Information diffusion and speed competition

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August 11, 2017

Abstract: Fast trading competition and information diffusion naturally arise with the development of trading technology such as HFT and increasing disclosure requirements from market regulators. We study the role of fast trading at different speed by introducing speed competition in a financial market with information diffusion process. Such information diffusion reflects that information diffuses gradually in financial markets or different assessment or view of information among investors, which can be significant and persistent. By introducing trading speed competition in to a benchmark information diffusion model, we show that trading speed competition and faster information diffusion can impede the market quality. Improvement on market transparency and trading technology through speed up the information transparency and fast-trading competition can have unintended and negative impact on market quality.

JEL code:

Keywords:

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1. Introduction

Sequential information arrival models provide a channel to better understand the dynamic market price adjustment process. However, these literatures typically assume that the diffusion of information takes place simultaneously among all speculators. The study of information effects includes three main stages: a) how information diffuses and disseminates among speculators; b) how information is received and processed by speculators; and c) how speculators react to the information. Thus, "the acquisition of information and its dissemination to other economic units are, as we all know, central activities in all areas of finance, and especially so in capital market (Merton, 1986)." There are growing literatures that study the diffusion of information in markets. Manela (2014) argues that faster information diffusion speed has two opposing effects on value of information, which can be explained as "faster-diffusing information means quicker and less noisy profits, but, also increases competing informed trading, impounding more information into prices and eroding profits".

The literature is largely focused on homogeneous information structure, but less so on heterogeneous information. "Financial market and commodity markets can be characterized by a number of informed traders, each with different information (Foster and Viswanathan, 1996)." As an example, consider that Tesla is developing long-haul, electric semi-truck that can drive itself and move in "platoons" that automatically follow a lead vehicle, and is getting closer to testing a prototype. In financial markets differing assessments of government policy about automatically driving, patent filings, corporate marketing policy and demand for products mean investors will have many, distinct views about the future value of the company. Even though the information is gradually diffusing across the investors, these differences of information can be significant and persistent.

The aim of this paper is to understand the role of the speed by which heterogeneous information diffuse and investors' trade and compete for each other. We focus on two distinct aspects and this challenging problem. First, we investigate the influence of faster information diffusion when speculators receive heterogeneous information exogenously by information diffusion process. "Modelling markets with heterogeneous information among the traders becomes complex very quickly because traders infer the value of an asset from not only their own private information, but also using any information revealed by other traders through trading (Foster and Viswanathan, 1996)." Second, recent developments in market practice and academic research have witnessed a significant speed heterogeneity and competition on trading speed in financial markets. We argue that trading at and competitions among different speed are crucial for understanding the impact of faster information diffusion and fast-trading competition.

The backbone of our model is the auction model that Kyle and others have used to capture strategic trading behavior. We model strategic interactions of market participants in an extended Kyle (1985) framework by incorporating information diffusion process and different trading speed among speculators. By allowing informed traders to have different speeds to receive the full information in addition to the information diffusion process, we examine the impact of trading speed competition. Such competition among informed traders affects both informed traders and uninformed traders who receive information only from information diffusion process.

The main insight to emerge is that the slow informed traders' crowd-out effect amplifies the speed's influence on the information value of the fast informed traders. Consequently, these impacts can change the speculators' incentive to become the fast informed traders. This has important implications for the information transparency on the market quality. We show that market becomes more efficient with faster information diffusion when there is no fast-trading competition. However, with the competition, faster information diffusion can impede market quality.

In our benchmark model, the speculators receive heterogeneous information exogenously through an information diffusion process at the same speed. In this case, market quality is improved for the reason that more informative speculators impound more information into price through their trading. To facilitate trading at different speed, we develop a two-period strategic interaction model with asymmetric information and allow some speculators to have the full information earlier than the others at some cost, while uninformed traders only receive the information according to the information diffusion process. We build on an economy populated by speculators who first invest in information technology and then trade a risky asset. Before each trading round, traders make their endogenous information acquisition choice by taking into account both future information diffusion and learning from market prices. Hence, the transmission of information influences equilibrium asset prices and trading volume. Interestingly, we find that faster information diffusion impedes the market quality when traders compete for fast trading.

The result is easily explained. Notice that the information value of the fast informed traders decreases with the fraction of the slow informed traders. Since the fraction of slow informed trader increases with faster information diffusion, the information value of the fast informed traders is more sensitive to the information diffusion speed, comparing to the situation where there is no slow informed trader on the market. As a result, the equilibrium fraction of the fast informed traders reacts more significantly to the information diffusion speed. Even though faster information diffusion improves the fraction of the slow informed traders and makes the uninformed traders become more informative, the sharply decreasing of the fast informed traders dominates the positive effects, which worsens the market efficiency.

2. Information Diffusion and Strategic Equilibrium

To examine the joint impact of information diffusion and competition among traders with different trading speed on traders' trading behaviour and market quality, in this section, we introduce an equilibrium benchmark model of information diffusion and strategic trading. Different from the one-period Kyle model in which the information about the payoff of a risky asset is fully revealed at the end of the period, we assume that the information is revealed gradually to the market over many periods. The amount of information revealed to the market is measured by the speed of information diffusion. To simply the analysis, in this section, we first extend the one-period Kyle model to a benchmark two-period information diffusion model. We then examine the impact of the information diffusion on the strategic trading behaviour of traders, price discovery, and market liquidity in equilibrium.

2.1 The Information Diffusion Model

Assets and traders: There are two assets; a riskless asset with a normalized payoff of one and a risky asset with normally distributed payoff $V \sim N(0, \sigma^2)$. Traders trade for the two assets discretely over two periods, $t = 0, 1, 2$. As in Kyle (1985), all traders are risk neutral. We consider trade among three types of traders over two periods: (i) strategic speculators who receive information gradually about the risky payoff through an information diffusion process (introduced below) and then trade strategically; (ii) liquidity traders who trade randomly

$z \sim N(0, {\sigma_z}^2)$ shares[3]; and (iii) competitive market-makers who absorb the net trading flow and set the market prices[4].

Information diffusion: Unlike the traditional Kyle-based models which assume that the informed traders have the full information about the payoff promptly, the speculators in our model receive the information gradually over two periods. Hence, the speed of the information diffusion influences speculators' informativeness, which in turn affects the revealed information in the market through the trading among traders over two periods.

To capture the idea that information diffuses gradually across the speculators, we consider a simple version of information diffusion, which is firstly introduced by Hong and Stein (1999), among N speculators. We use parameter n $(2 \leq n \leq N)$ to describe how information is diffused gradually over two periods. Specifically, we decompose the fundamental value V into n independent sub-innovations with the same variance,

$$V = \sum_{i=1}^{n} \epsilon_i, \qquad \epsilon_i \sim N\left(0, \frac{\sigma^2}{n}\right), \quad i = 1, 2, \ldots, n,$$

where ϵ_i are independent and identical random variable. The timing of the information diffusion is then as follows. Firstly, at time 0, the information starts to spread across the population. Each speculator randomly receives the information about one of the sub-innovation ϵ_i. We divide all N speculators evenly into n groups according to the sub-innovation they received[5]. The traders in group i receive the same information $S_0^i = \{\epsilon_i\}$ at time 0. At time 1, the information rotates. The traders in group i will receive the sub-innovation of the next group so that their information becomes $S_1^i = \{\epsilon_i, \epsilon_{i+1}\}$ now, and the information spreads further[6]. For convenience, we use parameter $\tau = 1/n$ to represent the speed of the information diffusion; the smaller the number of sub-innovations, the more new information the speculators receive in each time period, and the faster the information diffuses. In a two-period model, each speculator receives partially but the same amount of information about the fundamental value. For example,

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[3] Although liquidity traders on average lose in trading, they trade for some other reason, such as hedging.

[4] Competitive market makers means that, in equilibrium, the market makers set the price that makes zero expected profit. Li (2014) describes these market makers as "They do not, however, act like specialists or designated market makers in a dealer market. These market makers represent the large population of traders who have no information or speed advantage, and also no incentives to initiate trades".

[5] As in Fishman and Hagerty (1992), we allow the number of speculators to be a continuous variable (to avoid integer issues).

[6] Although we only consider the two-period model here, this information diffusion mechanism can be extended to multi-period model easily.

for $n = 2$, $V = \epsilon_1 + \epsilon_2, \epsilon_i \sim N(0, \sigma^2/2)$. We divide all the speculators into two groups. Traders in group one receive $S_0^1 = \{\epsilon_1\}$ and traders in group one receive $S_0^2 = \{\epsilon_2\}$, half of the full information at time $t = 0$. At time t=1, traders in group one receive $S_1^1 = \{\epsilon_1, \epsilon_2\}$ and traders in group two receive $S_1^2 = \{\epsilon_2, \epsilon_1\}$, so all traders receive the full information. For $n = 3$, we divide all the speculators into three groups and each speculator receives one-third of the full information at time $t = 0$ and then two-third of the full information at time $t = 1$. Therefore, the information diffuses faster for $n = 2$ than for $n = 3$. Note that, in both periods, the information received by the traders from each group can be different (with the same variance). This motivates strategic trading and competition within each group and among different group of traders to be discussed next.

Trading: At the beginning of each trading period t, the speculators in group i receive the signal S_t^i and anticipate the market makers' pricing rule. Then, each of them submits a market order of buying or selling x_t^i shares according to his strategy function. The liquidity traders exogenously submit a market order of z_t shares in total. Then the aggregate order flow in period t is given by

$$w_t = \tau N \sum_{i=1}^{n} x_t^i + z_t, \qquad t = 0, 1.$$

After observing the aggregate order flow and anticipating the speculators' strategy functions, the market maker sets the publicly observable price p_t according to the market makers' pricing function.

2.2 Equilibrium

We now define the equilibrium and then characterize the equilibrium of the benchmark information diffusion model.

Definition 2.1: A *perfect Bayesian equilibrium* of the trading is given by trading strategy profiles $X_0(S_0^i), X_1(S_1^i, p_0)$ of the speculators in group i and pricing function of the market maker, $P_0(w_0), P_1(p_0, w_1)$, at time t=0, 1; that is,

$$\{X_0(S_0^i), X_1(S_1^i, p_0), P_0(w_0), P_1(p_0, w_1)\}, \qquad i = 0, 1,$$

satisfyinging that

- each speculator in group i, maximizes his x expected trading profits in period-two, given market maker's price functions;

$$x_1^{i,*} = X_1(S_1^i, p_0) = arg \max_{x_1^i} E\left[x_1^i(V - p_1) \middle| S_1^i, p_0, P_1(\cdot)\right];$$

- each speculator maximizes his total expected trading profits over the two periods at time t=0, given market maker's price functions and his optimal trading strategy in period-two;

$$x_0^{i,*} = X_0\left(S_0^i\right) = arg \max_{x_0^i} E\left[x_0^i(V-p_0) + E_1^i\left[x_1^{i,*}(V-p_1)\right]\middle|S_0^i, P_0(\cdot),\right];$$

- the market maker sets the price functions $P_0(w_0), P_1(p_0, w_1)$ satisfying zero expected profits for each period;

$$E[w_1(p_1 - V)|p_0, w_1, X_1(\cdot)] = 0;$$
$$E[w_0(p_0 - V) + w_1(p_1 - V)|w_0, X_0(\cdot)] = 0,$$

where,

$$p_0 = P_0(w_0), \;\; p_1 = P_1(p_0, w_1);$$

- all traders have rational expectations in that each trader's belief about the others' strategies is correct in equilibrium.

This equilibrium has two important implications. First, all the agents in our model are sophisticated. Particularly, considering the asymmetric and heterogeneous information, in period-two, the speculators will learn from the equilibrium price in period-one and infer the fundamental value based on the price information (public information) in period-one and their private information in both periods. Thus, when they submit the market order in period-one, they will take this into consideration. The optimal trading strategies of the speculators in period-one reflect exactly their learning from the equilibrium price in period-one and their expected trading in period-two[7].

Second, the speculators and market maker are strategic in their trading and pricing, characterizing "*forecast the forecasts of others*". Indeed, in our model, the speculator's trading strategy depends on the trading strategies of the others and market maker's pricing rules, which in turn also depend on the speculators' trading strategies. As pointed out in Morris and Shin (2002), the key to our analysis is that the expectations of the speculators violate the "law" of iterated expectation,

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[7] At t=0, when the speculators know they will learn from the equilibrium price at period-one, their market order in period-one satisfies,

$$x_0^{i,*} \in arg \max_{x_0^i} E\left[x_0^i(V-p_0) + E_1^i\left[x_1^{i,*}(V-p_1)\right]\middle|S_0^i, P_0(\cdot), P_1(\cdot), X_1(\cdot)\right].$$

When the speculators do not know they will learn from the equilibrium price at period-one, their market order satisfies,

$$x_0^{i,*} \in arg \max_{x_0^i} E\left[x_0^i(V-p_0) + x_1^{i,*}(V-p_1)\middle|S_0^i, P_0(\cdot), P_1(\cdot), X_1(\cdot)\right].$$

$$E_0^i\left[E_1^i\left[x_1^{i,*}(V-p_1)\right]\right] \neq E_0^i\left[x_1^{i,*}(V-p_1)\right].$$

This injects genuine strategic uncertainty into the problem, characterizing higher-order beliefs or "forecasting the forecasts of others". This endogenous feedback of "one agent strategy affects other agents' strategies that affects himself own strategy" can be characterized by a fixed-point problem that considerably complicates the analysis.

