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Stock market dynamics with rational liquidity traders

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Abstract

In the Kyle (1985) finite horizon model of stock market dynamics with a trader who holds long-lived information, informed trading intensities rise with time, and the slopes of the equilibrium price schedules fall. This paper shows that this result depends crucially on the irrational liquidity trader assumption. We replace the irrational noise traders with a sequence of rational, risk averse, liquidity traders who receive endowment shocks to their holdings of the risky asset. We demonstrate that unless liquidity traders are sufficiently risk averse, the slope of equilibrium price schedule rises over time, while informed trading intensities fall. In particular, Kyle's result holds *only* when liquidity traders are so risk averse that they 'over-rebalance' their portfolio's holdings of the risky asset, so that their final holdings of the risky asset have the opposite sign of their initial position.

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1. Introduction

In a seminal paper, Kyle (1985) explores strategic trading in an asset market by an agent who has many opportunities to trade on his long-lived private

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information. Also trading each period are noise traders, who submit exogenously given (stochastic) orders. Trade is through a competitive market maker who observes the combined net order flow, but cannot distinguish the order of each trader type. The market maker sets a price equal to the expected value of the asset conditional on the entire history of net order flows. Consequently, the informed trader must consider not only how his order affects the current price, but also how it will affect future prices. The possibility of future opportunities to trade induces the informed agent to restrict his order size, forgoing current profits for future profits. The chief finding is that when the informed agent is given arbitrarily many trading opportunities, he trades on his residual private information at the same rate each period, so that the competitive market maker sets the same linear marginal pricing schedule each period.

When the informed agent has fewer trading opportunities, the value of concealing his private information is reduced so that he will trade on his information more intensively, revealing his private information more quickly. Since the number of future trading opportunities declines with time, the informed agent trades ever more intensively as time passes. Therefore, the slope of the equilibrium price schedule declines with time. Holden and Subrahmanyam (1992) show that introducing additional informed agents to the Kyle environment does not affect this conclusion if the informed agents have the same information.[1]

While the intuition underlying the result that informed trading intensity rises with time seems compelling, this paper shows that this result relies crucially on the price insensitive (e.g. irrational) noise trading assumption. This assumption, that noise trader orders are completely insensitive to both the pricing of the asset and the uncertainty over the asset's value, can only be justified on the grounds of analytic convenience.

In a static framework, Spiegel and Subrahmanyam (1992) endogenize the trading motives of liquidity agents. They replace the noise traders with rational price-sensitive risk-averse agents who experience endowment shocks and show that some of the static Kyle results are sensitive to the noise trading assumption.

Here, we follow replace the exogenous noise traders with a sequence of rational price-sensitive risk-averse agents and document how outcomes are affected. We show that the most basic Kyle findings regarding the time paths of informed trading intensity and market maker pricing do not extend for reasonable parameterization of liquidity trader risk aversion.

We first investigate the consequences for liquidity trading patterns. Is there more intensive liquidity trade early, when there is more uncertainty about the

[1] Back et al. (1995), and Foster and Viswanathan (1996) show that if the informed agents have diverse signals then eventually the slope of the pricing schedule increases with time, once traders' private information becomes negatively correlated.

asset's value, but potentially more adverse selection; or do liquidity traders want to trade more heavily later, after information about the asset's value has been revealed? Does liquidity trade rise with informed trading intensity or fall? How do answers to these questions depend on the degree to which the liquidity trader is risk averse?

We next investigate the consequences for informed trade and equilibrium pricing. Will an informed agent ever trade less intensively on his information as time passes? If so, under what conditions? When will the equilibrium marginal pricing schedule decline over time? When will it rise? How will trading patterns vary across different stocks?

The answers to the questions posed above and hence, the qualitative predictions of our model depend intimately on the degree to which liquidity traders are risk averse. We show that unless liquidity traders are so risk averse that they 'over-rebalance' their portfolios, more than offsetting endowment shocks by trading from an initial long position to a short position or vice versa, then the qualitative conclusions of the Kyle model are reversed: price schedules become more order sensitive over time, and informed trading intensity falls.

To understand why the degree of risk aversion for liquidity traders affects the results so markedly, one must consider the sources of uncertainty that have an impact on liquidity trade. First, as time passes, information about the asset's value is revealed through the informed trade, so that intrinsic uncertainty about the asset's value declines. One might think that the reduced uncertainty about the asset's value always leads expected liquidity trade to decline over time, because the need to insure against uncertainty in the asset value is reduced. Further, one might think that this would be reinforced by the indirect effects of reduced liquidity trade on the marginal pricing schedule: Less liquidity trade leads to greater adverse selection for the competitive market maker and hence to steeper marginal pricing schedules.

What complicates this line of reasoning is that there is a second source of uncertainty for the liquidity trader, price uncertainty due to the random (from the perspective of the liquidity trader) order of the informed agent. It is this additional source of uncertainty that affects the qualitative results. Even as the liquidity trader becomes arbitrarily risk averse, the economy does *not* converge to the Kyle economy, because the liquidity trader is averse both to uncertainty about the value of his holdings of the risky asset, and to uncertainty about the price he will pay on any portfolio rebalancing trades that he makes. In fact, to completely eliminate total portfolio risk, liquidity traders must over-rebalance their portfolio holdings of the risky asset, so that their final holding of the risky asset has the opposite sign of their initial position.

Whether liquidity traders increase their trading intensity in response to greater informed trading intensity, and hence greater price risk, depends on their level of risk aversion. Unless liquidity traders are so risk averse that they 'over-rebalance', increases in informed trading intensity reduce liquidity trading intensity. It is this fact that underlies our counter-intuitive findings regarding the time paths of pricing and informed trade.

We also characterize how intraday pricing and trading patterns vary with the volatility of the innovation about which the informed trader has information. We find that there is a U-shaped relationship between the amount of private information that the informed agent has on average, and the equilibrium slopes of the price schedules. Unless the innovation is highly volatile, the slopes of the price schedules rise as the time until the event grows close — spreads widen. Thus, our model imposes cross-sectional restrictions on the dynamics of pricing and volume. These restrictions could be tested in at least two ways. If one can identify stocks about which traders tend to have more private information — perhaps smaller or more narrowly held stocks — then one could test to see whether allowing for rational, risk-averse liquidity traders can help explain cross-sectional variations in pricing and trading patterns.

An alternative approach is to recognize that the model most closely adheres to the real world for temporally separated, well-defined events such as earnings announcements, etc. This is because one can identify the timing of events about which informed traders are likely to have information. For reasonable levels of risk aversion, in contrast to the standard Kyle model, the rational liquidity trader model predicts that bid–ask spreads will widen as we approach the event announcement, as Brooks (1994) and Krinski and Lee (1996) find for earnings announcements. Further, if one can distinguish ‘large’ events from ‘small’ for a specific stock, one can control for stock specific sources of heterogeneity and again investigate whether the dynamic predictions across event sizes accord with the data.

Our paper is in the spirit of Spiegel and Subrahmanyam (1992), who find that many of the conclusions derived from the static Kyle model are altered when the trading motives of liquidity agents are endogenized. In particular, they show that adding more uninformed hedgers may lower their welfare if they are sufficiently risk averse, because of the added price risk. So, too, adding informed traders always lowers hedger welfare because of the added price risk, despite the greater competition among the informed.

Our paper is related in sentiment to Admati and Pfleiderer (1988). Admati and Pfleiderer consider informed agents with short trading horizons, and two types of noise traders, those who can time when they submit their orders and those who cannot. They show that for reasonable parameter values, discretionary liquidity traders want to trade at the same time. In contrast, our paper details how the trades of rational liquidity traders with short trading horizons evolve over time when information is long-lived.

The next section develops the one-shot trading equilibrium that is essentially a special case of Spiegel and Subrahmanyam (1992). Section 3 extends the theoretical analysis to two periods. Section 4 characterizes the dynamics numerically. Both the effects of varying the degree of risk aversion and the variance of the distribution of the asset's value are detailed. We characterize equilibrium price schedules, trading strategies of informed and uninformed agents, expected informed profits, the amount of information revealed through trade, and the price and holding risks to liquidity traders. All proofs are in an appendix.

2. The bench-mark model

In this section, we motivate our dynamic analysis of trade in financial markets featuring both informed and rational risk averse liquidity traders by considering the one-shot trading environment.

In the bench-mark model, a single risky asset is exchanged for a riskless asset by three types of agents: A single risk neutral insider who has private information about the ex-post liquidation value of the risky asset; a single uninformed risk averse liquidity trader who has private information about the liquidity shock that he receives and trades rationally to insure against the unknown shock to the asset's value; and uninformed, risk neutral competitive market makers who set price equal to the expected value of the asset conditional on their information.

To reduce notation without affecting our analysis, we assume that the time zero public information value of the risky asset is zero. At date zero, there is an innovation to the asset's liquidation value, δ, which is drawn from a normal distribution with zero mean and variance Σ_0. The innovation, δ, is private information of the informed agent.

There is a single risk averse liquidity trader with preferences over end-of-date 1 wealth given by $u(w) = -\mathrm{e}^{-\eta w}$, where $\eta \geqslant 0$ is the agent's coefficient of risk aversion and w is end-of-date 1 wealth. The liquidity trader's endowment of the risk-free asset is y, and he has a random endowment of the risky asset, $-Q/2$. We assume that the liquidity shock (random endowment) is private information to the liquidity trader, and that Q is drawn from a normal distribution with mean zero and variance σ. Further, δ and Q are independently distributed, and the distributions from which they are drawn are public information.

At date 1, the informed and liquidity traders simultaneously choose, given their private information, their orders of the risky asset to submit to a risk neutral, uninformed market maker. Let the informed trader's order function be given by $X(\cdot)$ and the liquidity trader's order function be given by $U(\cdot)$, and let x and u denote the corresponding realized orders. The market maker only observes the total net order from these two traders, $x+u$, from which he attempts to infer the innovation to the asset's value, δ. Competition induces the market maker to set the price of the risky asset to be equal to the expected value of the asset given his information. Let $P(\cdot)$ be the pricing function and p be the realized price at which orders are filled. Then, the asset's liquidation value is realized and agents consume.

