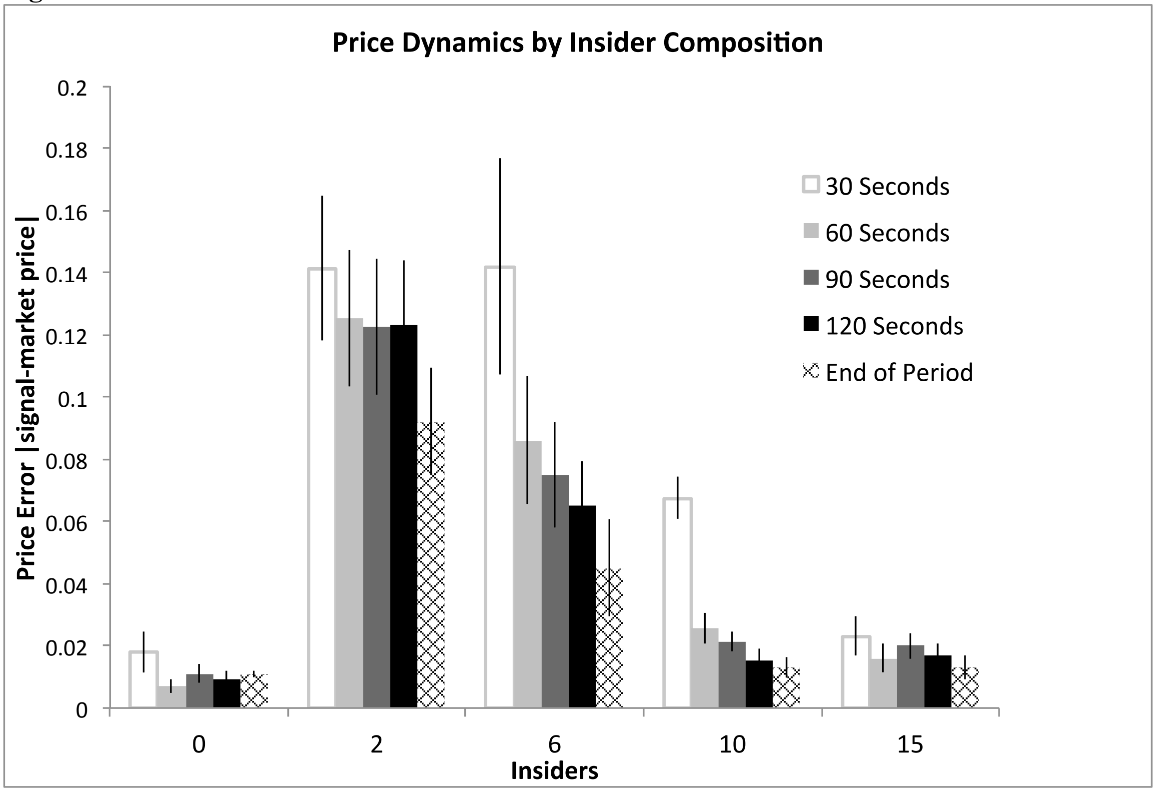
Figure 1



[Reproduced from (Holden and Subrahmanyam (1992))]

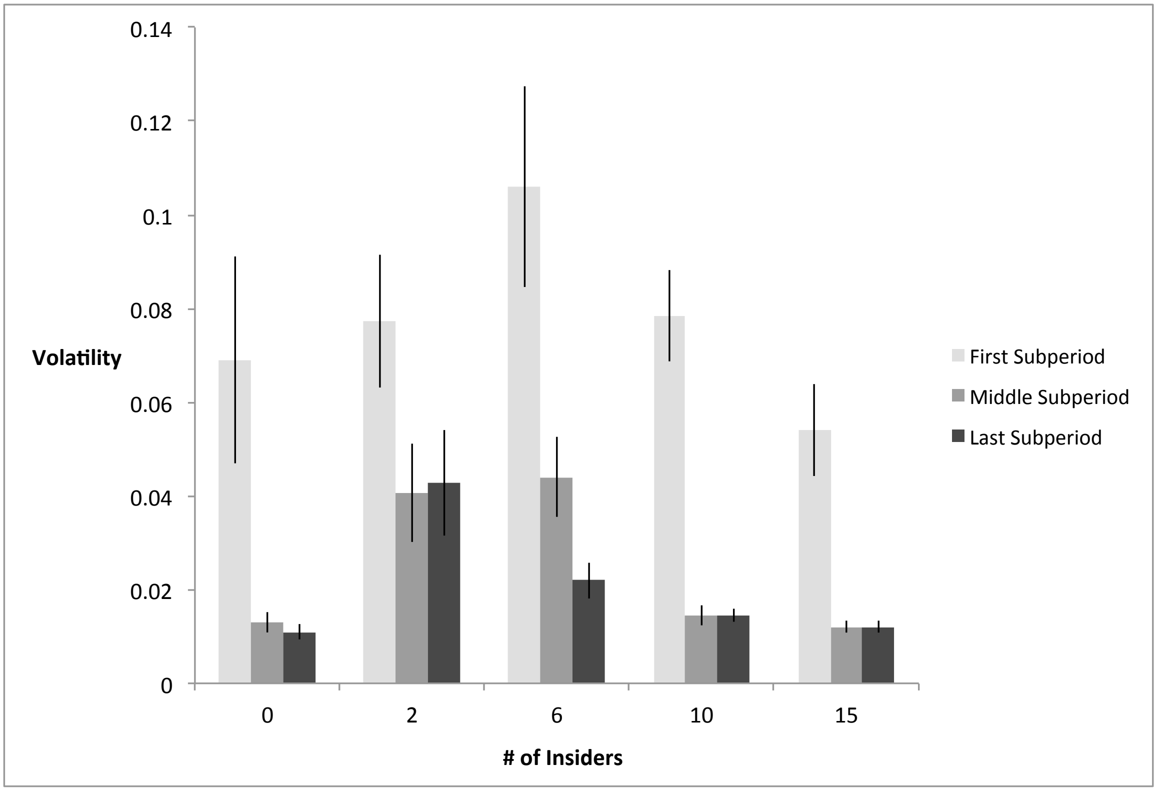
Caption: As the number of competing insiders increases, the price quality augments at an increasing rate, and hence, the error (variance) in the price relative to the inside information decreases.