We now examine the equilibrium. We present the main result and provide the proof in the appendix. Following the literature, we focus on linear pricing function.

Assumption 2.1 (Linear pricing function) Up on receiving the order flows w_0 and w_1 at time 0 and 1, the market makers absorb the order flow by setting the prices as

$$p_0 = \lambda_0 w_0, \quad p_1 = p_0 + \lambda_1 w_1.$$

Based on the linear pricing function assumption, the strategy functions and the expected fundamental value of the speculators can be described by the following linear equilibria in Theorem 2.1.

Theorem 2.1 Under assumption 2.1, there is a unique linear equilibrium characterizing the speculators' strategy functions and their expected fundamental value, and the pricing function of the market maker as follows,

Speculator's period-1 demand function: $x_0^i = l_0 S_0^i$;

Speculator's period-2 demand function: $x_1^i = l_1 S_1^i + h_1 p_0$;

Market maker's period-1 pricing rule: $p_0 = \lambda_0 w_0$;

Market maker's period-2 pricing rule: $p_1 = p_0 + \lambda_1 w_1$;

Speculator's period-2 expectation: $E\left[V \middle| S_1^i, p_0\right] = k_1 S_1^i + k_2 p_0$.

Here parameters $l_0, l_1, h_1, k_1, k_2, \lambda_0$ and λ_1 satisfy

$$l_0 = \frac{(1+N)^2(1+2\tau N k_1)^2\lambda_1 + 2(1+N)k_1(k_2-1-2\tau N k_1)\lambda_0}{(\tau N+1)(1+N)^2(1+2\tau N k_1)^2\lambda_0\lambda_1 - 2\tau N(k_2-1-2\tau N k_1)^2{\lambda_0}^2};$$

$$l_1 = \frac{k_1}{\lambda_1(1+2\tau N k_1)}; \quad h_1 = \frac{k_2-1-2\tau N k_1}{\lambda_1(1+N)(1+2\tau N k_1)};$$

$$\lambda_0 = \frac{\tau N l_0 \sigma^2}{(\tau N)^2 {l_0}^2\sigma^2 + {\sigma_z}^2}; \quad \lambda_1 = \frac{2\tau N l_1 \sigma^2}{(\tau N)^2\left({l_0}^2 + 4{l_1}^2\right)\sigma^2 + {\sigma_z}^2};$$

$$k_1 = \frac{{\sigma_z}^2}{(1-2\tau)(\tau N)^2{l_0}^2\sigma^2 + {\sigma_z}^2}; \quad k_2 = \frac{(1-2\tau)\tau N l_0\sigma^2}{(1-2\tau)(\tau N)^2{l_0}^2\sigma^2 + {\sigma_z}^2}.$$

Theorem 2.1 implies that, in equilibrium, the optimal demand of the speculators of group i in period-two can also be described as,

$$x_1^i = \frac{k_1}{\lambda_1(1+2\tau N k_1)} S_1^i + \frac{k_2 - 1 - 2\tau N k_1}{\lambda_1(1+N)(1+2\tau N k_1)} p_0$$

$$= \frac{k_1 S_1^i + k_2 p_0}{\lambda_1(1+2\tau N k_1)} - \frac{1}{\lambda_1(1+2\tau N k_1)} p_0 - \frac{N k_2 + 2\tau N k_1 - N}{\lambda_1(1+N)(1+2\tau N k_1)} p_0$$

$$= \frac{1}{\lambda_1(1+2\tau N k_1)} \left(E\left[V \middle| S_1^i, p_0\right] - p_0\right) - \frac{N k_2 + 2\tau N k_1 - N}{\lambda_1(1+N)(1+2\tau N k_1)} p_0.$$

This strategy has two terms. The first term captures how aggressively the speculator trades on the pricing error from the expected fundamental value based on their information about V and the equilibrium price in period-one. The second term indicates how the speculator adjusts his market order by using the equilibrium price p_0 in period-one. More importantly, both terms depend on the equilibrium price in period-one, which contains the information of the other speculators in period-one. This means that the speculator take not only his information in both periods but also the others' information in period-one into account when trading in period-two.

The above equilibrium result shows a similar impact factors as in the traditional Kyle model. However these facts depend on the speed of information diffusion, measured by τ, the competition within each group, measured by τN, and among n different groups of the speculators. It is clearly that the transmission by which information diffuses has significant impact on both the trading behavior and market quality. Intuitively, under the information diffusion process, an increase in the speed of information diffusion, on average, makes the traders become more informative. Therefore their trading impounds more information into prices and improves price discovery and market liquidity. We next turn to an equilibrium analysis to examine whether this intuition holds. Due to the complexity of the endogenous determination of these equilibrium parameters in Theorem 2.1, we conduct the analysis numerically (using Matlab).

2.3 Equilibrium analysis

For given parameter values σ, σ_z, n and N, the equilibrium parameters are fully characterized by the system of nonlinear algebraic equations. In the following analysis, we let the number of speculators $N = 100$, the volatility of the fundamental value $\sigma = 1$, and the volatility of the order flow of the liquidity traders $\sigma_z = 1$. By changing parameter n and hence τ, we examine how the information diffusion speed can affect the trading behavior and profit of the speculators, price discovery, and market liquidity.

We first discuss the equilibrium market quality with respect to price efficiency and market liquidity. As in the traditional Kyle model, we use parameter $L_t = 1/\lambda_t$ (t=0, 1) to measure the market liquidity for the two periods. As in Li (2014), the price efficiency is measured from the market maker's perspective. When the market maker learns more about the fundamental value from the order flow information, the market becomes more informational efficient.

Definition 2.1. The informational efficiency at time t is measured by

$$\emptyset_t = 1 - \frac{Var\,(V|\{w_\tau\}_{\tau \le t})}{Var\,(V)}.$$

The information efficiency measures how much uncertainty about the fundamental value the market maker has explored from the information diffusion and order flows. In an extreme case when the market maker knows the true value of the fundamental value, then $Var(V|\{w_\tau\}_{\tau \le t}) = 0$ and hence $\emptyset_t = 1$. When the market maker has no information about the fundamental value, than $Var(V|\{w_\tau\}_{\tau \le t}) = Var(V)$, which is the unconditional variance of fundamental value, and then $\emptyset_t = 0$. With the chosen parameters, we report the results in Figures 2.1 and 2.2.

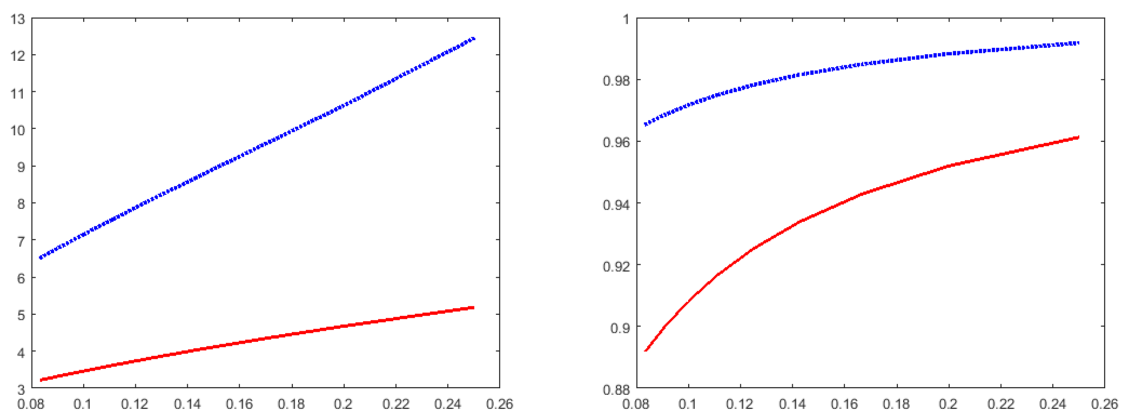

Fig 2.1 Market quality with respect to the liquidity, the left panel, and the price efficiency, the right panel, in the information diffusion speed $\boldsymbol{\tau}$. In both panels, the solid (red) line is for period-one and the dotted (blue) line is for period-two.

Figure 2.1 shows that, with an increase in the information diffusion speed, the market quality with respect to the market liquidity (the left panel) and the price efficiency (the right panel) improves. More interestingly, both market liquidity and price efficiency improve more significantly in period-two comparing to period-one. With faster information diffusion, trading activity increases. Together with the learning, the trading activity impounds more information into the prices, making the market more informative. This further improves the market quality, in particular in period-two.

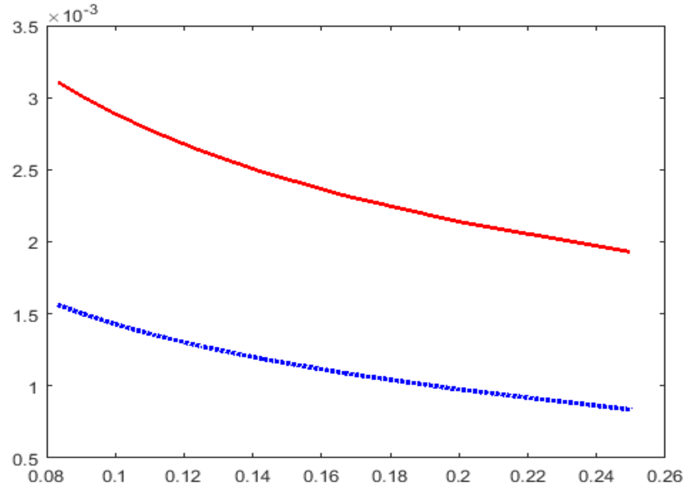

Fig 2.2 The equilibrium profit of the speculators with respect to the information diffusion speed τ. The solid (red) line is for period-one and dotted (blue) line is for period-two.

The profit or revenue of the speculators over the two periods is reported in Figure 2.2. It illustrates that the speculators' profit decreases as the speed of the information diffusion increases. Intuitively, the increasing in the information transmission has two opposite effects. On the one hand, fast information diffusion brings information advantage for the speculator; on the other hand, it makes the market more informative, which reduces the information advantage of the speculators. More specifically, with an increase in the information diffusion, the speculators have more information advantage, which improves their profit. However, it also makes the competition between different groups of speculators more intensive and the learning more effective, which impounds more information into the market prices. As a result, the market maker becomes more informative, making the price more informative, which then reduces the information advantage and hence the profit of the speculators. Overall, this trade-off is dominated by the competition and learning effect, demonstrated by the improving market quality in figure 2.1, which reduces the profit of the speculators and the effect becomes even more significantly in period-two. This is demonstrated by higher profit in period-one than in period-two, but both are decreasing in the speed of the information diffusion.

2.4 The effect of the learning and competition

An understanding of this trade-off mechanism plays a very important role in explaining the impact of trading speed competition in the next section. For this reason, we conduct a further study on the model without learning and Kyle-type model.

Kyle-type model: When the speculators have homogenous information (essentially n=1) but still receive information gradually over the two periods, Figure 2.3 reports the profit of the speculators over the two periods. The details and derivation for this case are given in the appendix. This reduces to the original Kyle-type model and we can interpret the information diffusion speed as the precision of the informed trader's signal. Faster information diffusion means less noise signal that the speculator preserves. In this case, there is no competition among speculators with heterogeneous information; they also do not from the equilibrium price of period-one due to their homogeneous information. Therefore the result reflects the effect of competition with in the same group.

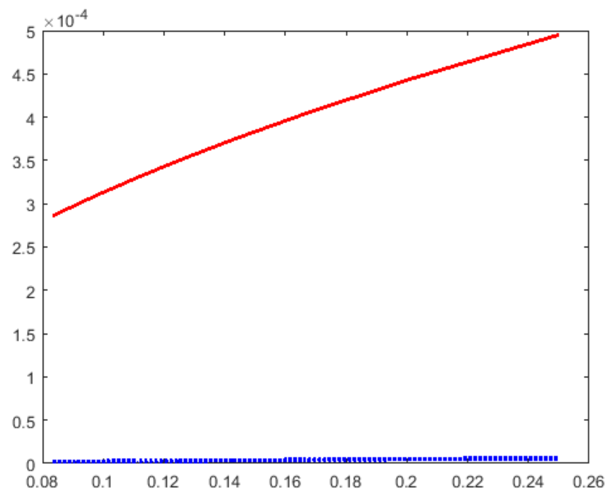

Fig 2.3 Equilibrium profit of the speculators with homogeneous information with respect to the information diffusion speed τ. The solid (red) line is for period-one and the dotted (blue) line is for period-two.