The informed trader's profits are $\pi(\delta, x, p) = (\delta - p)x$, and the risk averse liquidity trader's end-of-period wealth is $w(\delta, u, Q, p) = y + \delta(u - Q/2) - pu$. The informed agent strategically selects his order to maximize expected profits given his information, δ, taking into account the expected effects on price; and the liquidity trader strategically selects his order to maximize his expected utility given his liquidity shock, $-Q/2$, taking into account the effects of his order on price.

We restrict attention to linear equilibria in which the market maker's pricing function, and the strategies of the informed and liquidity traders are linear with respect to the information structure. In particular, we conjecture that:

1. The equilibrium pricing function takes the form $P(x+u) = \lambda(x+u)$, where λ is a constant coefficient.
2. The informed trader's equilibrium order function takes the form $X(\delta) = \beta\delta$, where β is a constant coefficient.
3. The liquidity trader's equilibrium order function takes the form $U(Q) = \mu Q$, where μ is a constant coefficient.

Equilibrium: A linear equilibrium is a triple of strategies, (X, P, U), such that:

1. The informed agent maximizes expected profit conditional on his information:

$$X(\delta) = \underset{x}{\operatorname{argmax}}\ \mathrm{E}_Q[x(\delta - \lambda(x + \mu Q)] \quad \forall \delta. \tag{1}$$

2. The liquidity trader maximizes expected utility conditional on the liquidity shock:

$$\begin{aligned} U(Q) = \underset{u}{\operatorname{argmax}}\ & \mathrm{E}_\delta\left[y + \delta\left(u - \frac{Q}{2} \right) - \lambda(\beta\delta + u)u \right] \\ & - \frac{\eta}{2}\mathrm{var}\left[y + \delta\left(u - \frac{Q}{2} \right) - \lambda(\beta\delta + u)u \right], \quad \forall Q. \end{aligned} \tag{2}$$

3. Market makers earn zero profits conditional on their information:

$$P(x+u) = \mathrm{E}_{\delta,Q}[\delta \mid x+u], \quad \forall (x+u). \tag{3}$$

Proposition 1. *If $\eta > 4/\sqrt{\Sigma_0 \sigma}$, then a unique linear equilibrium exists and is characterized by*

- *The slope of the equilibrium pricing function, which measures market depth*:

$$\lambda = \frac{\eta \Sigma_0}{2[\eta\sqrt{\Sigma_0 \sigma} - 4]}. \tag{4}$$

- *The intensity with which the informed agent trades on private information*:

$$\beta = \frac{[\eta\sqrt{\Sigma_0\sigma} - 4]}{\eta\Sigma_0}. \tag{5}$$

- *The intensity with which the liquidity agent trades to rebalance his portfolio in response to the liquidity shock*:

$$\mu = \frac{\eta\sqrt{\Sigma_0\sigma} - 4}{\eta\sqrt{\Sigma_0\sigma}}. \tag{6}$$

- *The variance of the liquidation value of the asset conditional on the net order flow, which reflects how much of the insider's private information is not yet incorporated in the prices*:

$$\Sigma_1 = \mathrm{var}(\delta\,|\,x+u) = \frac{\sigma\Sigma_0}{\beta^2\Sigma_0 + \mu^2\sigma}. \tag{7}$$

If $\eta \leqslant 4/\sqrt{\Sigma_0\sigma}$ *then liquidity demand is so price elastic that the market maker cannot set a price schedule that breaks even. As a result, no* (*linear*) *equilibrium exists*.

To understand the content of this proposition and the equilibrium dynamics in the next section, it helps to look at the liquidity trader's optimization problem more carefully. The liquidity trader's expected wealth is $y - \lambda u^2$, and the variance of wealth is $\Sigma_0[(1-\lambda\beta)u - Q/2]^2 = \Sigma_0 Q^2[(\mu - \frac{1}{2} - \lambda\beta\mu]^2$. If we substitute the informed trader's choice of $\beta = 1/2\lambda$ into the liquidity trader's objective, the liquidity trader's optimization problem becomes

$$\max_u\, y - \lambda u^2 - \frac{\eta}{8}\Sigma_0[(u-Q)^2]. \tag{8}$$

Note that as the liquidity trader becomes arbitrarily risk averse, as η becomes large, the variance term dominates and $u \to Q$. Since the liquidity trader's endowment shock was $-Q/2$, this implies that an arbitrarily risk averse liquidity trader actually *reverses* his holdings. The reason for this result is that one can decompose the sources of portfolio risk that the liquidity trader faces into three components:

- The holding risk from his final position on the asset, $(U - Q/2)\delta$, equals

$$HR = \Sigma_0 Q^2(\mu - \tfrac{1}{2})^2. \tag{9}$$

- The price risk from trading U in the market with the informed trader, PU, equals

$$PR = \Sigma_0 Q^2(\lambda\beta\mu)^2. \tag{10}$$

- The covariance between $(U - Q/2)\delta$ and PU equals

$$\mathrm{Cov}\left[\left(U - \frac{Q}{2}\right)\delta, PU\right] = \Sigma_0 Q^2(\mu - \tfrac{1}{2})(\lambda\beta\mu). \tag{11}$$

- Total portfolio risk can be decomposed into

$$HR + PR - 2\mathrm{Cov}\left[\left(U - \frac{Q}{2}\right)\delta, PU\right]. \tag{12}$$

The covariance between $(U - Q/2)\delta$ and PU is positive only if $\mu > 0.5$, i.e. only if the liquidity trader's final position on the risky asset has the opposite sign of his endowment shock. To completely eliminate the random component of wealth when trading in the asset market with the informed trader, the liquidity trader must reverse his position completely: when he receives an endowment shock of $-Q/2$, he must buy $\mu Q = [1/2(1 - \lambda\beta)]Q = Q$, buying twice the endowment shock and ending up with a positive holding of the asset, in order to purge all portfolio uncertainty. More generally, the liquidity trader 'over-rebalances', setting $\mu > 0.5$, if and only if $\eta > 8/\sqrt{\Sigma_0\sigma}$. In turn, $\eta > 8/\sqrt{\Sigma_0\sigma}$ is a necessary and sufficient condition for the market maker to set a less steep price schedule than in Kyle (1985), when the variance of noise trade is $\sigma/4$ — that is, the equilibrium price schedule with rational, price elastic, liquidity trade is less steep than the equilibrium price schedule with noise traders if and only if the rational liquidity trade exceeds the noise trade.[2]

More generally, the equilibrium intensity with which the liquidity trader rebalances his portfolio increases as he becomes more risk averse (η rises); as the riskiness of his position increases (Σ_0 rises); and as the volatility of his liquidity shock increases (σ rises). These comparative statics reflect tradeoffs of opposing effects. For example, as the volatility of his liquidity shock increases, informed trade rises but the equilibrium pricing function becomes less order size sensitive; the net effect is to induce the liquidity trader to increase his order.

3. The dynamic trading model

In order to investigate the consequences of rational liquidity trade in general, and risk aversion in particular for trading patterns, informed trade, and equilibrium pricing over time, we allow for multiple rounds of trade. In this section, we first present a dynamic version of the benchmark model. Because the model

[2] Spiegel and Subrahmanyam (1992) also find that a 'hedger may choose to more than offset his endowment by trading from an initial long position to a short position or vice versa (i.e. he may wish to over–hedge himself)'.

cannot be completely solved in closed-form, we provide numerical characterizations of the results. Finally, we furnish a discussion that details exactly how the qualitative predictions of the model depend on the degree to which liquidity traders are risk-averse.

3.1. The model

We extend the one-shot trading model in the simplest way, by allowing for two rounds of trade, assuming that one liquidity trader arrives in each trading period. Now, the equilibrium price in the second period reflects the information contained in both periods of trade. Accordingly, the insider maximizes his expected profit taking into account his effect on the price in both periods. Traders in the second period have more information since they observe the first period price.

Again, the informed trader, who does not discount profits, privately observes the innovation to the asset's liquidation value, δ, at date zero. In each trading period, there is a single risk averse liquidity trader who can submit an order *only* in that period. Giving a liquidity trader but one opportunity to trade is the simplest way to introduce strategic liquidity trade in a dynamic context. The assumption is meant to capture that trade timing by uninformed casual traders is likely to be dictated by features exogenous to the model that determine when it is convenient to trade. Each liquidity trader has identical preferences over end-of-date 2 wealth $u(w) = -e^{-\eta w}$, where $\eta \geqslant 0$ is the agent's coefficient of risk aversion and w is end-of-date 2 wealth. The period t liquidity trader's endowment of the risk-free asset is y, and his privately observed random endowment of the risky asset is $-Q_t/2$, $t = 1, 2$. The liquidity shocks are identically distributed — Q_t is drawn from a normal distribution with mean zero and variance σ. All random variables are independently distributed, and the distributions from which they are drawn are public information.

At date t, the informed and liquidity traders simultaneously choose their orders of the risky asset to submit to a risk neutral, uninformed market maker, given their private information. Let the informed trader's order function in period t be given by $X_t(\cdot)$, let the period t liquidity trader's order function be given by $U_t(\cdot)$, and let x_t and u_t denote the corresponding realized orders. The informed agent's first period trade will be a function of δ, and his second period trade will be a function of both δ and the first period price, p_1. The first period liquidity trader's order will be a function of Q_1, and the second period liquidity trader's order will be a function of Q_2.[3] In period 1, the market maker observes

[3] The second period liquidity trader's order will not vary with p_1 because in equilibrium, p_1 will equal the expected value of the asset given the second period liquidity trader's information.

the total net order from these two agents, $x_1 + u_1$, from which he attempts to infer the innovation to the asset's value, δ. In period 2, the market attempts to infer the innovation to the asset's value, δ, from the history of net trades, $(x_1 + u_1, x_2 + u_2)$. Competition leads the market maker to set the price of the risky asset at each date equal to the expected value of the asset given his information. Let $P_t(\cdot)$ be the pricing function in period t, and let p_t be the realized price at which the market maker fills orders. At the end of period 2, the asset's liquidation value is realized and agents consume.