Figure 2



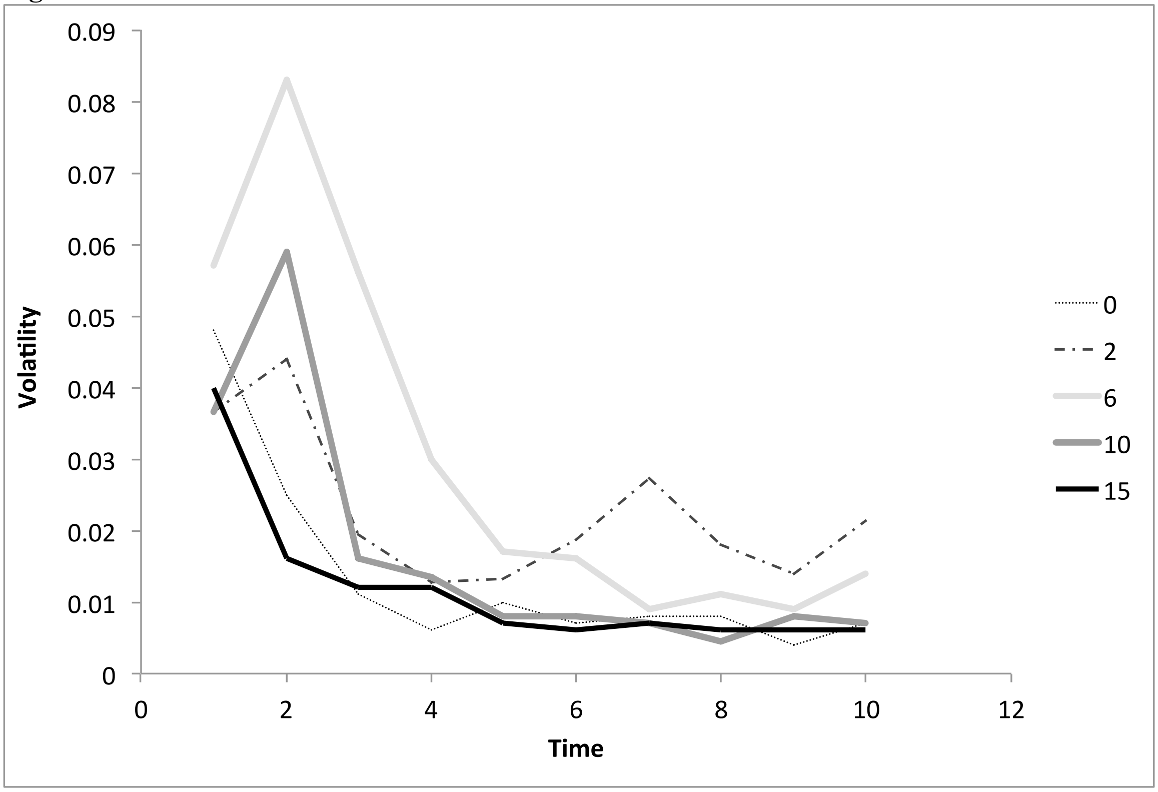
Caption: Price quality (absolute difference between market price and insider signal) after 30s, 60s, 90s, 120s, and at the end of a period (300s), stratified by number of insiders (out of 20 participants). Averages across replications with the same number of insiders (different insider signals). Vertical bars depict interval around average of length equal to two standard errors.