Figure 2.3 shows that the profit of the speculators, in particular in period-one, increases in the speed of the information diffusion. This result is consisting with Kyle model. However, comparing to figure 2.2, we show that it is the competition among different speculators groups with heterogeneous information, not the competition within the group that reduces their profit as the speed of the information diffusion increases. When all the speculators have homogeneous information, faster information transmission improves their information advantage and hence their profit.

Learning effect: Apart from the competition, does learning always improve the profit of the speculators? To answer this question, we examine a model when the speculators do not learn from the equilibrium price of period-one in period-two. We report the results in Figure 2.4 about the equilibrium profit (on the left panel) and market efficiency (on the right panel) when the speed of the information diffusion changes.

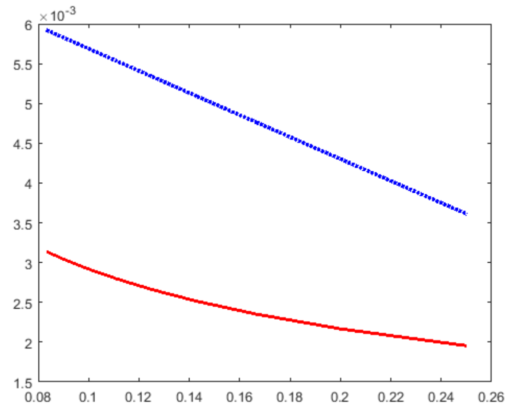

Fig 2.4 Equilibrium profit of the speculators when they do not learn in period-two (left) and market efficiency (right) with respect to the information diffusion speed τ. The solid (red) line is for period-one and the dotted (blue) line is for period-two.

There are two main results in figure 2.4. First, with a given information diffusion speed, with the competition among different groups of the speculators but without learning in period-two from the price in period-one, their profit in period-two is higher comparing to the profit in period-one and that in figure 2.2. While learning from the market is usually perceived as a positive effect to improve market information efficiency, which in turn reduces the profit of the speculators in period-two. This is consistent with the result in figure 2.2. However, the result in the left panel of figure 2.4 is somehow surprising; without learning, the speculators can improve their profit in period-two significantly (comparing to their profit in period-one and figure 2.2). The speculators' learning turns out to facilitate strategic trading among the speculators and to smooth their trading over the two periods, making their trading in period-two less aggressive. Without learning in period-two, the speculators trade more aggressively. This impounds more information to the market and hence makes the market more efficient; at the same time, more aggressive trading of the speculators generates more profit in period-two. This is clearly demonstrated by the market efficiency in the right panel and profit in the left panel of figure 2.4.

Therefore, it is the learning that improves market efficiency and the profit of the speculators in period-two comparing to period-one. Second, the above analysis shows that it is the strategic competition among different groups of trading, neither the competition with the same group not the learning of the speculators, that reduces the profit of the speculators in both periods as the information diffusion speed increases. To better understand the positive contribution of the aggressive trading of the speculators without learning, we examine further the effect of the learning when the speculator is naïve.

Theorem 2.2 When the speculator is naïve, there is a unique linear equilibrium characterizing the speculators' strategy function. When the speculator learns from the previous equilibrium price, their trading strategy at period 2 is given by,

$$x_2^i = \sqrt{N+n}\frac{\sqrt{k_1}}{\sqrt{2N}}\frac{\sigma_z}{\sigma}S_2^i + \sqrt{N+n}\frac{k_2 - 1 - 2\tau N k_1}{2Nk_1(1+N)}\frac{\sigma_z}{\sigma}p_1;$$

where,

$$k_1 = \frac{1}{(\tau - 2\tau^2)N + 1}; \qquad k_2 = \frac{(\tau - 2\tau^2)\sqrt{Nn}}{(\tau - 2\tau^2)N + 1}.$$

When the speculator does not learn from the previous equilibrium price, their trading strategy at period 2 is given by,

$$x_2^i = \frac{\sqrt{N+n}}{\sqrt{2N}}\frac{\sigma_z}{\sigma}S_2^i - \sqrt{N+n}\frac{1 + 2\tau N}{2N(1+N)}\frac{\sigma_z}{\sigma}p_1.$$

Since $k_1 < 1$, the speculators without learning trade more aggressively in period-two, which improves their profit in period-two significantly.

In summary, for the benchmark information diffusion model, learning and more importantly the competition among heterogeneous speculators contribute to market efficiency positively, making the trading in period-two less profitable for the speculators when information diffuses gradually. Faster information diffusion always improves market efficiency, but reduces the profit of the speculators; the effect is more significant for period-two than for period-one.

3. Speed Competition and Strategic Trading

Recent developments in market practice and academic research have witnessed a significant speed heterogeneity and competition on trading speed in financial markets. The development of trading technology such as HFT and increasing disclosure requirements from market regulators have also speeded up information diffusion and increased competition of fast trading. It is commonly believed that HFT is profitable; however the impact of information diffusion and fast trading on market efficiency and liquidity is less clear and often debatable.

In the benchmark model of information diffusion in Section 2, we have examined how the profit of the speculators and market quality are affected by the speed of information diffusion. With given mass of traders, fundamental uncertainty and noise trading volatility, we show that the equilibrium is fully characterized by the information diffusion speed. With faster information diffusion, market quality is improved. Because of the competition, the profit of the speculators is reduced. However, for a given information diffusion speed, due to their learning and competition of the speculators, the trading prices become more efficient and less profitable for the speculators, more for period-two than for period-one. This provides an incentive for the speculators to trade earlier when the information diffuses gradually. Intuitively, when some traders have information advantage than the others, they would prefer to trade earlier and faster. However, this may not be the case when information diffuses gradually and traders may choose not to trade fast. To better understand the incentive of fast trading and its impact, in this section, we introduce a fast trading mechanism which allows some traders to receive information faster than other traders. More specifically, we consider a case in which there are two types of informed traders with full information at different time and hence trade at different speeds compete in financial market and examine their equilibrium trading behavior and the impact on market quality.

3.1 Trading with different speed

It is well recognized that “speed has raised as a focal point of modern financial securities markets” (Huang and Yueshen, 2017). The HFT are spending billions of dollars to buy real estates that are co-located with exchange’s central matching engine and to invest in infrastructures like transatlantic fibre-optic cables and microwave towers in order to competition each other. They compete with different speed. To capture this speed heterogeneity, in this section, we introduce a fast trading mechanism with different speed into our benchmark information diffusion model developed in Section 2.

To distinguish the speculators with different trading speed, we call the traders in the benchmark model as “uninformed” traders and introduce fast “informed” traders who pay certain cost to receive the full information earlier than the normal information diffusion process. Different from traditional informed traders, we introduce two types of fast informed traders with two different speeds in order to examine the impact of the trading speed competition. They can either pay a cost of $C_1(>0)$ to have the full information at time t=0, called the fast informed traders, or pay a cost of $C_2(>0)$ to have the full information at time t=1, called the slow informed traders. In equilibrium, the numbers of the traders who choose to be either the fast or slow informed or uninformed depend endogenously on the costs and information structure..

Figure 3.1 illustrates the timeline of the information structure and trading at different speed in general. It contains three periods ($t = -1,0,1,2$). The initial t=-1 period corresponds to the information acquisition status for the fast and slow informed traders and the other two periods represent the trading periods in the financial market.

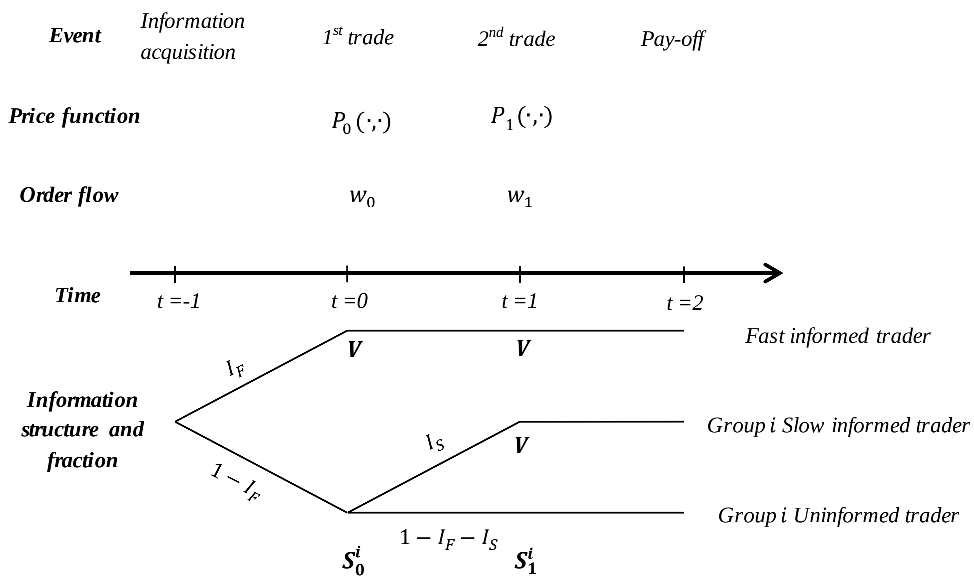

Fig 3.1 The timeline of the information structure and trading at different speed. At time -1, the speculator endogenously acquires the information. At time t=0 and time t=1, the speculators and liquidity traders submit market orders simultaneously; market makers absorb the order imbalance and set the market prices accordingly.

At the initial time t=-1, with the given costs C_1 and C_2, the speculators make strategical information acquisition decisions on whether to pay the cost of C_1 to become the fast informed traders to have the full information at time $t = 0$, or to pay C_2 to become the slow informed traders to have the full information at time $t = 1$; otherwise the speculators receive information gradually according to the information diffusion process specified by the benchmark model in Section 2. All the traders trade in both trading periods. Apart from the strategic trading and learning considered in the benchmark information diffusion model, traders with different trading speed compete with each other. In equilibrium, traders make their decision based on the cost structure (C_1 and C_2), a fraction I_1 of traders who chooses to be the fast informed traders and a fraction I_2 of traders who chooses to be the slow informed traders. *At t=0,* the trading starts and each trader trade strategically across the two trading periods. The fast informed traders receive the full information at time 0 and submit a market order x_0^{FI}; while the slow informed traders and uninformed traders receive partial information according to the information diffusion process and submit their order $x_0^{SI_i}$ and $x_0^{U_i}$ respectively. With the orders from all the speculators and liquidity traders, the market maker receives an aggregate order flow of w_0. The market maker then takes the opposite position to absorb the order flow and cleans the market at price p_0. *At t=1*, both the fast and slow informed traders have the full information. Therefore they submit the same market order of $x_1^{FI} = x_1^{SI_i}$; while the uninformed traders receive information according to information diffusion process and submit an order of $x_1^{U_i}$. As in the first trading period, the market maker receives an aggregate order flow of w_1 and cleans the market at price p_1.

3.2 Bayesian Equilibrium

To understand the equilibrium behaviour (in the next section), we first characterize the equilibrium with exogenous information structure, where the fractions of the fast and slow informed traders are given I_F and I_S respectively. In Section 4, the traders endogenously choose their information structures. We first take a glance of defining a Bayesian equilibrium, similar to definition 2.1 in Section 2.