An equilibrium is defined by the market efficiency conditions — $P_1(x_1 + u_1) = \mathrm{E}[\delta \,|\, x_1 + u_1]$ and $P_2(x_1 + u_1, x_2 + u_2) = \mathrm{E}[\delta \,|\, x_1 + u_1, x_2 + u_2]$ — and optimization by both informed and liquidity traders at each date conditional on the information available to them. As in Kyle (1985), we restrict attention to recursive linear equilibria, so that the market maker's pricing function, and the strategies of the informed and liquidity traders are linear with respect to the information structure. In particular, we conjecture and verify that

1. The equilibrium pricing functions take the form $P_1(x_1 + u_1) = \lambda_1(x_1 + u_1)$, $P_2(x_2 + u_2) = p_1 + \lambda_2(x_2 + u_2)$, where λ_1 and λ_2 are constant coefficients.
2. The informed trader's equilibrium order functions take the form $X_1(\delta) = \beta_1 \delta$, and $X_2(\delta, p_1) = \beta_2(\delta - p_1)$, where β_1 and β_2 are constant coefficients.
3. The liquidity traders' equilibrium order functions take the form $U_t(Q_t) = \mu_t Q_t$, where μ_1, μ_2 are constant coefficients.

In particular, the informed agent trades strategically at date 1 to maximize expected lifetime profits. The informed agent recognizes that first period trade will affect both first and second period prices. In contrast, while each liquidity trader behaves strategically in that each takes into consideration the effect of his trade on the equilibrium price in that period, they ignore the implications for prices in other periods.

Proposition 2. *If a recursive linear equilibrium exists, then it is unique and is characterized by the solution to the following system of equations*:

- *The slopes of the equilibrium pricing functions*:

$$\lambda_1 = \frac{\beta_1 \Sigma_0}{\beta_1^2 \Sigma_0 + \mu_1^2 \sigma}, \quad \lambda_2 = \frac{\beta_2 \Sigma_1}{\beta_2^2 \Sigma_1 + \mu_2^2 \sigma}. \tag{13}$$

- *The intensities with which the informed agent trades on private information*:

$$\beta_2 = \frac{1}{2\lambda_2}, \quad \beta_1 = \frac{1 - \lambda_1/2\lambda_2}{2\lambda_1(1 - \lambda_1/4\lambda_2)}. \tag{14}$$

- *The intensities with which the liquidity agents trade to rebalance portfolios*:

$$\mu_2 = \frac{\eta\Sigma_1}{\eta\Sigma_1 + 8\lambda_1}, \quad \mu_1 = \frac{\eta\Sigma_0(1-\lambda_1\beta_1)}{2(2\lambda_1 + \eta\Sigma_0(1-\lambda_1\beta_1)^2)}. \tag{15}$$

- *The conditional variances of the innovation to the asset's value*:

$$\Sigma_1 = \frac{\mu_1^2\sigma\Sigma_0}{\beta_1^2\Sigma_0 + \mu_1^2\sigma}, \quad \Sigma_2 = \frac{\mu_2^2\sigma\Sigma_1}{\beta_2^2\Sigma_1 + \mu_2^2\sigma}. \tag{16}$$

3.2. The properties of the equilibrium

Proposition 2 characterizes the linear equilibrium of the dynamic trading model by a system of nonlinear equations (13)–(16). No analytic solution to this system of equations exists. As in Spiegel and Subrahmanyam (1992), Holden and Subrahmanyam (1992), and Foster and Viswanathan (1996), we solve for equilibrium outcomes numerically for different values of the parameters Σ_0, σ and η. We find that the equilibrium dynamics are dramatically different from those in Kyle (1985).

3.3. Varying the coefficient of risk aversion, η

The decomposition of portfolio risk into price and holding risks that the liquidity traders face in each period is given by

$$PR_t = \Sigma_{t-1}Q^2(\lambda_t\beta_t\mu_t)^2, \quad t = 1, 2. \tag{17}$$

$$HR_t = \Sigma_{t-1}Q^2(\tfrac{1}{2} - \mu_t)^2, \quad t = 1, 2. \tag{18}$$

$$\mathrm{Cov}\left[\left(U_t - \frac{Q}{2}\right)\delta, P_t U_t\right] = \Sigma_{t-1}Q^2(\mu_t - \tfrac{1}{2})(\lambda_t\beta_t\mu_t), \quad t = 1, 2. \tag{19}$$

Fig. 6 illustrates the decomposition of portfolio risk (per unit of Q) for different levels of risk aversion for the liquidity trader. Note that the second period price risk is a sharply increasing function of the liquidity trader's coefficient of risk aversion, indicating that the informed agent trades more aggressively in response to the more volatile liquidity trade, that is reflected in the equilibrium price. In contrast, first period price risk has a relatively flat, inverted U-shaped relationship with the coefficient of risk aversion, reflecting the informed agent's first-period incentives to conceal his information. The holding risk for each period's liquidity trader is a U-shaped function of the coefficient of risk aversion, reflecting that if they are sufficiently risk averse, they will trade so as to more than reverse their portfolio holding of the risky asset.

To understand the equilibrium characterizations of trade, it helps to look at how an exogenous (out of equilibrium) increase in informed trading intensity affects the trade of liquidity agents with different levels of risk aversion. The liquidity trader's equilibrium trading intensity is given by

$$\mu_t = \frac{\eta \Sigma_{t-1}(1-\lambda_t \beta_t)}{2(2\lambda_t + \eta \Sigma_{t-1}(1-\lambda_t\beta_t)^2)}. \tag{20}$$

Differentiating, we see that

$$\text{sign}\left[\frac{\partial \mu_t}{\partial \beta_t}\right] = \text{sign}[-2\lambda_t + \eta\Sigma_{t-1}(1-\lambda_t\beta_t)^2]. \tag{21}$$

Thus, if and only if the liquidity trader is sufficiently risk averse does greater informed trading intensity raise liquidity trading intensity. In particular, in the second period, where $\beta_2 = \lambda/2$, an increase in informed trading intensity would raise the liquidity agent's trading intensity if and only if the liquidity agent is so risk averse that $\mu > \frac{1}{2}$, i.e. if and only if the liquidity trade is so risk averse that he 'over-rebalances' his portfolio holdings of the risky asset.

Figs. 1–7 illustrate equilibrium outcomes for different values of the risk aversion parameter, η, when the variances of the liquidity shock and innovation to the asset's value are set at $\sigma = 1$, and $\Sigma_0 = 1.5$, respectively. Observe first, that if the liquidity trader is only slightly averse to risk, $\eta < 4.75$, then his order is so price elastic that the market makers cannot break even. As a result, no (linear) equilibrium exists. For $\eta > 4.75$, an equilibrium always exists. A few qualitative features stand out:

- Whether the standard Kyle pricing results obtain, depends on how risk averse the liquidity traders are. As Fig. 1 reveals, the slope of the equilibrium price schedules decline with time if and only if the liquidity traders are extremely risk averse, $\eta > 7.2$. The slopes of both equilibrium pricing functions are declining functions of η, reflecting that more risk averse liquidity agents trade more intensively on their endowment shocks (see Fig. 3).
- The intensities with which liquidity agents trade on their private endowment shocks rise with time if and only if $\eta > 8.5$.
- The informed agent trades more intensively on his information as time passes if and only if $\eta > 5.75$ (see Fig. 2). The intensity with which the informed agent trades in the second period is a sharply increasing function of how risk averse the liquidity trader is, while his first period trading intensity is relatively insensitive to the degree of risk aversion, and actually declines for sufficiently high levels of liquidity trader risk aversion.
- As the liquidity trader becomes more risk averse, the percentage of the informed agent's private information that is revealed through the equilibrium price falls (see Fig. 7). This is because more risk averse liquidity agents trade more intensively, so that the net order flow contains less information.

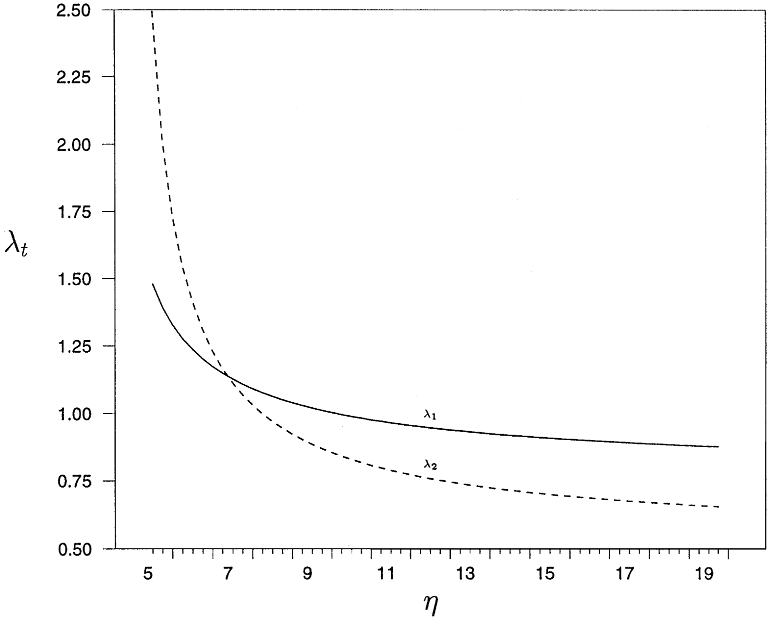

Fig. 1. Slopes of the market maker's price schedules. (Parameter values are: $\sigma = 1$ and $\Sigma = 1.5$.)

