Economics Department

Exchange Rate Volatility's Dependence on Different Degrees of Competition under Different Learning Rules

A Market Microstructure Approach

NORBERT WUTHE

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Exchange Rate Volatility's Dependence on Different Degrees of Competition under Different Learning Rules

- A Market Microstructure Approach

Norbert Wuthe*
12 April 2000

Abstract

We assess the phenomenon of excess volatility in intra-day foreign exchange markets using a market microstructure approach. Introducing different degrees of competition in the forex market and applying different learning mechanisms we are able to give a rationale for traders' use of rather simple learning rules: Behaving less rationally turns out to be more profitable, thus preserving rationality in traders' choice. Competition's impact on volatility is ambiguous: Depending on the variance measure applied volatility can be increasing in competition.

^{*}Keywords: Exchange rates, exchange rate volatility, learning, market microstructure, competition.- I would like to thank Professors A. Kirman and S. Vassilakis, and G. Fernandez de Cordoba for many useful discussions and comments, and Prof. M. Artis for his support.

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1 Introduction

The present paper extends the analysis of Wuthe (1999). There, the commonly observed phenomenon of excess volatility in intra-day foreign exchange markets was assessed using a market microstructure approach. Focusing on the learning behavior of a monopolistic trader and the institutional setting it was possible to reproduce exchange rate behavior which calibrates well with observed time series characteristics.

We continue this analysis introducing different degrees of competition in the foreign exchange market. It will be of interest to see how competition influences traders' behavior and exchange rate volatility, and to compare these results with the outcome of the monopoly case. As will be seen exchange rate fluctuations diminish with increasing competition for many volatility measures, but not for all.

More importantly, we will be able to give a rationale for the use of less sophisticated learning rules without the need of referring to the concept of bounded rationality. It can be shown that traders in financial markets are behaving fully rationally when deciding to apply an unsophisticated learning rule. Put differently: Choosing from a menu of different rationality levels the seemingly least rational one can be seen as a sign of full rationality.

The paper will follow the subsequent plan: Section 2 gives a short summary of the literature on inventory models with competition. Section 3 presents a dynamic model with competition. Section 4 introduces the different learning rules the impact of which is being analyzed in the simulation part. Sections 5 and 6 describe the simulation set-up and present the results. We conclude comparing our results with the literature.

2 Competition in Inventory Models

The introduction of competition into inventory models is an exercise which can amount to a considerable degree of complexity: Since traders will usually transact with the dealer quoting the best price, each dealer's pricing problem depends on the actions of every other dealer. Hence, a dealer's optimal pricing strategy depends on his expectations over the actions of the other dealers. In a multi-period framework with order flow uncertainty and, maybe, differing risk preferences or knowledge of the order flow the decision problem rapidly becomes intractable. To control for this various simplifications are usually introduced.

An issue of particular interest to securities markets has been addressed in the early literature on competition in inventory models: In the presence of other dealers willing to provide immediacy market orders requiring immediate execution can be crossed with limit orders submitted by traders. Thus, the possibility arises that the interaction of market and limit orders provides a sufficient amount of liquidity for a viable securities market similar to the spirit of Demsetz - without the necessity of a specialist. Furthermore, an analysis of the characteristics of these two order types may indicate how liquidity arises in markets in a different way than directly from the market maker. Cohen, Maier, Schwartz, and Whitcomb (1981) address these questions. Assuming exogenously given transaction costs - for submitting a limit-order and for its execution or for submitting a market order - they are able to construct an interesting dynamics of the movement of traders between limits and markets which in turn determines the size of the spread. The movement of the competitive traders who try to minimize transaction costs depends on the execution probability of a market order. The spread exists because, given the underlying transaction costs, some traders prefer to submit a market order with certain execution rather than to trade continuously. In the absence of transaction costs all orders would be limit orders because the continuity of the price process would guarantee execution. Hence, the spread

arises as a consequence of transaction costs. With the spread widening more traders prefer to enter limit orders which leads to an increase in liquidity available in the market.

The model of Cohen, Maier, Schwartz, and Whitcomb does not explicitly include inventory. However, if traders act as dealers one should expect the inventory position to affect the dealers' willingness to buy or sell. Ho and Stoll (1983) investigate this aspect in a model with competitive dealers. Rather than allowing for limit orders dealers can either trade between themselves or with customers. While this set-up seems quite different from the previous one it should be noted that trading with another trader in the interdealer market allows to lock in a certain price. Customer deals, on the other hand, allow for more favorable prices but imply uncertain execution. Given this kind of environment and the presence of competition a dealer's optimal price-setting task is more complex than the mere balancing of orders. His inventory position exposes him to higher risk now since he does not hold a monopoly position for clearing order flows.