Definition 3.1: A *perfect Bayesian equilibrium* of the trading is given by strategy profile and pricing rules

$$\{X_0^I(S_0^i), X_1^I(S_1^i, p_0), X_0^U(S_0^i), X_1^U(S_1^i, p_0), P_0(w_0), P_1(p_0, w_1)\}$$[8],

satisfying:

- *The informed trader's trading strategy* $X_0^I(S_0^i), X_1^I(S_1^i, p_0)$: each informed trader maximizes the expected trading profits, given market maker's price functions and uninformed trader's trading strategy;

$$x_1^{I,*} = X_1^I(S_1^i, p_0) = arg \max_{x_1^I} E\left[x_1^I(V - p_1)\middle|S_1^i, p_0, P_1(\cdot), X_1^U(\cdot)\right];$$

[8] Both the fast and slow informed traders have the same trading strategy. In another words, they have the same coefficients (trading intensify) for their information or signal. This is due to the fact that they have share the same information advantage in period 2 and hence the same optimal strategies. In order to prove this results, one can start from assume that they have different trading strategy and then get the same expression for both type of the informed trader. We show this in our appendix.

$$x_0^{I,*} = X_0^I(S_0^i) = arg \max_{x_0^I} E\left[x_0^I(V-p_0) + E_1^I\left[x_1^{I,*}(V-p_1)\right] \middle| S_0^i, P_0(\cdot), X_0^U(\cdot)\right].$$

- *The uninformed trader's trading strategy* $X_0^U(S_0^i), X_1^U(S_1^i, p_0)$: each informed trader maximizes the expected trading profits, given the market maker's price functions and informed trader's trading strategy;

$$x_1^{U,*} = X_1^U(S_1^i, p_0) = arg \max_{x_1^U} E\left[x_1^U(V-p_1) \middle| S_1^i, p_0, P_1(\cdot), X_1^I(\cdot)\right];$$

$$x_0^{U,*} = X_0^U(S_0^i) = arg \max_{x_0^U} E\left[x_0^U(V-p_0) + E_1^U\left[x_1^{U,*}(V-p_1)\right] \middle| S_0^i, P_0(\cdot), X_0^I(\cdot)\right].$$

- *The price function* $P_0(w_0), P_1(p_0, w_1)$: the market maker cleans the security market for each period for an expected profit of zero;

$$E[w_1(p_1 - V)|p_0, w_1, X_1^U(\cdot), X_1^I(\cdot)] = 0;$$

$$E[w_0(p_0 - V) + w_1(p_1 - V)|w_0, X_0^U(\cdot), X_0^I(\cdot)] = 0,$$

where,

$$p_0 = P_0(w_0), \qquad p_1 = P_1(p_0, w_1).$$

- All the agents have rational expectations in that each agent's belief about the others' strategies is correct in equilibrium.

Again, we have the "*learning problem*" and "*forecast the forecasts of others*" here, as in Section 2. Therefore, the speculators are sophisticated in the sense that the informed traders trade optimally and strategically, while the uninformed traders learn from the equilibrium price in period-one. Besides, the strategy, pricing and expectation functions can be very general. For tractability, we assume that the market maker has following linear pricing functions.

Assumption 3.1 (Linear pricing functions) Up on receiving the aggregate order flow w_t at time t=0, 1, the market maker cleans the market at the price of

$$p_0 = \lambda_0 w_0, \quad p_1 = p_0 + \lambda_1 w_1.$$

Based on this assumption, the strategy functions and the expected fundamental value of speculator i can be expressed in linear forms.

$$x_0^i = l_0^i S_0^i;$$

$$x_1^i = l_1^i S_1^i + h_1^i p_0;$$

$$E[V|S_1^i, p_0] = k_1 S_1^i + k_2 p_0.$$

Especially, when the uninformed traders do learn from the equilibrium price in period-one, $k_1 = 1$ and $k_2 = 0$. As in Kyle (1985), we consider a linear equilibrium, which means that the trading strategy and price rule are linear. In equilibrium, the perfect Bayesian equilibrium is fully characterized by parameters, $l_0^i, l_1^i, h_1^i, \lambda_0, \lambda_1, k_1, k_2$.

The intuition behind the linear equilibrium is similar to the Kyle model. Parameters k_1 and k_2 characterize the learning intensity of the uninformed traders. After observing the equilibrium price in period-one and the current information signal, the uninformed traders form their expectation about the fundamental value. Parameters l_0^i, l_1^i and h_1^i represent the trading intensity of trader I; higher values of l_0^i, l_1^i and h_1^i mean that trader trades more aggressively based on the information. Parameters λ_1 and λ_2 represent the price impact of a market order. Higher λ_1 and λ_2 values indicate low liquidity. Different from the Kyle model, our linear equilibrium reflects the heterogeneity and gradually diffusive information across the traders. At time t=0, the uninformed traders only have partial information about the fundamental value, while at time 1, all the traders have the historical information and the equilibrium price in period-one. Therefore, the uninformed trader can learn from the equilibrium price. The fast and slow informed traders have both speed and information advantages. Their speed advantage further enhances their information advantage. This increases the adverse selection risk which impedes market liquidity. However their active trading can also impound more information into the prices, which makes the trading prices more efficient. To understand this trade-off, we conduct an equilibrium analysis when a) traders are sophisticated; and b) the uninformed traders learn from the equilibrium price in period-one. A detailed analysis for other situations is given in the appendix.

3.3 Equilibrium Analysis

In the above, for given fractions of the fast and slow informed traders, we have provided a procedure to derive the perfect Bayesian equilibrium of the speculator's trading strategies and the market maker's pricing functions respectively. Here, we combine the optimal trading strategies of the speculators, including the fast and slow informed and uninformed traders, and the market maker's pricing functions to determine all the coefficients of the optimal trading strategies and pricing functions in market equilibrium.

Theorem 3.1 For given fractions of the fast and slow informed traders, I_F and I_S, respectively, in the linear strategy equilibrium, both the fast and slow informed traders have the same coefficients on their trading strategies in both periods, that is $l_1^F = l_1^S, h_1^F = h_1^S, l_0^F = l_0^S$. We use I to represent them and they satisfy the following equations,

$$l_1^I = \frac{1}{\lambda_1(1+(I_F+I_S)N+2(1-I_F-I_S)\tau N k_1)};\ h_1^I = -\frac{1+N-(1-I_F-I_S)N(1-2k_1\tau-k_2)}{\lambda_1(1+N)(1+(I_F+I_S)N+2(1-I_F-I_S)\tau N k_1)};$$

$$l_1^U = \frac{k_1}{\lambda_1(1+(I_F+I_S)N+2(1-I_F-I_S)\tau N k_1)};\ h_1^U = -\frac{(1+(I_F+I_S)N)(1-k_2)+2(1-I_F-I_S)\tau N k_1}{\lambda_1(1+N)(1+(I_F+I_S)N+2(1-I_F-I_S)\tau N k_1)};$$

$$l_0^I = \frac{1 + 2\lambda_0 \lambda_1 h_1^I l_1^I + (2\lambda_1 (h_1^I \lambda_0)^2 - \lambda_0)(1 - I_F - I_S)\tau N l_0^{U_i}}{\lambda_0\left((I_F + I_S\tau)N + 1\right) - 2\lambda_1 (h_1^I \lambda_0)^2 (I_F + I_S\tau)N};$$

$$l_0^U = \frac{1 + 2\lambda_0 \lambda_1 h_1^U l_1^U + (2\lambda_1 (h_1^U \lambda_0)^2 - \lambda_0)(I_F + I_S\tau)N l_0^I}{\lambda_0\left((1 - I_F - I_S)\tau N + 1\right) - 2\lambda_1 (h_1^U \lambda_0)^2 (1 - I_F - I_S)\tau N};$$

while the coefficients of the pricing functions of the market maker are given by,

$$\lambda_0 = \frac{\left((I_F + I_S\tau)N l_0^I + (1 - I_F - I_S)\tau N l_0^U\right)\sigma^2}{\left((I_F + I_S\tau)N l_0^I + (1 - I_F - I_S)\tau N l_0^U\right)^2 \sigma^2 + {\sigma_z}^2};$$

$$\lambda_1 = \frac{\left((I_F + I_S)N l_1^I + 2(1 - I_F - I_S)\tau N l_1^U\right)\sigma^2}{\left[\left((I_F + I_S\tau)N l_0^I + (1 - I_F - I_S)\tau N l_0^U\right)^2 + \left((I_F + I_S)N l_1^I + 2(1 - I_F - I_S)\tau N l_1^U\right)^2\right]\sigma^2 + {\sigma_z}^2};$$

where,

$$k_1 = \frac{{\sigma_z}^2}{(1 - 2\tau)\left((I_F + I_S\tau)N l_0^I + (1 - I_F - I_S)\tau N l_0^U\right)^2 \sigma^2 + {\sigma_z}^2};$$

$$k_2 = \frac{(1 - 2\tau)\left((I_F + I_S\tau)N l_0^I + (1 - I_F - I_S)\tau N l_0^U\right)\sigma^2}{(1 - 2\tau)\left((I_F + I_S\tau)N l_0^I + (1 - I_F - I_S)\tau N l_0^U\right)^2 \sigma^2 + {\sigma_z}^2}.$$

Therefore the linear strategy equilibrium is uniquely determined when the above system of equations has a unique solution.

Theorem 3.1 characterizes the linear perfectly rational equilibrium of the information diffusion and trading speed competition among the fast, slow informed traders and the uninformed traders. With different information advantages among the fast informed, slow informed and uninformed traders, whether a speculator take the advantage depends on the cost of being informed which is closely related to the information value. In equilibrium, the value of the information being the fast informed or slow informed traders determines how many speculators will trade at different speed, which in turn determines the aggregate information endogenously. To understand the role played by such endogenous information and incentive of trading fast in the next section, we first examine the information value in this section. The traders pay a cost to become the informed trader, however; they only acquire the costly information when their expected payoff from the trading is sufficient to cover the information cost. An important feature in the equilibrium is that the uniformed traders are rational traders; they anticipate that the informed agents may be present in the market and therefore learn from market information and adopt trading strategies to account for this.

3.4 Information value

We first introduce information value, and then numerically analyze how the information structure and diffusion speed affect the information value.

Definition 3.2(Information value). The information value of being the fast (slow) informed trader is defined by the difference in the expected revenue between the fast (slow) informed traders and the uninformed traders.

$$v_F(I_F,I_S,\tau) = E\left[x_0^{FI,*}(V-p_0) + E_1^{FI}\left[x_1^{FI,*}(V-p_1)\right]\right] - E\left[x_0^{U,*}(V-p_0) + E_1^{U}\left[x_1^{U,*}(V-p_1)\right]\right];$$

$$v_S(I_F,I_S,\tau) = E\left[x_0^{SI,*}(V-p_0) + E_1^{SI}\left[x_1^{SI,*}(V-p_1)\right]\right] - E\left[x_0^{U,*}(V-p_0) + E_1^{U}\left[x_1^{U,*}(V-p_1)\right]\right].$$

According to Theorem 3.1, we substitute all the coefficients into the above definition and present the result in the following.

Theorem 3.2(Information value). Based on the information diffusion process and information structure, the value of the information for being the fast informed trader v_F and the slow informed trader v_S are given by, respectively,

$$\begin{aligned} v_F(I_F,I_S,\tau) = {} & (l_0^I - l_0^U\tau)(1-\lambda_0\varphi) + 2\tau\lambda_1\left[(l_1^I + \lambda_0 h_1^I\varphi)^2 - (l_1^U + \lambda_0 h_1^U\varphi)^2\right] \\ & + (1-2\tau)\lambda_1\left[(l_1^I + \lambda_0 h_1^I\varphi)^2 - (\lambda_0 h_1^U\varphi)^2\right] + \lambda_1(\lambda_0 h_1^I)^2 - \lambda_1(\lambda_0 h_1^U)^2; \\ v_S(I_F,I_S,\tau) = {} & (l_0^I - l_0^U)\tau(1-\lambda_0\varphi) + 2\tau\lambda_1\left[(l_1^I + \lambda_0 h_1^I\varphi)^2 - (l_1^U + \lambda_0 h_1^U\varphi)^2\right] \\ & + (1-2\tau)\lambda_1\left[(l_1^I + \lambda_0 h_1^I\varphi)^2 - (\lambda_0 h_1^U\varphi)^2\right] + \lambda_1(\lambda_0 h_1^I)^2 - \lambda_1(\lambda_0 h_1^U)^2; \end{aligned}$$

where,

$$\varphi = (I_F + I_S\tau)Nl_0^I + (1 - I_F - I_S)\tau N l_0^U.$$

The value of the information for the fast informed trader v_F and the slow informed trader v_S describes the informed trader's relative information advantages or gains to the uninformed trader. When the cost of trading fast is less than the information value, the speculators are willing to trade fast. Therefore, given the cost of the fast trading technology, an increasing in the information value has a positive effect on the speculator's intensive to invest in fast trading technology, leading to the arms race of fast trading. We now examine the effect of fractions of the fast and slow informed traders, I_F, I_S and the information diffusion speed τ on the information value in equilibrium numerically (using Matlab).

The information value of the fast informed traders: The fast informed trader has a rapid speed to receive the full information and make profit through their information advantage. With the increasing in the competition and the information diffusion speed, their information advantage will decrease. This is demonstrated by figure. 3.2.