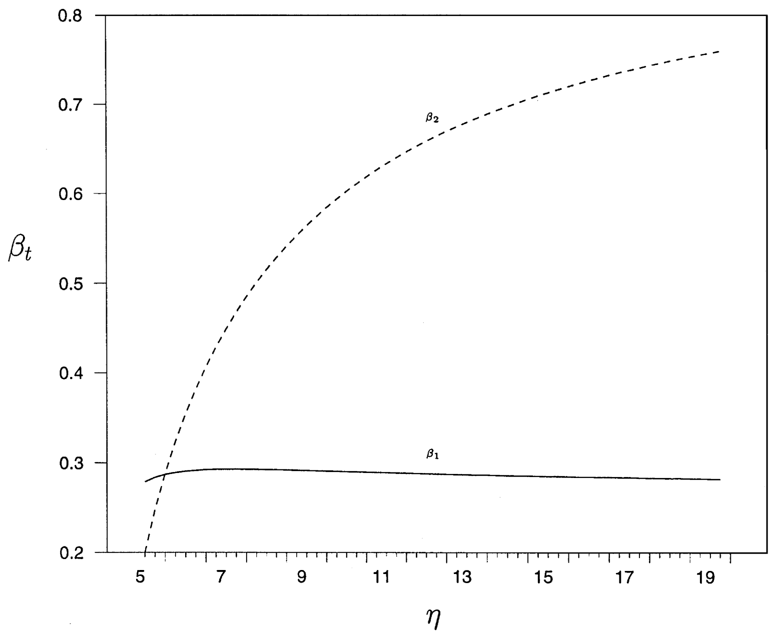

Fig. 2. Intensity of informed trade. (Parameter values are: $\sigma = 1$ and $\Sigma = 1.5$.)

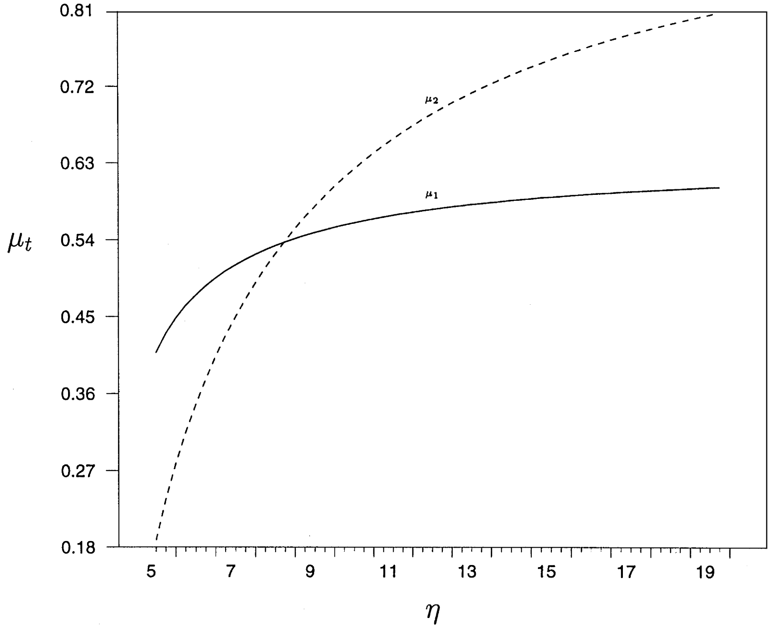

Fig. 3. Intensity of liquidity trade. (Parameter values are: $\sigma = 1$ and $\Sigma = 1.5$.)

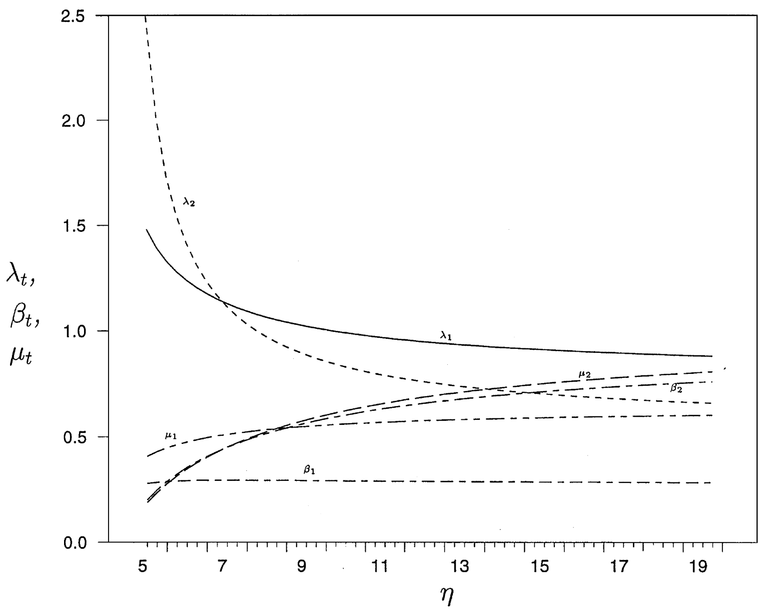

Fig. 4. Equilibrium parameter values. (Parameter values are: $\sigma = 1$ and $\Sigma = 1.5$.)

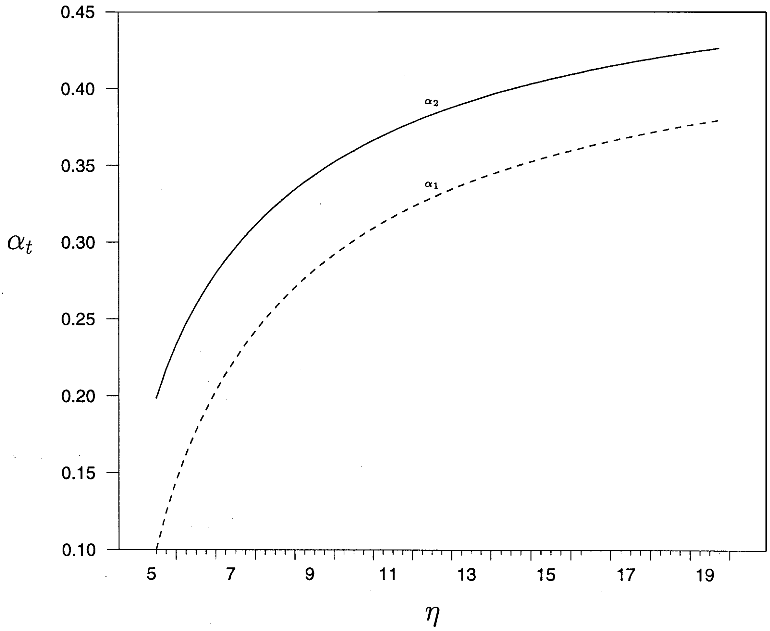

Fig. 5. Slopes of the informed trader's period profit functions. (Parameter values are: $\sigma = 1$ and $\Sigma = 1.5$.)

3.4. Intuition for the qualitative results

We now provide the intuition underlying our qualitative results. We summarize exactly how the liquidity trader's risk aversion affects the properties of the equilibrium. In particular, there are five critical cut points for the liquidity trader's coefficient of risk aversion at which the qualitative predictions change.

- *Very high risk aversion*: $\eta > 8.5$. If liquidity traders are extremely risk averse, then the qualitative predictions match those of Kyle: The marginal pricing schedule becomes less steep with time so that both liquidity and informed agents trade more intensively as time passes. As Fig. 1 illustrates, given extremely risk averse liquidity traders, the slope of the first period equilibrium price schedule slightly exceeds its second period counterpart; and as Figs. 2–4 reveal the intensity with which both the informed agent and liquidity agents trade increases with time. The informed trader is particularly reluctant to trade intensively on his first period information in order to better profit on second period trade. *The liquidity traders are so risk averse that they over-hedge, more than offsetting their endowments by trading from an initial long position to a short position or vice versa, in order to offset the high price risk they face.* Because the informed agents trade with such greater intensively in the second period, second period liquidity agent trade intensity is higher.

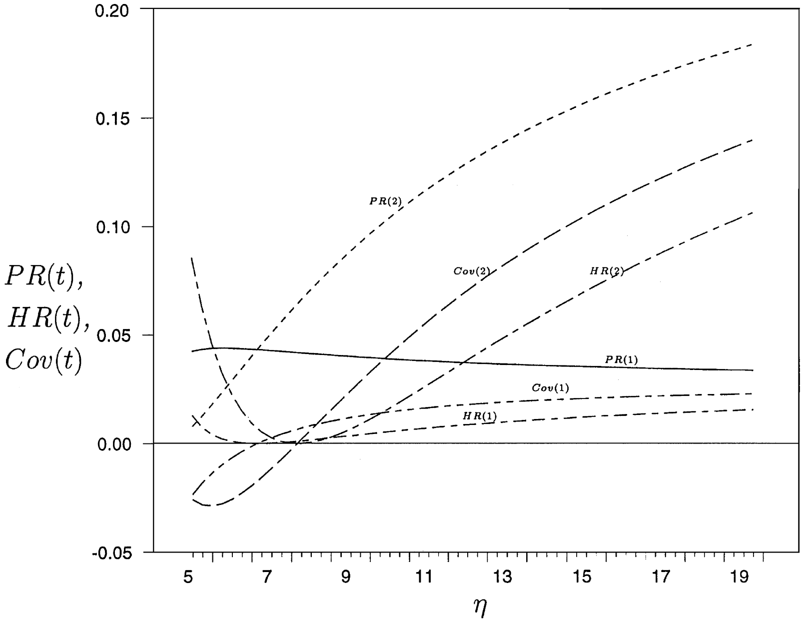

Fig. 6. Decomposition of portfolio risk. (Parameter values are: $\sigma = 1$ and $\Sigma = 1.5$.)