Figure 3



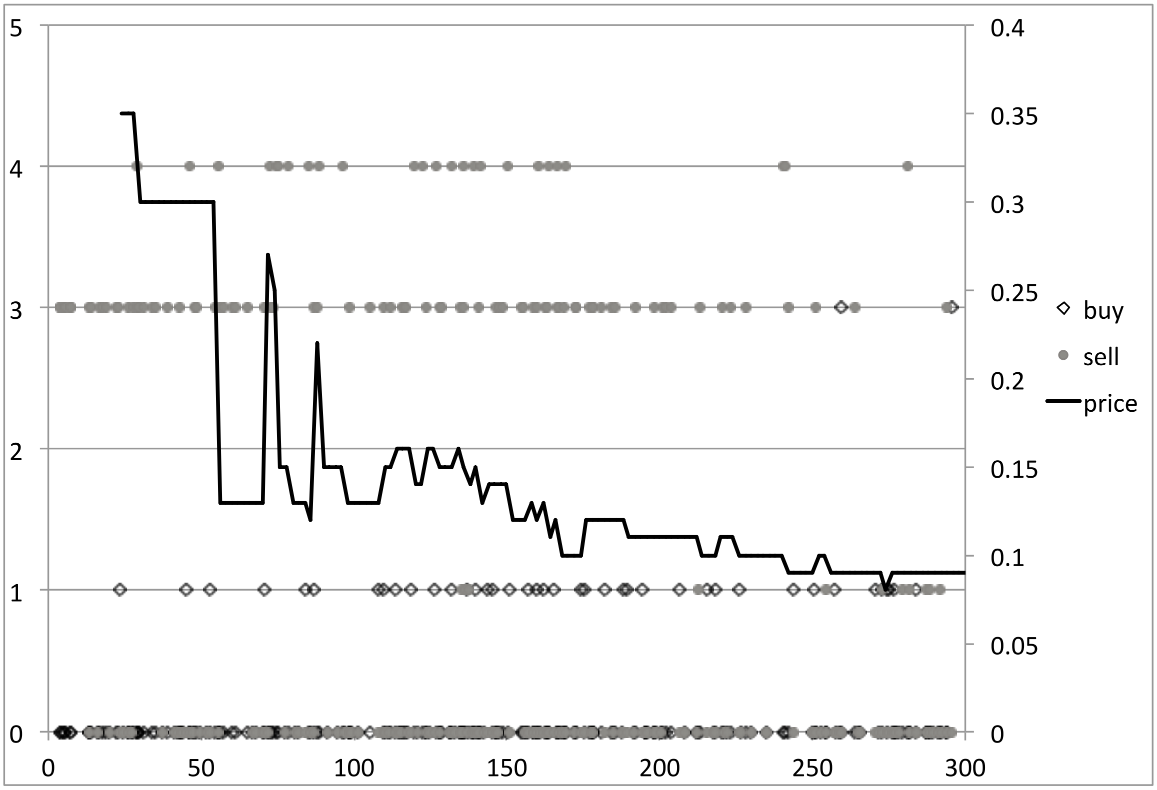
Caption: Average volatility (measured as transaction price range) in three sub-periods of 100s (First, Middle, and Last), stratified by number of insiders.

Figure 4



Caption: Average volatility (measured as transaction price range) per sub-period of 30s, stratified by number of insiders (0, 2, 6, 10 and 15, out of 20 participants).

Figure 5



Caption: Transaction prices (solid black line; right scale) in one illustrative period with six insiders whose signal of the final dividend equaled $0.05. Timing of order flow, per identity of the order initiator (left scale), as follows: (0) uninformed limit order arrivals, bids (black diamonds) and asks (gray circles); (1) uninformed bid and ask market order arrivals; (3) informed bid and ask limit orders; (4) informed bid and ask market order arrivals.

Table 1: Experimental Design. Each row indicates a single period, ordered by number of insiders. Actual experimental sessions consisted to 13 periods each. First column: Number of insiders. Second column: absolute difference between final market price and signal. Third column: insider signal ("x" indicates no signal).

Insiders	Difference	signal
0	0	x
0	0	x
0	0	x
0	0.01	x
0	0.01	x
0	0.01	x
0	0.01	x
0	0.02	x
0	0.02	x
0	0.03	x
2	0.01	0.14
2	0.02	0.31
2	0.03	0.31
2	0.04	0.13
2	0.05	0.19
2	0.07	0.4
2	0.08	0.45
2	0.08	0.45
2	0.09	0.42
2	0.09	0.48
2	0.11	0.14
2	0.12	0.37
2	0.15	0.49
2	0.21	0.49
2	0.23	0.49
6	0	0.12
6	0.01	0.12
6	0.02	0.14
6	0.02	0.46
6	0.03	0.37
6	0.03	0.07
6	0.04	0.37
6	0.04	0.05
6	0.13	0.49
6	0.13	0.46
10	0	0.09
10	0	0.12
10	0	0.41
10	0	0.08
10	0	0.08
10	0	0.4
10	0.01	0.15
10	0.01	0.14
10	0.01	0.12
10	0.01	0.06
10	0.01	0.45
10	0.01	0.06
10	0.01	0.45
10	0.02	0.41
10	0.02	0.28
10	0.02	0.31
10	0.02	0.4
10	0.02	0.31
10	0.03	0.06
10	0.06	0.46
14	0.01	0.41
14	0.01	0.15
14	0.01	0.05
14	0.01	0.41
14	0.04	0.46
15	0	0.05
15	0	0.05
15	0.01	0.19
15	0.02	0.01
15	0.02	0.46

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