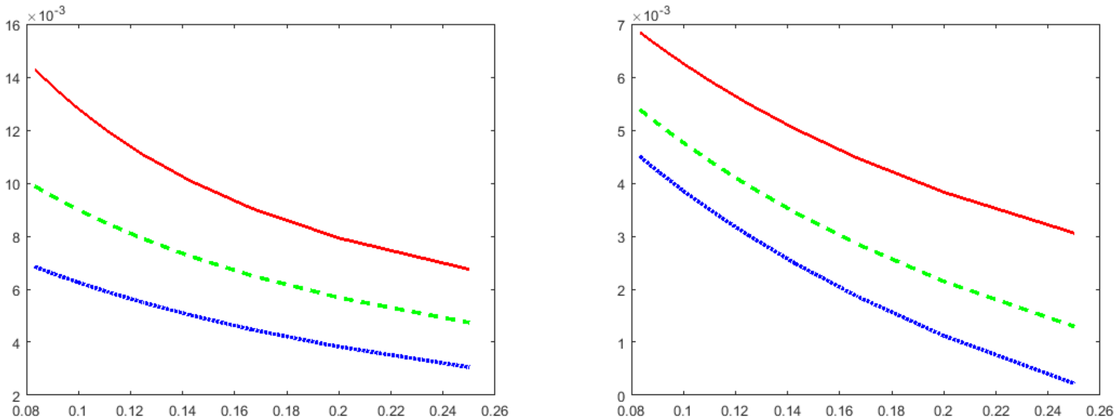

Fig 3.2 The information value of the fast traders with respect to the information diffusion speed τ for three different values of the fraction of the fast informed trader $I_F = 0.1$ (solid), 0.15(dashed), 0.2(dotted) and a fixed fraction of the slow informed traders $I_S = 0.3$ in the left panel and for three different values of the fraction of the slow informed trader $I_S = 0.2$(solid), 0.3(dashed), 0.4(dotted) and a fixed fraction of the fast informed traders $I_F = 0.2$ on the right panel.

We report the information value for the fast informed traders with respect to the speed of the information diffusion in figure. 3.2 with different combinations of the fractions of the fast and slow informed traders. We have two results from figure. 3.2. First, with a given speed of the information diffusion, figure. 3.2 confirms the intuition that the information value for the fast informed traders decreases in the fraction of the fast informed (the left plot) and the slow informed (the right plot) traders in the market. Their information advantage is reduced due to the intensified competition of more informed traders. Second, the information value of the fast informed traders decreases in the speed of the information diffusion. For the fast informed traders, they receive the full information at the beginning of the trading. Therefore, the faster the information diffuses, the less information advantage they have comparing to the slow informed and the uninformed traders, and hence less profitable for the fast informed traders, as shown in figure. 3.2. In summary, we have the following result.

Result 3.1 The information value of being the fast informed trader is decreasing in the number of the informed traders and the information diffusion speed; that is,

$$\frac{\partial v_F(I_F, I_S, \tau)}{\partial I_F} < 0, \qquad \frac{\partial v_F(I_F, I_S, \tau)}{\partial I_S} < 0 \quad and \quad \frac{\partial v_F(I_F, I_S, \tau)}{\partial \tau} < 0.$$

The information value of the slow informed traders: Comparing to the fast informed trader's information value, how the information diffusion speed affects the information value of the slow informed traders seems more complicated. Intuitively, there is a trade-off effect that affects the information value for the slow informed traders. When the speed of the information diffusion increases, their information disadvantage comparing to the fast informed traders becomes less significant, this improves their profitability. However, due to the trading of the informed traders, the uninformed traders become more informative as the speed of the information diffusion increases, which improves the profit of the uninformed traders but reduces the profit for the informed traders. Figure 3.3 report the result on this trade-off.

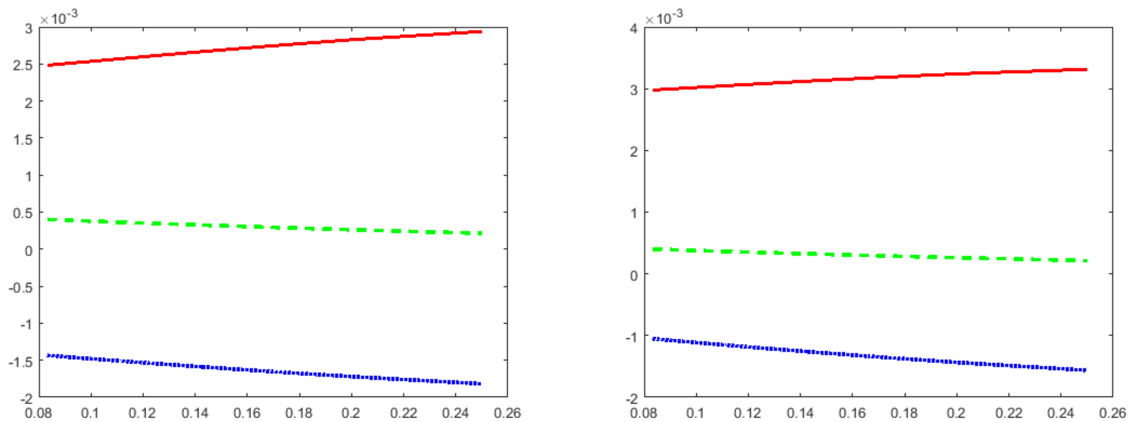

Fig 3.3 The information value of the slow traders against the information diffusion speed τ for three different values of the fraction of the fast informed trader $I_F = 0.1$ (solid), 0.2(dashed), 0.3(dotted) and a fixed fraction of the slow informed traders $I_S = 0.3$ on the left panel and for three different values of the fraction of the slow informed trader $I_S = 0.2$(solid), 0.3(dashed), 0.4(dotted) and a fixed fraction of the fast informed traders $I_F = 0.2$ on the right panel.

As in figure 3.2, we report the information value for the slow informed traders with respect to the speed of the information diffusion in figure 3.3 with different combinations of the fractions of the fast and slow informed traders. Given the speed of the information diffusion, the information value of the slow informed traders is reduced in the fraction of fast informed (the left plot) or of the slow informed (the right plot) traders, as in the previous case. However, surprisingly, figure 3.3 shows that the information value of the slow informed traders can increase or decrease in the speed of the information diffusion depends on the relative information structure. In figure 3.4[9] we illustrate the effect of the information diffusion speed on the

[9] The figure 3.4 is just the diagrammatic sketch to illustrate our result. The accurate quantitative relationship depends on the parameter N. In the appendix, we plot this relationship when $N = 100$.

information value of the slow informed traders for various combinations of the fractions of the fast and slow informed traders.

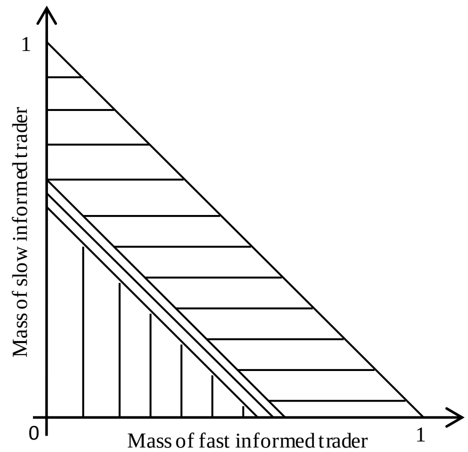

Fig 3.4 The impact of the information diffusion speed on the information value of the slow informed traders for various combinations of the fractions of the fast and slow informed traders. The fractions of the fast informed trader, slow informed trader and uninformed trader sum to one. In the region with vertical lines, the information value increases with the speed; in the region with horizon lines, the information value increases with the speed; while in the region with tilt lines, the information value is hump-shaped with the speed.

The composition of the market with different fractions of the fast, slow informed and uninformed can be depicted graphically on the triangle region in figure 3.4. The x-axis represents the fraction of the fast informed traders, denoted by I_F, and the y-axis represents the fraction of the slow informed traders, denoted by I_S. The remaining fraction is the uninformed traders, so that thei fractions sum to one. The effect of the information diffusion speed on the information value of the slow informed traders depends on the total fraction of the informed traders: when the total fraction of the informed traders is relatively low, the information value increases with the information diffusion speed; while when the total fraction of the informed traders is relatively high, the information value decreases with the information diffusion speed. At the first glance, this result seems not very intuitive. However, there is a trade-off effect that affects the profit (and hence the information value) for the slow informed traders.

Theorem 3.1 has several important observations, one is that the trading strategy of the informed traders in period-two reflects their information advantage in period-two and the equilibrium price in period-one. In fact, the optimal trading strategy of the informed traders in period-two has two components,

$$x_1^I = \frac{1}{\lambda_1(1 + (I_F + I_S)N + 2(1 - I_F - I_S)Nk_1\tau)}(S_1^I - p_0) + \frac{(1 - I_F - I_S)N(1 - 2k_1\tau - k_2)}{\lambda_1(1 + N)(1 + (I_F + I_S)N + 2(1 - I_F - I_S)Nk_1\tau)}p_0;$$

The first component captures how aggressively the informed trader trades on their information advantage about V in period-two, while the second component indicates how the informed traders potentially adjust their period-2 market order by using the equilibrium price p_0 in period-one. Since in period-two the uninformed traders learn from the equilibrium price in period-one about the fundamental value when submitting their market orders for period-two, the informed traders also take the advantage of this predictive pattern and use this information as well.

Our numerical results show that, in the equilibrium, the informed traders trade more aggressively on their information advantage about V in period-two as the information diffusion speed increases. This on the one hand improves market efficiency; on the other hand, amplifies trading volume. To better understand this trade-off effect, we consider a situation in which the fraction of the slow informed traders equals to 0.4 and the fraction of uninformed trader equals to 0.6 (so that there is no fast informed traders) and calculate the revenue numerically. The results are reported in figure 3.5.

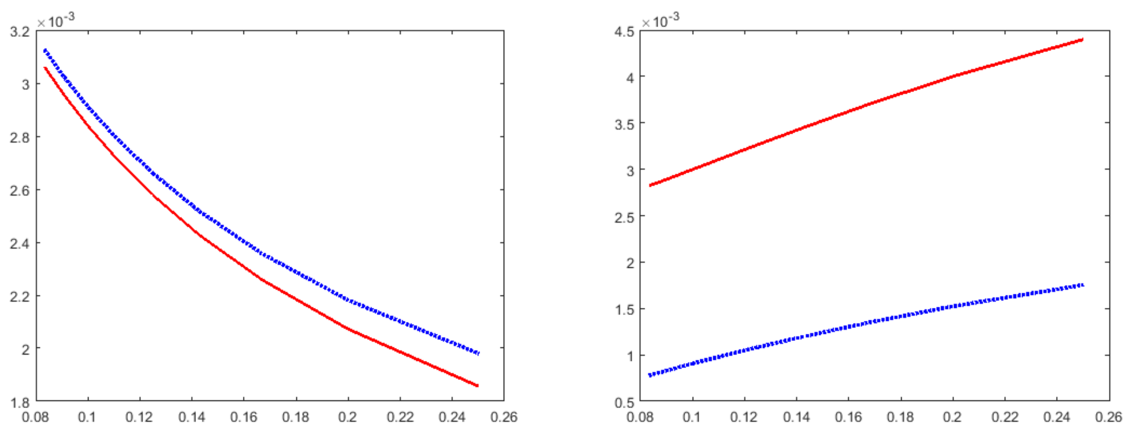

Fig 3.5 The profit of the slow traders and the uninformed traders against the information diffusion speed for the first period (the left panel) and the second period (the right panel) with $I_F = 0.4$ and $I_U = 0.6$. The solid (red) line represents the profit for the slow informed trader; the dotted (blue) line represents the profit for the uninformed trader.

The left panel in figure 3.5 indicates that the profit in the first period for both the slow informed trader and the uninformed trader decreases in the speed of the information diffusion, similar to the benchmark model. In the first period, both types of the traders receive the information according to the information diffusion process. Because of the intensified competition, their profits are reduced. However, at the same time, the profit of the slow informed trader decreases more due to their less aggressively reaction to the faster information diffusion than the uninformed traders in period-two[10].

However, the right panel in figure 3.5 shows a different story for the slow informed and uninformed traders. For the uninformed trader, their profit in period 2 increases in the speed of the information diffusion. This is different from the result in Section 2, where the uninformed trader's revenue decreases with faster information diffusion due to the intensified competition among the uninformed traders. When traders can trade at different speed, the uninformed trader faces the competition mainly from the fast informed traders instead of the competition among the uninformed traders themselves. Thus, with faster information diffusion, the uninformed traders now have relatively more information advantage comparing to the fast informed trader. In general, a faster information diffusion intensifies the competition within the group, which improves the aggregate market information and hence the information efficiency and profit for the uninformed traders.