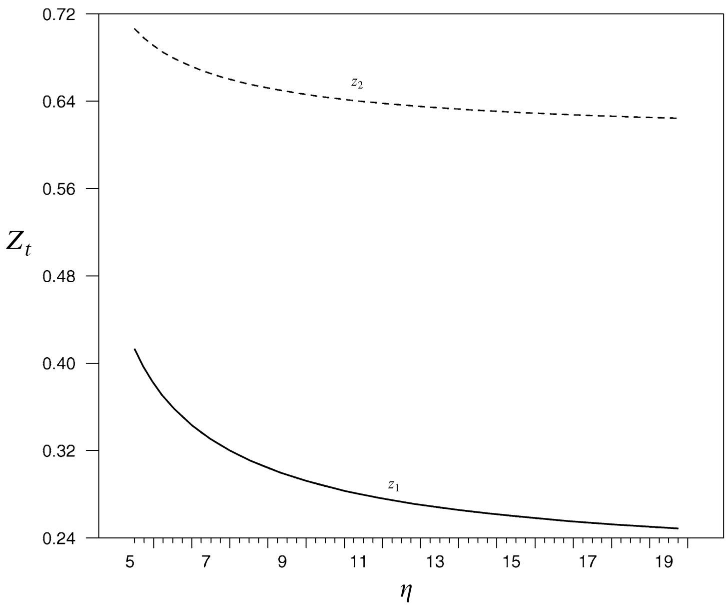

Fig. 7. Percentage of private information revealed by informed trade. (Parameter values are: $\sigma = 1$ and $\Sigma = 1.5$.)

- *High risk aversion*: $\eta \in (7.2, 8.5)$. For slightly lesser levels of risk aversion, the qualitative features of the economy differ from Kyle's noise trader model. As Fig. 2 reveals, because of his first period incentives to conceal his information in order to raise future profits, the informed agent still trades far more intensively on his information in the second period than the first. Fig. 1 shows that the consequence is that the market maker's marginal pricing schedule still falls over time. Whether greater informed trading intensity induces liquidity agents to trade more or less depends on the coefficient of risk aversion. For this range of risk aversion, liquidity trade is a declining function of informed trading intensity. Because the intensity with which the informed agent trades, and hence the price risk, increases significantly with time, the second period liquidity trader actually trades less intensively than the first period liquidity agent, even though he faces less adverse selection in pricing, $\lambda_2 < \lambda_1$. *Consequently, liquidity agents trade less intensively on their private endowment shocks as time passes.*
- *Moderate risk aversion*: $\eta \in (5.75, 7.2)$. For moderate levels of liquidity trader risk aversion, the standard Kyle pricing result fails to hold. Liquidity orders fall by so much with time, that as Fig. 1 documents, *the slope of the market maker's pricing schedule rises over time.* The informed agent's incentive to conceal information initially in order to profit in the future is still enough to induce him to trade more aggressively on his information in the second period than the first, despite the steeper second period price schedule. This greater second period informed trading intensity causes the liquidity agent to trade with greater intensity in the first period. This greater first period liquidity trading intensity so overwhelms the more aggressive second period informed trade that the slope of the zero profit price schedule *rises* with time.
- *Low risk aversion*: $\eta \in [4.75, 5.75)$. As Fig. 1 illustrates, for low levels of liquidity trader risk aversion, the slope of the first period equilibrium pricing schedule is substantially lower than its second period counterpart, $\lambda_1 \ll \lambda_2$. The slope of the market maker's pricing schedule rises by so much with time that the informed agent's incentive to conceal initially his information in order to profit in the future is overwhelmed by the better first period prices. Consequently, *informed trading intensity falls with time.* The market maker's price schedule rises with time because liquidity trading intensity is so much higher at earlier dates. Enough uncertainty about the asset is revealed that the modestly risk averse liquidity traders' orders fall sharply with time.
- *Very low risk aversion* $\eta < 4.75$. For such low levels of liquidity trader risk aversion, a (linear) equilibrium does not exist. As is often found in models with rational liquidity traders (e.g. Glosten and Milgrom, 1985; Spiegel and Subrahmanyam, 1992, or Bernhardt and Hughson 1997), if liquidity trade is too price sensitive, the market maker cannot set a finitely sloped price schedule that will allow it to break even.

3.5. Varying the volatility of the liquidity trader's endowment shock, σ

Varying the coefficient of risk aversion amounts to varying the intensity with which the liquidity trader dislikes an undiversified portfolio. Varying the volatility of the endowment shock amounts to varying the average extent to which the liquidity trader's portfolio is away from his ideal portfolio. Not surprisingly, the qualitative implications for pricing and trade are similar. If σ is sufficiently small, market makers cannot break even and an equilibrium does not exist. For slightly larger levels of σ, the slope of the second period price schedule exceeds the first. Finally, if the volatility is very high, the standard Kyle result that the slope of the marginal price schedule decreases with time holds (see Fig. 8). The slopes of both price schedules are sharply decreasing functions of σ. Both the informed agent and liquidity agents trade more intensively on their information, particularly in the second period, as the volatility of the endowment shock increases (see Fig. 9). This just reflects the fact that the slopes of the equilibrium schedules decline as σ rises, causing average liquidity trade to increase.

3.6. Varying the variance of asset value innovations, Σ_0

We now characterize how pricing and trading dynamics vary across stocks that differ in the amount of private information to which informed traders have access (i.e., Σ_0). Fig. 14 reveals that there is a U-shaped relationship between Σ_0 and the equilibrium slopes of the price schedules. This U-shaped pattern in equilibrium pricing leads to the opposite, inverted U-shaped relationship between Σ_0 and the informed agent's trading intensity in each period (see Fig. 15). In contrast, trading intensities for the liquidity agents increase monotonically with Σ_0, reflecting a secular rise in both price and holding risk (see Figs. 16 and 19). It is this feature that drives the U-shaped pattern in prices. Otherwise, the qualitative results are similar to those that obtain when varying η or σ. Again, the standard Kyle result that the slopes of the price schedules fall with time hold if and only if the innovation to the value of the asset is highly volatile.

These qualitative predictions can be tested at least loosely, because we have some idea about which stocks informed traders would tend to have more private information about. If, for example, they have more private information regarding smaller or more narrowly held stocks, one could test cross-sectionally whether allowing for rational, risk-averse liquidity traders can help explain cross-sectional variations in intraday pricing and trading patterns. A better, more direct test would be to recognize that the model most closely adheres to the real world around temporally separated, well-defined events such as earnings announcements, etc. Then if one can distinguish 'large' events from 'small', one can control for stock specific sources of heterogeneity and test to see whether the model is consistent with the dynamic cross-sectional variations in pricing and trade across event size.

4. Conclusion

In the classic Kyle (1985) finite horizon model of stock market dynamics with a trader who holds long-lived information, informed trading intensities rise with time, and the slopes of the equilibrium price schedules fall. So that the market maker cannot unravel the trades of the informed trader from the net order flow, Kyle introduces an irrational liquidity trader. Although, this model is a powerful analytic tool, the fact that 'noise' or 'liquidity' traders are assumed to trade exogenous quantities without regard to the parameters of the economy is potentially a serious shortcoming. In particular, this analytic shortcut is a reasonable one only if the model's qualitative predictions are largely robust to endogenizing the trading motives of liquidity agents.

The content of the present model is that the predictions of the standard Kyle model are *not* robust, they do not hold up when we endogenize the trading motives of liquidity agents by replacing the noise traders with a sequence of rational, risk averse, liquidity traders who receive endowment shocks. In particular, unless liquidity traders are quite risk averse, the qualitative predictions are substantively reversed: the slopes of equilibrium pricing schedule rise with time, while the trading intensities of informed and liquidity agents fall.

Appendix A

Proof to Proposition 1. *Step 1: Maximize the informed agent's expected profit.*

$$\max_x E_Q[x(\delta - \lambda(x + \mu Q)]. \tag{A.1}$$

The associated first order condition is

$$\delta - 2\lambda x = 0.$$

Solving,

$$x = \frac{1}{2\lambda}\delta \rightarrow \beta = \frac{1}{2\lambda}. \tag{A.2}$$

Step 2: Maximize the liquidity agent's expected utility.

$$\max_u \mathrm{E}_\delta\left[y + \delta\left(u - \frac{Q}{2}\right) - \lambda(\beta\delta + u)u\right] - \frac{\eta}{2}\mathrm{var}\left[y + \delta\left(u - \frac{Q}{2}\right) - \lambda(\beta\delta + u)u\right]. \tag{A.3}$$

Simplifying expected wealth:

$$\mathrm{E}_\delta\left[y + \delta\left(u - \frac{Q}{2}\right) - \lambda(\beta\delta + u)u\right] = y - \lambda u^2,$$

and substituting for $\beta = 1/2\lambda$ to simplify the variance of wealth,

$$\mathrm{var}\left[y + \delta\left(u - \frac{Q}{2}\right) - \lambda(\beta\delta + u)u\right] = \tfrac{1}{4}\Sigma_0[(u - Q)^2]$$

yields the following objective:

$$\max_u \; y - \lambda u^2 - \frac{\eta}{8}\Sigma_0[(u - Q)^2]. \tag{A.4}$$

The associated first order condition is

$$-2\lambda u - 2\frac{\eta}{8}\Sigma_0[u - Q] = 0.$$

Solving for u yields:

$$u = \frac{\eta\Sigma_0}{8\lambda + \eta\Sigma_0}Q \rightarrow \mu = \frac{\eta\Sigma_0}{8\lambda + \eta\Sigma_0}. \tag{A.5}$$

Step 3: Pricing.

$$P(x + u) = \mathrm{E}[\delta \,|\, \beta\delta + \mu Q]. \tag{A.6}$$

Exploiting the projection theorem, and substituting for $x + u = \beta\delta + \mu Q$ yields

$$P(x + u) = \lambda(x + u) = \frac{\mathrm{cov}(\delta,\, \beta\delta + \mu Q)}{\mathrm{var}(\beta\delta + \mu Q)}(\beta\delta + \mu Q).$$

Expanding the covariance and variance terms yields:

$$\lambda = \frac{\beta\Sigma_0}{\beta^2\Sigma_0 + \mu^2\sigma}. \tag{A.7}$$

Step 4: Solving.

Solving the three Eqs. (A.2), (A.5) and (A.7) simultaneously yields the equilibrium values of β, λ and μ.

Step 5: The conditional variance of δ:

To derive the variance of the liquidation value of the asset conditional on the net order flow, substitute for informed and uninformed demands, using the definition of the conditional variance:

$$\mathrm{var}[\delta \,|\, x + u] = \mathrm{var}[\delta] - \frac{(\mathrm{cov}[\delta,\, \beta\delta + \mu Q])^2}{\mathrm{var}[\beta(\delta) + \mu Q]}.$$

Expanding the variance and the covariance operators yields:

$$\Sigma_1 = \frac{\mu^2\sigma\Sigma_0}{\beta^2\Sigma_0 + \mu^2\sigma}. \tag{A.8}$$

Finally, note that if $\eta \leqslant 4/\sqrt{\Sigma_0\sigma}$, then a linear equilibrium does not exist because demand is so price elastic that market makers can never earn non-negative profits. Essentially, if liquidity agents are sufficiently risk neutral, they reduce their orders by too much when market makers set steeper price schedules, so that markets break down as in Glosten and Milgrom (1985), or Spiegel and Subrahmanyam (1992). □

Proof to Proposition 2. We solve recursively for any linear equilibrium.

Period 2:

Step 1: Maximize the insider's expected profit given p_1.

$$\max_{x_2} \mathrm{E}_{Q_2}[(\delta - [p_1 + \lambda_2(x_2 + \beta_2 Q_2)]x_2. \tag{A.9}$$

The first order condition is

$$\delta - p_1 - 2\lambda_2 x_2 = 0.$$

Solving,

$$x_2 = \frac{\delta - p_1}{2\lambda_2}. \tag{A.10}$$

Step 2: Maximize the period 2 liquidity agent's expected utility

$$\max_{u_2}\left[\mathrm{E}_\delta[w_2 \mid p_1, Q_2] - \frac{\eta}{2}\mathrm{var}(w_2 \mid p_1, Q_2)\right]. \tag{A.11}$$

Expected wealth is

$$\mathrm{E}_\delta\left[y + \delta\left(u_2 - \frac{Q_2}{2}\right) - (p_1 + \lambda_2(\beta_2(\delta - p_1) + u_2))u_2 \mid p_1, Q_2\right]$$
$$= \mathrm{E}_\delta\left[y + \delta\left(u_2 - \frac{Q_2}{2}\right) - \left(p_1 + \frac{\delta - p_1}{2} + \lambda_2 u_2\right)u_2 \mid p_1, Q_2\right]$$
$$= y - p_1\frac{Q_2}{2} - \lambda_2 u_2^2,$$

where the first equality follows from substituting for β_2, and the second equality follows from the market efficiency condition.

The conditional variance of wealth is

$$\mathrm{var}(w_2 \mid p_1, Q] = \mathrm{E}_\delta\left[\left\{\left(u_2 - \frac{Q_2}{2}\right)(\delta - p_1) - \tfrac{1}{2}u_2(\delta - p_1)\right\}^2 \middle| p_1, Q_2\right]. \tag{A.12}$$

Using $\mathrm{E}[(\delta - p_1)^2 \,|\, p_1, Q_2] = \Sigma_1$, the conditional variance simplifies to

$$\mathrm{var}(w_2 \,|\, p_1, Q_2] = \frac{\Sigma_1}{4}(u_2 - Q_2)^2. \tag{A.13}$$

The liquidity agent's objective then becomes

$$\max_{u_2} y - p_1 \frac{Q_2}{2} - \lambda_2 u_2^2 - \frac{\eta \Sigma_1}{8}(u_2 - Q_2)^2.$$

The first order condition is

$$-2\lambda_2 u_2 - 2\frac{\eta\Sigma_1}{8}(u_2 - Q_2) = 0.$$

Solving

$$u_2 = \frac{\eta\Sigma_1}{8\lambda_2 + \eta\Sigma_1} Q_2 \tag{A.14}$$

Step 3: Market efficiency:

$$p_2 = \mathrm{E}[\delta \,|\, x_1 + u_1, x_2 + u_2]. \tag{A.15}$$

Using the fact that the first period price reflects the market maker's first period information, we can subtract p_1 from both sides of the market efficiency condition which gives:

$$p_2 - p_1 = \mathrm{E}[\delta - p_1 \,|\, x_2 + u_2]. \tag{A.16}$$

Exploiting the projection theorem yields:

$$\lambda_2(x_2 + u_2) = \frac{\mathrm{cov}(\delta - p_1, x_2 + u_2)}{\mathrm{var}(x_2 + u_2)}(x_2 + u_2). \tag{A.17}$$

Substituting for $x_2 = \beta_2(\delta - p_1)$ and $u_2 = \mu_2 Q_2$, the covariance term becomes

$$\mathrm{cov}(\delta - p_1, x_2 + u_2) = \beta_2 \mathrm{var}[\delta - p_1]. \tag{A.18}$$

Note that $\mathrm{var}[\delta - p_1]$ is the unconditional variance of the liquidation value of the asset in the second period. As before, using the fact that the first period price, p_1, reflects all of the market maker's first period information, i.e. the net order flow, $x_1 + u_1$, the second period unconditional variance of the liquidation value is equal to the variance of the liquidation value of the asset, Σ_1, conditional on $x_1 + u_1$. Thus, the market efficiency condition becomes:

$$\lambda_2 = \frac{\beta_2 \Sigma_1}{\beta_2^2 \Sigma_1 + \mu_2^2 \sigma}. \tag{A.19}$$

Step 4: The informed agent's expected second period profit.

Substitute the second period equilibrium pricing function (A.19), liquidity trade (A.14), and the informed agent's order (A.10), into the informed agent's second period expected profit function (A.9) to obtain

$$\mathrm{E}[\pi_2 \,|\, p_1, \delta] = \frac{1}{4\lambda_2}(\delta - p_1)^2. \tag{A.20}$$

Step 5: The second period variance of δ conditional on the net order flows.

To derive the second period variance of δ conditional on the net order flows in each period, we use the fact that the unconditional variance, $\mathrm{E}[\delta - p_1]^2$, is equal to the conditional variance of the liquidation value of the asset, Σ_1, in Eq. (16). Then by using iterative conditional expectations, we obtain

$$\Sigma_2 = \mathrm{var}(\delta - p_1 \,|\, x_2 + u_2). \tag{A.21}$$

Substituting for x_2 and u_2 from (A.10) and(A.14), respectively and use the definition of the conditional variance yields:

$$\mathrm{var}[\delta - p_1 \,|\, x_2 + u_2] = \mathrm{var}[\delta - p_1] - \frac{(\mathrm{cov}[\delta - p_1, (\beta_2(\delta - p_1) + \mu_2 Q_2)])^2}{\mathrm{var}[\beta_2(\delta - p_1) + \mu_2 Q_2]}. \tag{A.22}$$

Expanding the variance and the covariance operators yields:

$$\Sigma_2 = \frac{\mu_2^2 \sigma \Sigma_1}{\beta_2^2 \Sigma_1 + \mu_2^2 \sigma}. \tag{A.23}$$

Period 1:

Step 1: Maximize the informed agent's expected lifetime profit

The informed agent chooses x_1 to maximize expected lifetime profits, taking into account the effects on second period profits:

$$\max_{x_1} E_{Q_1}[(\delta - \lambda_1(x_1 + \mu_1 Q_1))x_1 + \frac{1}{4\lambda_2}(\delta - \lambda_1(x_1 + \mu_1 Q_1))^2, \tag{A.24}$$

Differentiating and solving for the optimal choice of x_1 yields

$$x_1 = \frac{1 - 2\lambda_1/4\lambda_2}{2\lambda_1(1 - \lambda_1/4\lambda_2)}\delta. \tag{A.25}$$

Step 2: Maximize the first period liquidity agent's expected utility

Using the same argument as in the second period, the first period liquidity agent's optimization problem is

$$\max_{u_1} \left\{ y - \lambda_1 u_1^2 - \frac{\eta \Sigma_0}{2}\left(\left(u_1 - \frac{Q_1}{2}\right)^2 + \lambda_1^2 \beta_1^2 u_1^2 - 2\lambda_1 \beta_1 u_1 \left(u_1 - \frac{Q_1}{2}\right)\right)\right\}. \tag{A.26}$$

The associated first order condition is

$$\left(\frac{\eta\Sigma_0}{4}(1-\lambda_1\beta_1)\right)Q_1 = u_1\left(\lambda_1 + \frac{\eta\Sigma_0}{2}(1-\lambda_1\beta_1)^2\right).$$

Solving,

$$u_1(Q_1) = \frac{(\eta\Sigma_0/4)(1-\lambda_1\beta_1)}{\lambda_1 + (\eta\Sigma_0/2)(1-\lambda_1\beta_1)^2}Q_1. \tag{A.27}$$

Step 3: The market efficiency condition

$$p_1 = \mathrm{E}[\delta \mid x_1 + u_1]. \tag{A.28}$$

Following the logic for the second period price, the market depth parameter is

$$\lambda_1 = \frac{\beta_1\Sigma_0}{\beta_1^2\Sigma_0 + \mu_1^2\sigma}. \tag{A.29}$$

Step 4: The first period conditional variance of δ

To derive the first period variance of the liquidation value of the asset conditional on the first period net order flow, expand the conditional variance operator and substitute for x_1 and u_1. After some simplification, we obtain

$$\Sigma_1 = \frac{\mu_1^2\sigma\Sigma_0}{\beta_1^2\Sigma_0 + \mu_1^2\sigma}. \tag{A.30}$$

This concludes the proof. □

Appendix B

This appendix graphs (Figs. 8–13) the equilibrium values of different variables for the dynamic trade model with risk-averse liquidity traders, illustrating how the variance of the liquidity agents' shock effects equilibrium outcomes when the liquidity agents' coefficient of risk aversion is $\eta = 4.75$ affects outcomes and the variance of the innovation to the asset's value is $\Sigma = 1.5$.