For the slow informed traders, their revenue in period-two also increases in the speed of the information diffusion, as shown in the right plot in figure 3.5. As discussed in the above, the uninformed traders are not able to benefit from the trading with the slow informed traders. Therefore, the information advantage of the slow informed traders makes them trade more aggressive in period-two. They face a trade-off between more aggressive trading behavior and better market quality. The more aggressive trading behaviour, on the one hand, improves market quality and hence reduces the average revenue per share; on the other hand, it provides more profit opportunity for larger trading volume. Our results show that the "trading volume" effect dominates. Thus, the slow informed trader's profit increases with the diffusion speed as showed in figure 3.5. At the same time, the slow informed trader's profit increases more than the uninformed trader. However, when the total fraction of the informed traders is relatively high, the "market efficiency" effect dominates, which make the increasing in the profit of the slow informed traders less significant. Although the slow informed trader's profit still increases, their information value (difference between slow informed trader and uninformed trader's period 2 profit) in period-two does not increase significantly.

[10] This result comes from their different period 2 objective function.

We finally link the information value to the different type of speculators' profit. When the total fraction of the informed traders is relatively high, the "market efficiency" effect dominates, which make the increase in the profit for the slow informed traders less significant. Hence, the information value increase in period-two is off-set by the decreasing in period-one. When the total fraction of the informed traders is relatively low, the "trading volume" effect dominates, so the slow informed trader's profit increases more significantly. Therefore, the positive effect of the information value in period-two dominates the negative effect in period-one. In summary, we have the following result.

Result 3.2 The information value of the slow informed traders decreases in the fractions of the informed traders; that is,

$$\frac{\partial v_S(I_F, I_S, \tau)}{\partial I_F} < 0, \quad \frac{\partial v_S(I_F, I_S, \tau)}{\partial I_S} < 0;$$

However the effect of the information diffusion speed on the information value is ambiguous depending on the total fraction of the informed traders.

4. Equilibrium Analysis of Endogenous Information Acquisition

With different speed of the information diffusion, we have introduced trading at different speed and examined the information value of trading fast. When the information value of trading fast increases, more traders choose to trade fast; this improves the aggregate information. However this also reduces the information advantage and hence the incentive to trade fast. Therefore the endogenous information plays a very different role in trading speed competition when information diffuses gradually rather then immediately. What is the impact of the information diffusion speed on the endogenous equilibrium information structure? We examine this question in this section.. In Section 3, the equilibrium is determined for given fractions of the fast and slow informed traders by focusing on the perfectly Bayesian trading strategies and rational equilibrium prices. In this section we focus on the equilibrium that, for given costs, the speculators choose endogenously to be either the fast informed, or slow informed or uninformed traders. We first characterize the endogenous equilibrium and then examine the impact of the endogenous information on the trading strategies of the speculators and market prices in equilibrium.

4.1. Endogenous equilibrium definition

In the benchmark case in Section 2, we focus on the effect of the information diffusion. We now incorporate fast trading into our model. By analysing the equilibrium strategic choice of the fast trading, we explore the connection between the information diffusion speed and the information value, and then the effect of the information diffusion on the equilibrium information acquisition strategy.

As in Section 3, we call the traders who receive information from the information diffusion process as the uninformed traders; while the traders who receive the full information earlier as the informed traders. By paying some fixed costs, the informed traders have information advantage; but they only acquire costly information if they are able to increase their expected payoff in the trading round and to cover the information cost. One important aspect of our model is that the uniformed traders are rational traders who do not acquire information, but anticipate that the informed traders may be present in the market, and therefore adopt their trading strategies accordingly. We now focus on the equilibrium definition and the procedure of deriving the equilibrium. In general, the speculators choose to be the fast informed trader only if

$$E\left[x_0^{F,*}(V-p_0)+E_1^F\left[x_1^{F,*}(V-p_1)\right]\right] \geq C_1+E\left[x_0^U(V-p_0)+E_1^U\left[x_1^{U,*}(V-p_1)\right]\right];$$

while they choose to be the slow informed traders only if

$$E\left[x_0^{S,*}(V-p_0)+E_1^S\left[x_1^{F,*}(V-p_1)\right]\right] \geq C_2+E\left[x_0^U(V-p_0)+E_1^U\left[x_1^{U,*}(V-p_1)\right]\right];$$

where C_1 and C_2 are the respective information costs being the fast and slow informed traders. These conditions intuitively describe the equilibrium. To calculate the equilibrium information acquisition strategy, we let the information value be the same as the cost. In addition, the equilibrium fractions of being the fast and slow informed traders satisfy the following three boundary conditions,

$$0 \leq I_F \leq 1;\;\; 0 \leq I_S \leq 1;\;\; 0 \leq I_F + I_S \leq 1.$$

We now provide the details about how to obtain the equilibrium.

Theorem 4.1. Given the information diffusion speed τ,the procedure to calculate the equilibrium in our model is described as following:

a) if the cost C_1 and C_2 satisfy

$$v_F(0,0,\tau) < C_1;\;\; v_S(0,0,\tau) < C_2;$$

then the equilibrium information structure (or the fractions of the fast and slow informed traders) is given by $I_F^* = 0\ and\ \ I_S^* = 0$;

b) if the cost C_1 and C_2 satisfy

$$v_F(0,0,\tau) < C_1;\ v_S(0,0,\tau) > C_2;$$

then the equilibrium information structure is given by $I_F^* = 0\ and\ I_s^*$ satisfying, $v_S(0, I_s^*, \tau) = C_2;$

c) if the cost C_1 and C_2 satisfy

$$v_F(0,0,\tau) > C_1;\ v_S(0,0,\tau) < C_2;$$

then the equilibrium information structure is given by $I_S^* = 0\ and\ I_F^*$ satisfying $v_F(I_F^*, 0, \tau) = C_1;$

d) if the cost C_1 and C_2 satisfy

$$v_F(0,0,\tau) > C_1;\ v_S(0,0,\tau) > C_2;$$

then the equilibrium information structure I_F^* and I_S^* satisfy $v_F(I_F^*, I_S^*, \tau) = C_1 and\ v_S(I_F^*, I_S^*, \tau) = C_2.$

Given that the informed traders have the opportunity to trade earlier (or faster), we are interested in the effect of such speed heterogeneity on the equilibrium strategic choice of fast trading. Intuitively, the fast informed traders and slow informed traders compete with each other; therefore the fractions of the fast and slow informed traders should be substituted. From Section 3, we know that faster information diffusion has a negative effect on the information value of the fast traders. In addition, the presence of the slow informed traders amplifies this negative impact on the equilibrium strategic choice of being the fast informed traders. This phenomenon is referred as the slow informed traders "crowd-out" the fast informed traders. In the following, we examine the endogenous information structure.

4.2 Endogenous information structure

This subsection studies the influence of the cost structures and information diffusion speed on the endogenous information structure. We focus on how the information costs $C_1$and C_2, and the information diffusion speed affect the endogenous information structure in equilibrium.

The impact of the information cost is intuitive. When C_1 is relatively high than C_2, no trader choos to be the fast traders; similarly, when C_2 is relatively high than C_1, no trader choose to be the slow informed traders. Otherwise, some traders choose to be the faster informed traders and other traders choose to be the slow informed traders. Besides, with the increasing in the cost $C_1(C_2)$, the fraction of the fast informed trader (the slow informed trader) also decreases when there is speed heterogeneity. We summarize the results as follows.

Theorem 4.2 Given the speed of the information diffusion, as C_1 and C_2 increase, we progressively move through the following four possible information equilibria: (i) all the uninformed traders, fast informed traders and slow informed traders are active ($I_F > 0$ and

$I_S > 0$); (ii) the uninformed traders and the fast informed traders, but not the slow informed traders, are active ($I_F > 0$ and $I_S = 0$); (iii) the uninformed traders and the slow informed traders, but not the fast informed traders, are active ($I_F = 0$ and $I_S > 0$); (iv) only the uninformed, not the informed, traders are active ($I_F = 0$ and $I_S = 0$).

Hence, we mainly focus on the effect of the information diffusion. From the above discussion, we know that the endogenous information acquisition is the function of the cost structure and the information diffusion speed. The equilibrium parameters are in nonlinear form, which make it difficult to detangle the effect the cost structure from the information diffusion speed.

To understand how the information diffusion speed affects the endogenous information structure, we conduct a numerical analysis with the following parameter values: the number of the speculators $N = 100$, the volatility of the fundamental value $\sigma = 1$, and the volatility of the order flow of the liquidity traders $\sigma_z = 1$. In addition, we consider combinations of the cost structure to determine the equilibrium. We examine three different cost structures. To isolate the effect of information diffusion speed, we first explore two situations where there is only one type of the informed trader; either the fast or slow informed traders. Figure 4.1 shows how the information diffusion speed affects the information structure where there is only fast informed trader; figure 4.2 indicates the result of the cost structure where there is only the slow informed trader. Finally, figure 4.3 focuses on the effect for a cost structure where both the fast and slow informed traders exist in the market.

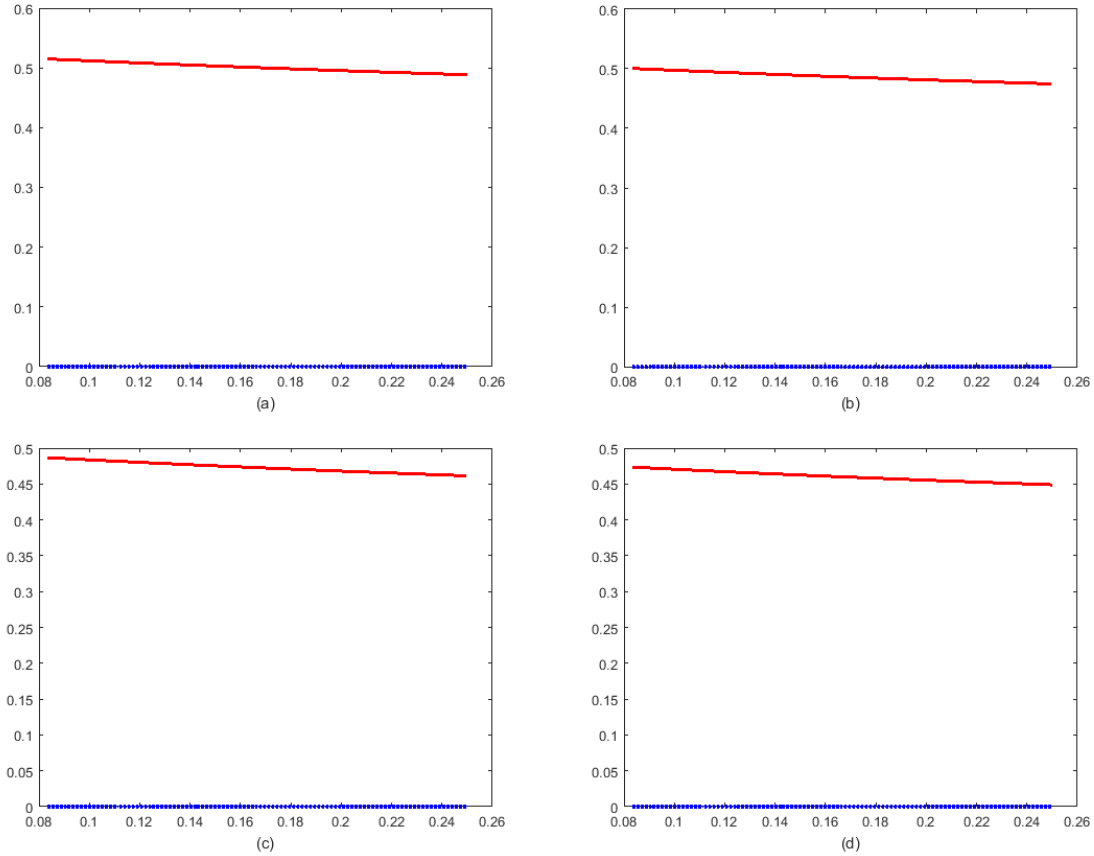

Fig 4.1 The equilibrium information acquisition with respect to the information diffusion speed for four different values of $C_1 = 0.002(a), 0.0025(b), 0.003(c), 0.0035(d)$ and a fixed C_2=0.002. The solid (red) line represents the fraction of the fast informed trader; while the dotted (blue) line represents the fraction of the slow informed trader.

When C_2 is relatively higher than C_1, no trader chooses to be the slow informed traders. According to Section 3, the fast informed trader's information value decreases in the information diffusion speed, which further decreases the speculators' incentive to become the fast informed traders. Hence, the fraction of the fast informed traders decreases in the information diffusion speed with the given cost structure. Also, with the increasing in the cost C_1, the faction of the fast informed trader decreases.