Appendix C

This appendix graphs (Figs. 14–19) the equilibrium values of different variables for the dynamic trade model with risk-averse liquidity traders, illustrating how the variance of the innovation to the asset's value, Σ, affects equilibrium outcomes when the liquidity agents' coefficient of risk aversion is $\eta = 4.75$ affects outcomes and the variance of the liquidity shock is $\sigma = 1.0$.

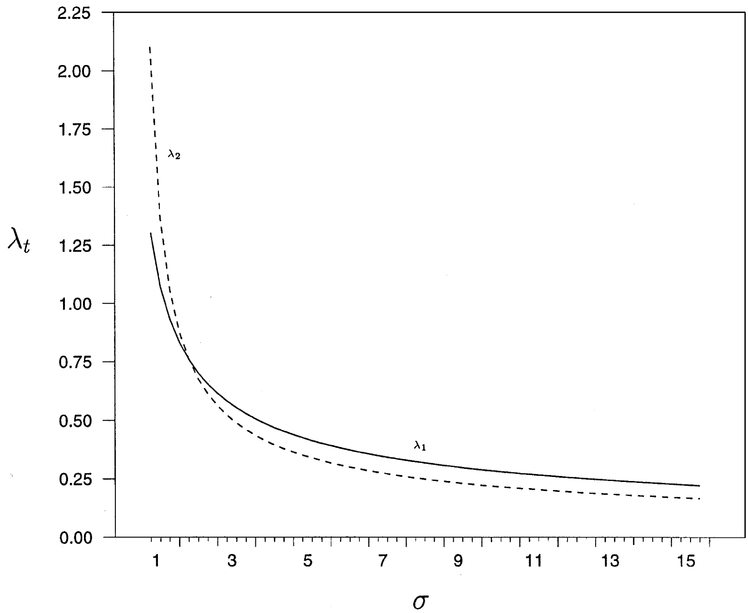

Fig. 8. Slopes of the market maker's price schedules.

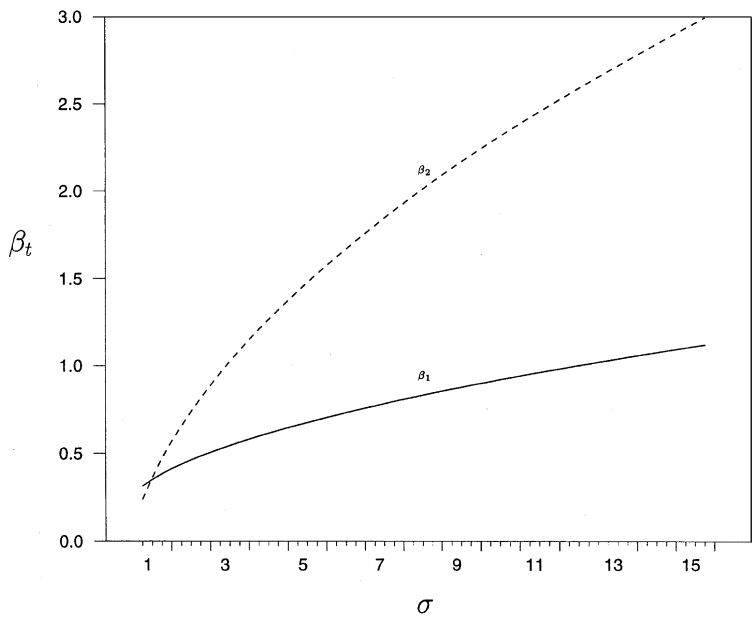

Fig. 9. Intensity of informed trade.

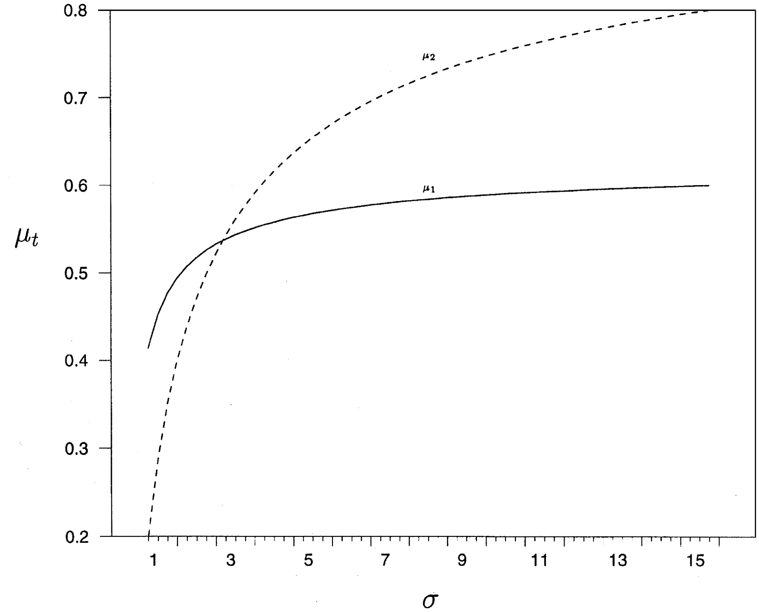

Fig. 10. Intensity of liquidity trade.

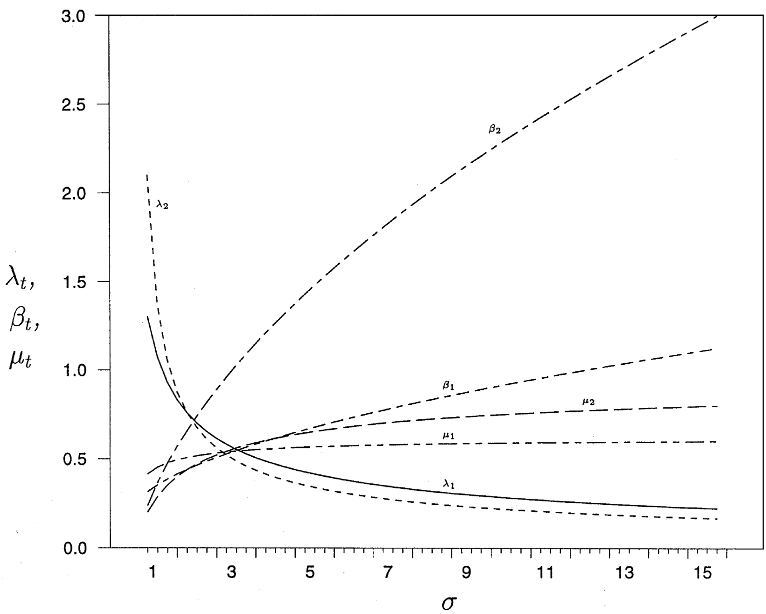

Fig. 11. Equilibrium parameter values.

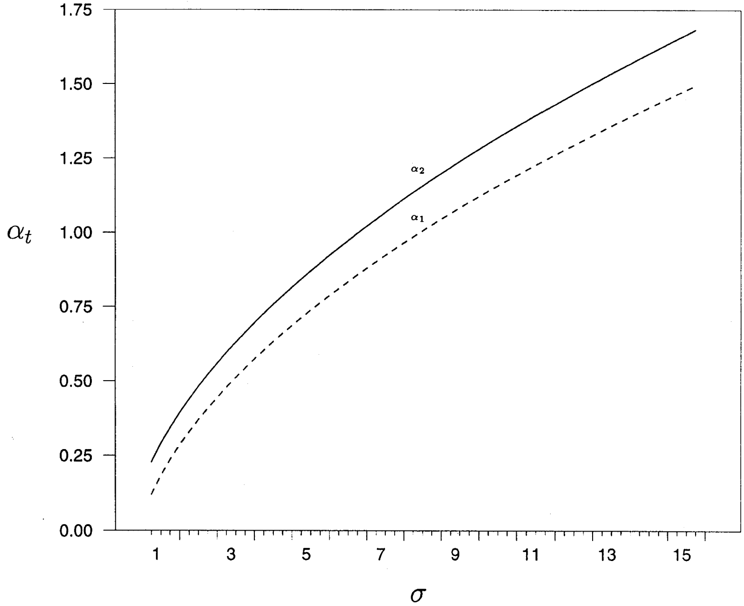

Fig. 12. Slopes of the informed trader's period profit functions.

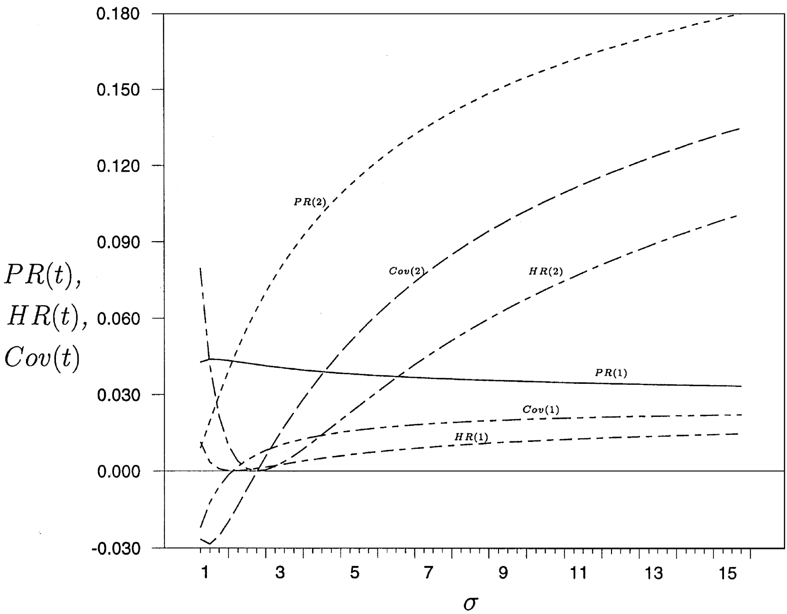

Fig. 13. Decomposition of portfolio risk.

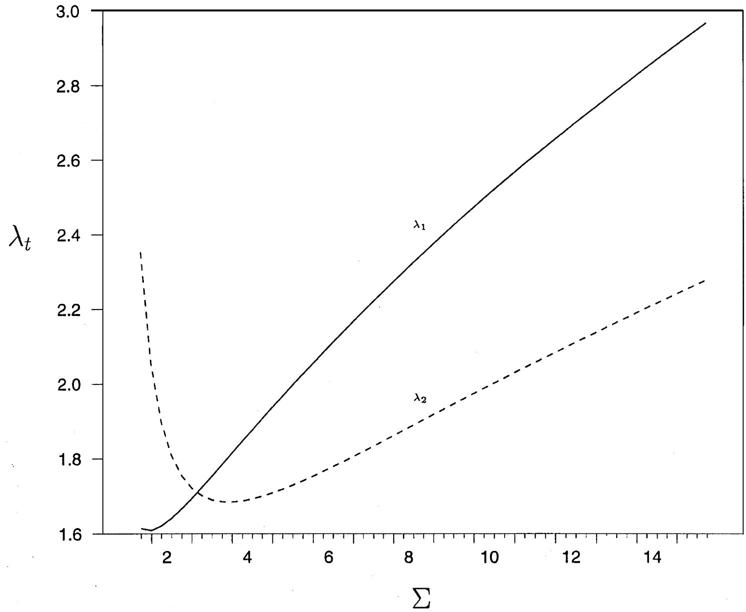

Fig. 14. Slopes of the market maker's price schedules.

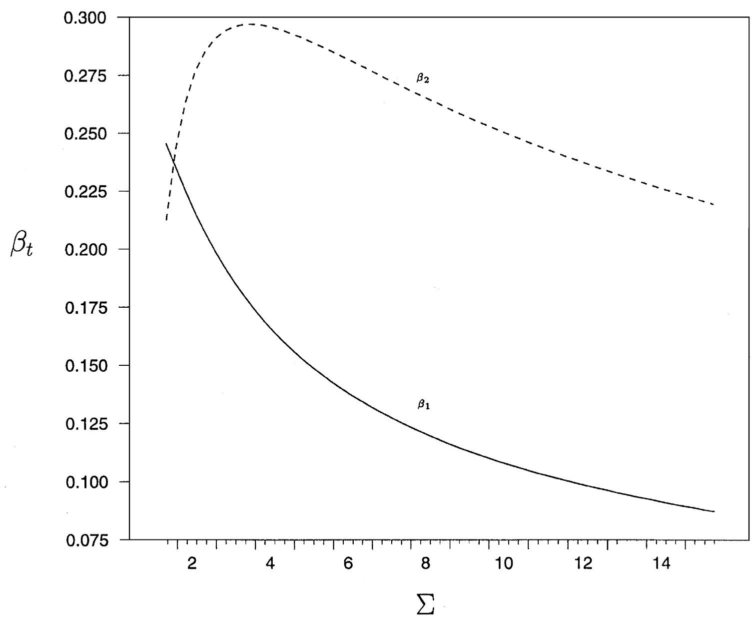

Fig. 15. Intensity of informed trade.

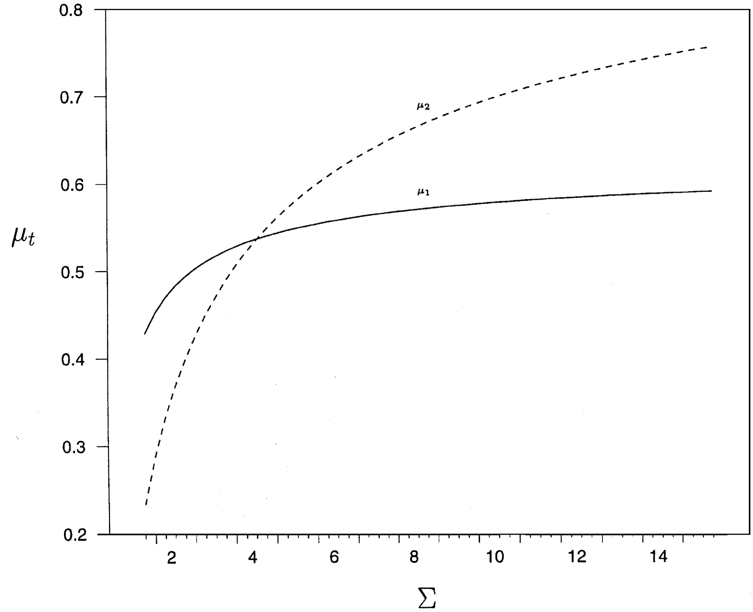

Fig. 16. Intensity of liquidity trade.

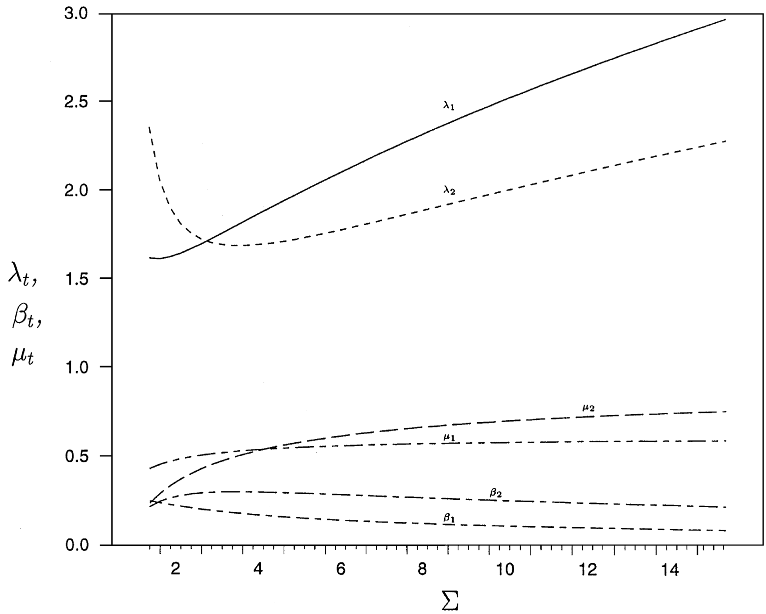

Fig. 17. Equilibrium parameter values.

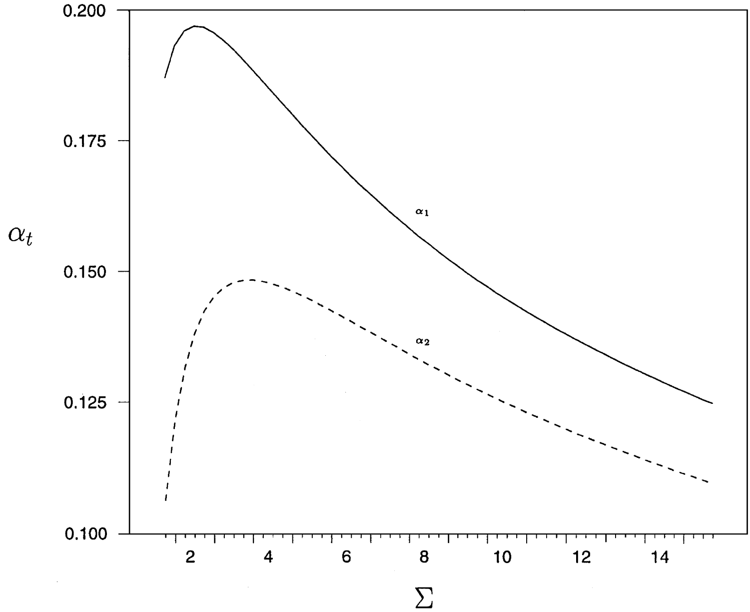

Fig. 18. Slopes of the informed trader's period profit functions.

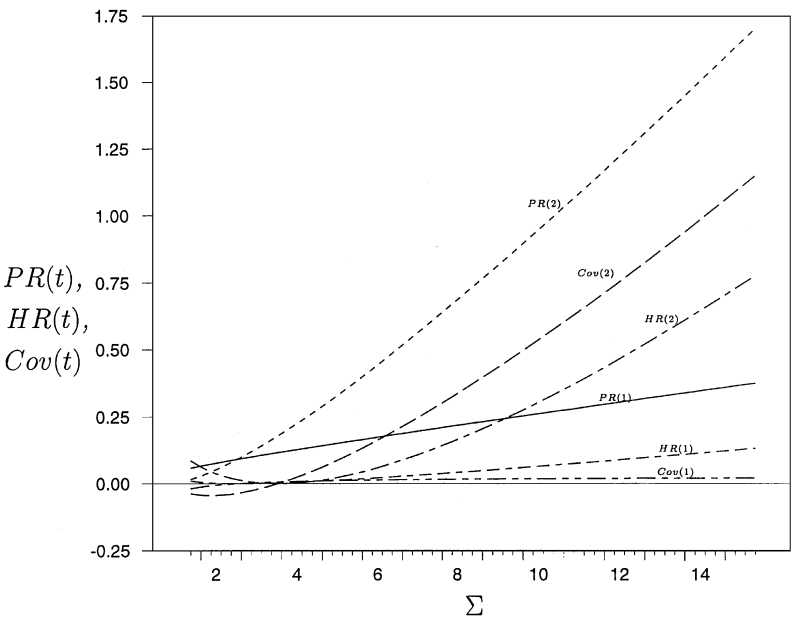

Fig. 19. Decomposition of portfolio risk.

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