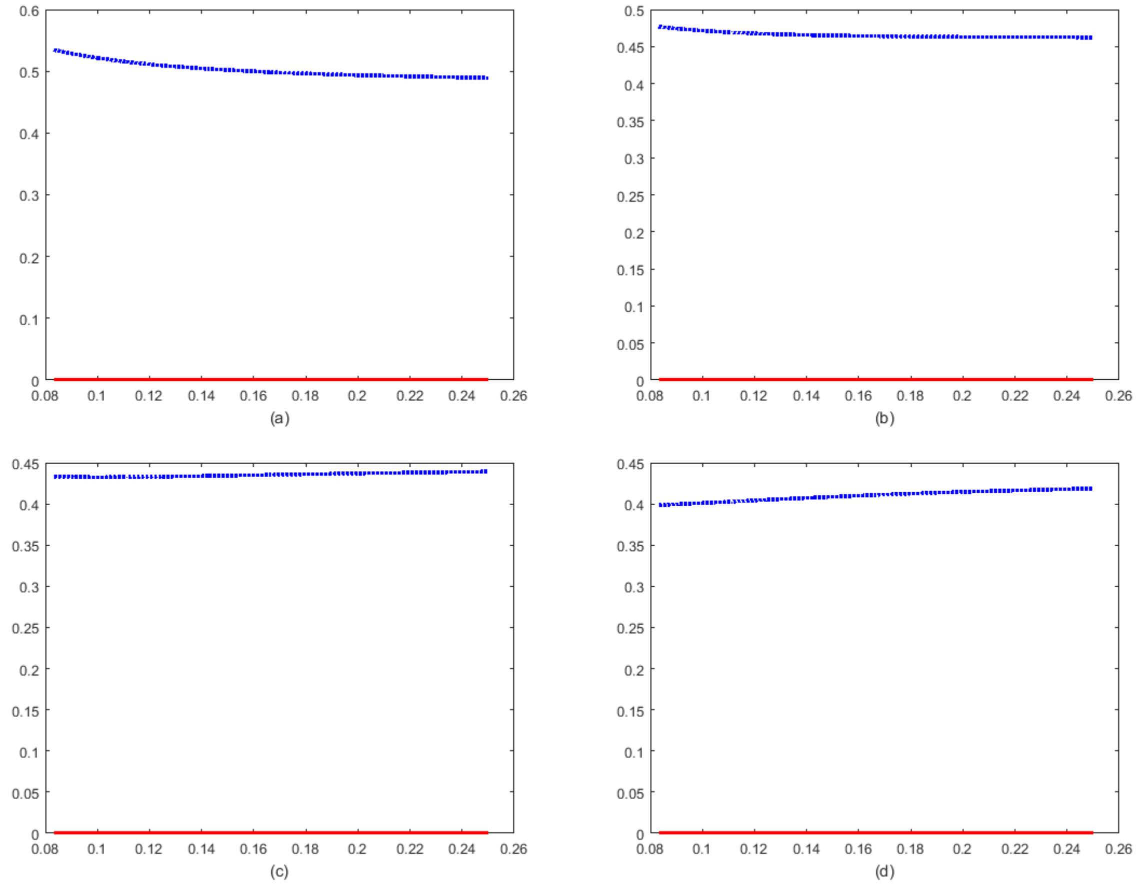

Fig 4.2 The equilibrium information acquisition with respect to the speed of the information diffusion for four different values of the cost $C_2 = 0.0005\,(a), 0.001(b), 0.00015(c), 0.002(d)$ and a fixed cost C_1=0.18. The solid (red) line represents the fraction of the fast informed traders; while the dotted (blue) line represents the fraction of the slow informed traders.

When C_1 is relatively higher than C_2, no trader chooses to be the fast traders. Comparing to figure4.1, the results in figure 4.2 shows that the effect of the information diffusion speed depend on the cost structure. This is because that the impact of the information diffusion speed on the information value of the slow traders is ambiguous. When the cost C_2 is lower (panel a and panel b), the fraction of the slow informed trader is relative higher. Hence, the faster information diffusion speed reduces the information value of the slow informed traders, similar to the results in figure 4.1. When the cost C_2 is higher (panel c and panel d), the fraction of the slow informed trader is relative lower. Hence, the faster information diffusion improves the information value of the slow informed traders, which further increases the fraction of the slow informed traders.

Interaction between fast and slow informed trader: When both the slow informed trader and fast informed trader are present at the market, the situation becomes more complicated due to their interactions. In fact, we can show that

$$\frac{dI_F(I_s,\tau)}{d\tau} = \frac{\partial I_F(I_s,\tau)}{\partial\tau} + \frac{\partial I_F(I_s,\tau)}{\partial I_s}\frac{\partial I_s}{\partial\tau}.$$

This expression has two terms. The first term describes the direct influence of the information diffusion speed, while the second indicates the interaction between the fast and slow informed traders. When there is only one type of the informed traders, the second term equals to zero. Therefore the information diffusion speed also affects the equilibrium information structure through the other type of informed trader. Figure 4.3 illustrates this effect.

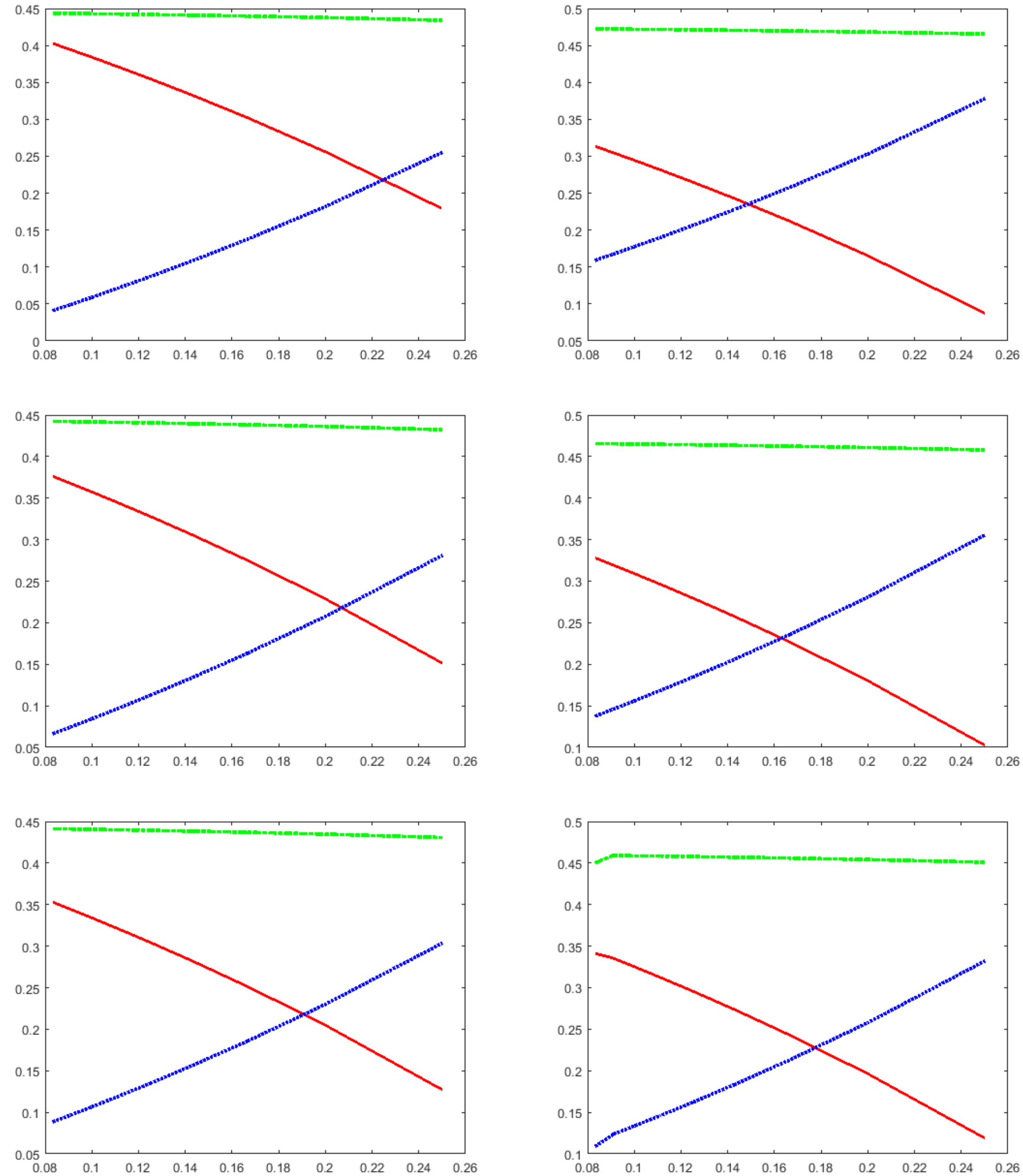

Fig 4.3 The equilibrium information acquisition with respect to the speed of the information diffusion. The left three plots are for three different values of the cost $C_1 = 0.005(up)$, $0.00525(medium)$, $0.0055\,(down)$, and a fixed cost C_2 equals to 0.02. The right three plots are for three different values of the cost $C_2 = 0.001(up)$, $0.0012(medium)$, $0.0014(down)$, and a fixed cost C_1 equals to 0.05. The solid (red) line represents the fraction of the fast informed traders; the dashed (green) line represents the total fractions of the informed traders; while the dotted (blue) line represents the fraction of the slow informed traders.

The most interesting result is that the presence of the slow informed traders amplifies the negative impact of the faster information diffusion on the equilibrium strategic choice of being the fast informed traders; while the presence of the fast informed traders changes the effect of the faster information diffusion on the equilibrium strategic choice of being the slow informed traders. On the one hand, for the fast informed traders, the directly influence of the faster information diffusion speed is negative. At the same time, the increase in the slow informed traders also has an indirectly and negative effect on the information value of the fast informed traders. Thus, the slow traders crowd out the fast traders. On the other hand, comparing to the case where there is only the slow informed traders, the fraction of the slow informed traders increases even further. This is due to the trader-off effects. The first effect is positive in the sense that a decrease in the fraction of the fast informed traders improves the information value of the slow informed traders. The second one is ambiguous; an increase in the information diffusion might increase or decrease the information value of the slow informed traders, depending on the total fraction of the informed traders. Our results show that the first effect dominates the second effects. Therefore, the slow informed traders increase with faster information diffusion.

5. Price efficiency

One of the most important functions of financial markets is the price discovery or efficiency. We have shown that the strategical competition among traders with different trading speed affects their relative profits which also affect their equilibrium information acquisition strategies. In this section, we examine how this endogenous information through the information diffusion process and strategical choice of trading at different speed affects information aggregation, market liquidity, and price efficiency. We measure price efficiency from the market maker's perspective. When the market maker learns more about the fundamental value from the order flow information, the market becomes more information efficient.

Following Definition 2.1, with an increase in the information efficiency, the market maker becomes more informative, which makes the informed traders become less advantage in their information and hence less profitable. Given that the strategical choice for the speculators to be fast informed, slow informed, or uninformed depends on the information cost structure, we consider five cases for five values of $C_1 = 0.002, 0.0042, 0.0052,\ 0.015$ and 0.018 with a fixed cost of $C_2 = 0.002$; they correspond to different market composition of the fast informed, slow informed, and uninformed traders in equilibrium. We calculate the equilibrium numerically and plot the equilibrium fractions, I_F and I_S, of the fast and slow informed trader and the information efficiency over period-one and period-two respectively.

Case 1 $\boldsymbol{C_1 = 0.002}$; $\boldsymbol{C_2 = 0.002}$: In this case, the cost to be the fast informed traders is relative lower comparing to the cost to be the slow informed traders. Obviously, no speculator chooses to be the slow informed; that is $I_S = 0$. However, although the cost to be the fast informed is small, not every speculator would choose to be the fast informed due to the diminishing information advantage with more fast informed traders. Fig, 5.1 reports the equilibrium information structure and market efficiency in this case. The first panel shows that, when C_1 is relative lower to C_2, there is only the fast informed traders. With the increasing in the information diffusion speed, the fraction of the fast informed trader decreases, while the fraction of the uninformed trader increases. Intuitively, there are two opposite effects to information efficiency. The first effect is that a reduction in the fast informed traders may provide less information and hence reduce price efficiency in the market. However, there is a second effect that an increase in the information diffusion speed improves the information for the uninformed traders and hence for the market. Our results in the second and third panels show that the second effect dominates the first effect over both trading periods. Therefore faster information diffusion improves price efficiency.

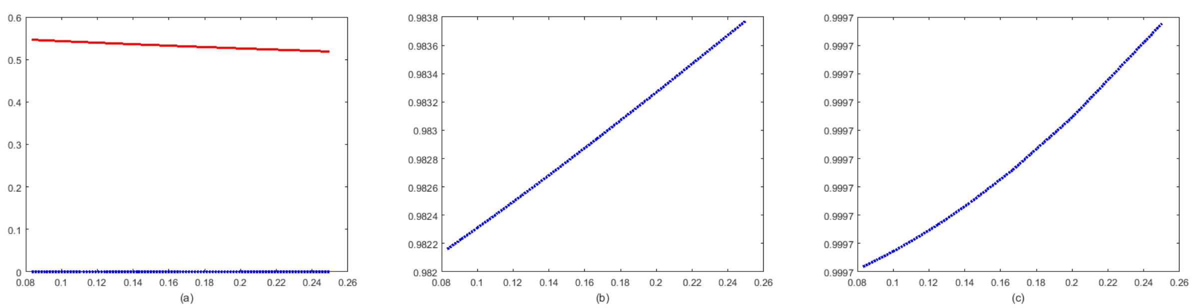

Fig 5.1 Case 1. The equilibrium fractions, I_F and I_S, of the fast and slow infomed traders (the first panel), and the information efficiency over period-one (the second panel) and period-two (the third panel) with respect to the information diffusion for $C_1 = 0.001$ and $C_2 = 0.002$. In the first panel, the solid (red) line represents the fraction of fast informed traders; while the dotted (blue) line represents the fraction of slow informed traders.

Case 2 $\boldsymbol{C_1 = 0.0042}$; $\boldsymbol{C_2 = 0.002}$: In this case, the cost to be the fast informed traders is more than the cost to be the slow informed traders. Figure 5.2 reports the equilibrium information structure and market efficiency for this case. Because the information value for the fast informed traders decreases in the information diffusion speed, the fraction of the fast informed trader decreases in the information diffusion speed. Similarly to case 1, the market efficiency increases with the information diffusion speed initially when the fraction of the fast informed traders does not drop too quickly. However, when fraction of the fast informed traders drops significantly, the slow informed traders are more profitable. In addition, the crowdout effect intensifies the decrease in the fast informed traders and hence the information they provide to the market through their trading. Although faster information diffusion makes the slow informed traders and the uninformed traders more informative, the negative effect on the information efficiency from the fast traders dominates the positive effect from the slow informed and uninformed traders. Therefore, the market efficiency depends on the trade-off; it decreases when the information diffuses very fast. In general, this trade-off leads to a hump-shaped relationship between the information diffusion speed and market efficiency.

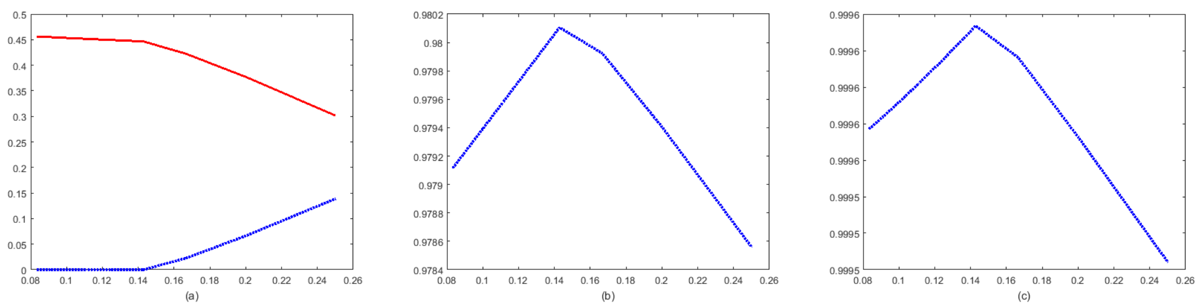

Fig 5.2. Case 2. The equilibrium fractions, I_F and I_S, of the fast and slow infomed traders (the first panel), and the information efficiency over period-one (the second panel) and period-two (the third panel) with respect to the information diffusion for $C_1 = 0.0042$ and $C_2 = 0.002$. In the first panel, the solid (red) line represents the fraction of fast informed traders; while the dotted (blue) line represents the fraction of slow informed traders.

Case 3 $\boldsymbol{C_1 = 0.0052}$; $\boldsymbol{C_2 = 0.002}$: Figure 5.3 reports the equilibrium information structure and market efficiency in this case. As the cost of being the fast informed traders increases comparing to Case 2, more speculators choose to be the slow informed. Therefore the effect of decreasing in the fast informed traders in Case 2 becomes more significant. Different from Case 2, the total fractions of the informed, both the fast and slow, traders increase in the information diffusion speed; however the effect of less fraction of the fast informed traders in period-one still dominates. Overall, the price efficiency decreases in the information diffusion speed.

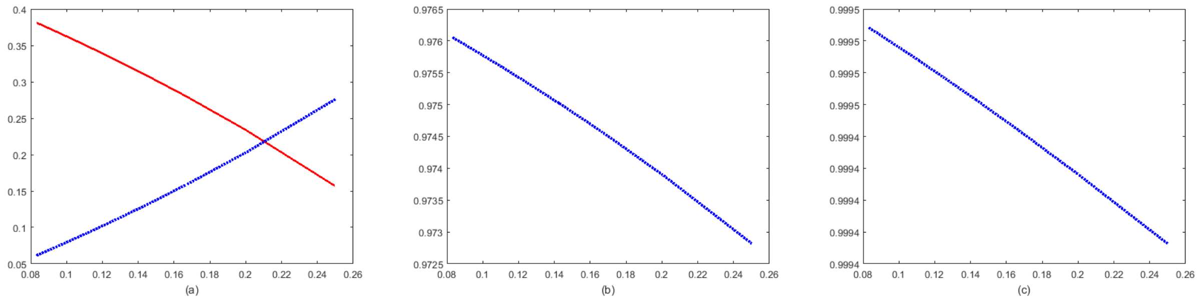

Fig 5.3 Case 3. The equilibrium fractions, I_F and I_S, of the fast and slow infomed traders (the first panel), and the information efficiency over period-one (the second panel) and period-two (the third panel) with respect to the information diffusion for $C_1 = 0.0052$ and $C_2 = 0.002$. In the first panel, the solid (red) line represents the fraction of fast informed traders; while the dotted (blue) line represents the fraction of slow informed traders.

Case 4 $\boldsymbol{C_1 = 0.015}$; $\boldsymbol{C_2 = 0.002}$: As C_1 increases further, we see more solow informed traders and less fast informed traders as the information diffusion speed increases in the first panel of figure 5.4. When both the fast and slow informed traders are active in the market, the price efficiency decreases in the information diffusion speed as in Case 3. At the speed when the fast informed traders are negligent, there are only the slow informed and uninformed traders. As the information diffusion speed increases further, both the slow informed and uninformed traders become more informative, which improves the price efficiency. This trade-off effect explored in Cases 2 and 3 leads to a U-shaped relation between the information diffusion speed and market efficiency in both trading periods, illustrated in the second and third panels of figure 5.4.

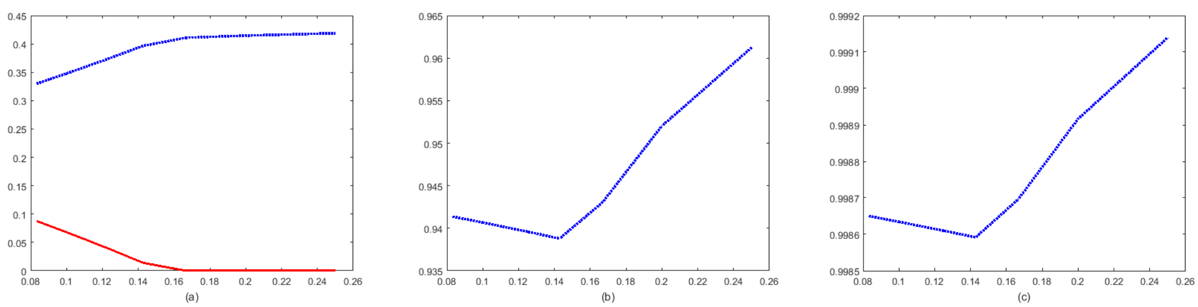

Fig 5.4 Case 4. The equilibrium fractions, I_F and I_S, of the fast and slow infomed traders (the first panel), and the information efficiency over period-one (the second panel) and period-two (the third panel) with respect to the information diffusion for $C_1 = 0.015$ and $C_2 = 0.002$. In the first panel, the solid (red) line represents the fraction of fast informed traders; while the dotted (blue) line represents the fraction of slow informed traders.

Case 5 $\boldsymbol{C_1 = 0.18}$; $\boldsymbol{C_2 = 0.002}$: Finally, when the cost being the fast informed traders increases further, no trader chooses to be the fast informed. Based on the results in Section 4, with an increase in the information diffusion speed, the fraction of the slow informed trader increases. Both the facts, that there are more slow informed traders and that the uninformed traders become more informative as the speed of information diffusion increases, improve the price efficiency. Therefore, the market quality increases with faster information diffusion.

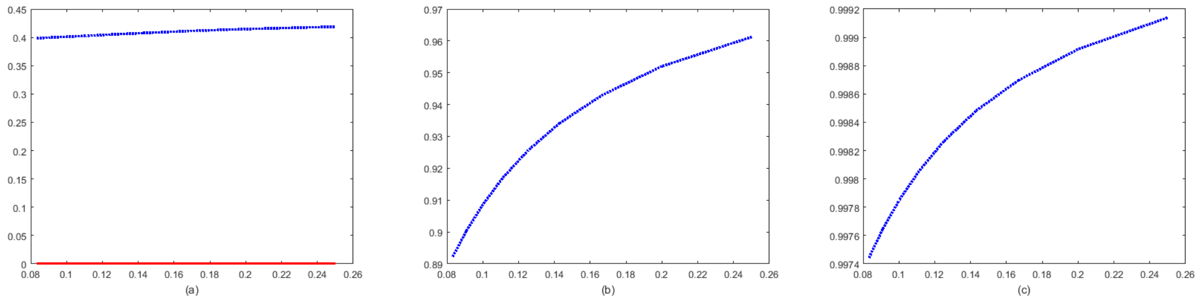

Fig 5.5 Case 5. The equilibrium fractions, I_F and I_S, of the fast and slow infomed traders (the first panel), and the information efficiency over period-one (the second panel) and period-two (the third panel) with respect to the information diffusion for $C_1 = 0.18$ and $C_2 = 0.002$. In the first panel, the solid (red) line represents the fraction of fast informed traders; while the dotted (blue) line represents the fraction of slow informed traders.

Overall, from the above analysis, we have shown that in an extended Kyle model solved in closed-form, the information diffusion speed can have different effects on the market efficiency and market liquidity. The market quality can either increase, or decrease, or have a U-shaped, or even a hump-shaped relation to the speed of the information diffusion, depending on the information cost structures and competition between traders with different trading speed.

6. Conclusion

The development of trading technology such as HFT and increasing disclosure requirements from market regulators have speeded up information diffusion and increased competition of fast trading. Recent developments in market practice and academic research have witnessed a significant speed heterogeneity and competition on trading speed in financial markets. When traders can trade at different speed, there is clearly a "first-mover advantage" based on the information advantage. With high cost associated with fast trading in general, traders may not choose to trade at the same speed; some chooses to trade fast while others may choose to trade slowly. Therefore trading at and competition among different speed naturally arises. Such speed heterogeneity and competition are significant characteristics of the underlying price discovery and market liquidity.

This paper explores the impact of fast trading competition when information diffuses gradually over the time. It emphasizes the importance of speed heterogeneity and speed competition for understanding the role of information diffusion process on the incentive of fast trading and the market quality. We first consider a benchmark model where speculators receive heterogeneous information exogenously by information diffusion process and then extend the model to allow for the fast and slow informed traders to receive full information about the fundamental value earlier at the first and second periods at some certain costs. In this paper, by considering information diffusion at different speed, we examine the strategic choice and incentive of trading at different speed, and more importantly, the joint impact of information diffusion and strategical trading speed competition among traders on market quality, including price discovery and market liquidity.

Our key result is that faster information diffusion speed can impede the market quality with fast trading competition, which is opposite to the perceived view that faster information diffusion benefits the market quality. This feature is innovative and has an important implication that improvement on market transparency and trading technology, which speed up the information diffusion and fast trading competition, can have unintended and negative impact on market quality.

The analysis reveals that the interaction between the fast and slow informed traders plays a very important role when traders can trade at different speed. The fast-trading competition amplifies the effect of the information diffusion speed on the information value for the informed traders. There are two key mechanisms at work. Firstly, the information value of the fast (slow) informed traders decreases with larger fraction of the slow (fast) informed trader. Also, the fraction of the slow (fast) informed trader increases (decreases) with faster information diffusion. Therefore the information value of the fast (slow) informed trader are more sensitive to the information diffusion speed comparing to the benchmark case where there is no fast-trading competition. Secondly, the impact of the information diffusion speed on the fraction of the fast informed traders depends on impact on the fraction of the slow informed traders, and vice versa. This feedback characterizes “the decreasing of the fast informed trader amplifies the increasing of the slow informed trader that then amplifies himself decrease to the faster information diffusion speed” and creates a problem that considerably complicates the analysis, which further makes the equilibrium fraction of the fast (slow) informed trader reacts relatively more to the information diffusion speed.

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