Ho and Stoll simplify the analysis by assuming a duopoly situation in which dealers maximize expected utility of wealth. As in Ho and Stoll (1981) dealers are concerned with their portfolio position when undertaking trading activity. The explicit solution of their model is for one period only leaving thus out intertemporal inventory- and possible strategic considerations. Optimal bid and ask prices for each of the two stocks traded depend then on the discounted sum of a fixed transaction value plus the inventory value (not its size), and on the return variance of the stock which is being priced. The inventory value, in turn, depends on the variance of the respective stock and the covariance of return between the two stocks.

The resulting spread is independent of the value of the inventory and the number of stocks that are being traded. Only the spread's placement is affected by the inventory. The size of the spread is basically equal to the monopoly spread because with two dealers only each of them acts as a monopolist on his side of the market. Trading between the two dealers, then, will not occur since prices are essentially identical. Ho and Stoll argue that with the presence of more dealers in the market the spread diminishes but will always remain positive. This outcome is due to interdealer trades which now do occur: A dealer who finds himself with a higher inventory position after a transaction has taken place will lower his bid price and thus widen the spread. Orders from other dealers will then be attracted as the market spread narrows. Consequently, a widening of the spread takes place.

Research by Pagano (1989) and Biais (1993) investigates the effects of an inclusion of expectations of the other dealers' actions and the size of their inventory. These elements could play no role in the one-period model of Ho and Stoll.

Zabel (1981) and O'Hara and Oldfield (1986) both employ a discretetime multiperiod framework and depart with this characteristic from previous modeling approaches, i.e. the continuous-time multiperiod model of e.g. Amihud and Mendelson.¹ This new framework with prices being called out at the beginning of each period allows to incorporate the realistic feature that traders can "hit a quote" by submitting an order. The dealer has to support his price by trading for his own account on demand. Extending the horizon infinitely but dividing each trading day in a finite number of periods allows also for the inclusion of an overnight market where trade settlement can take place independently of order processing.

Suvanto (1993) translates Zabel's model to the institutional specifics of the spot foreign exchange market. He includes competition and the presence of an interbank market in the dynamic framework. While traders remain price-setters also in a competitive environment their quotations are pulled into a given range around the average market price. Apart from inventory considerations the price now, with competition, is also adjusted when the average quotation changes.

¹Two other discrete-time models of dealer behavior has been developed by Bradfield (1979) and Bradfield and Zabel (1979).

The strategy for cover transactions in the interbank market is driven by two forces, basically: Traders who wish to undertake some position adjustment in the interbank market find themselves on the "wrong" side of the market. However, if the shadow price lies below the observed average interbank bid-rate then the dealer will prefer to cover at least part of his long position in the interbank market to a large downward adjustment of his own price.

The spread is influenced by two aspects: The fact that now also interbank traders can submit orders to a trader and not only customers implies a higher price sensitivity of those orders which will reduce the size of the spread. On the other hand, transactions uncertainty does increase since the volume of interbank transactions usually is bigger than customer transactions. A trader will try to protect himself against this increased uncertainty through a broadened spread. However, in general the spread under competition does diminish as compared to the monopoly case.

In the following we will build on Suvanto's framework but leave out the presence of an interbank market in order to ease comparison of results with the monopoly case.

3 An n-Period Dynamic Model With Competition

The basic structure of the model presented here is similar to the monopoly set-up in Wuthe (1999). It differs in that now the local dealer has to face not only clients' sensitivity towards his own price but also differences between his quotation and his competitors ones'. This construction is based on the assumption that customers are no longer constrained to trade in their local market only (a limitation which may be due to high transaction or information costs e.g.). Occurring higher transaction costs when trading outside the local market a continuum of clients may be imagined which is ordered according to their relative transaction costs - ranging

from the well-informed on the one end to the non-informed on the other end of the scale. The well-informed clients with low transaction costs can easily choose to leave the local market if they observe an only marginally better quotation elsewhere.- Another possibility for introducing competition is to assume the presence of many dealers in the same local market with customers differing in their degree of price sensitivity. 2

There are two different types of customers present in the market: One type - the HET type - is characterized by a high elasticity of net-supply, the other type - the LET type - by a low elasticity, all other parameters being equal between the two groups.

The two different arrival rates of customers' demand in period t, x_t , can be described as follows:

$$\begin{aligned} x^h_t &= a - c s^a_t - e \left(s^a_t - S^a_t \right); \\ x^l_t &= a - d s^a_t - f \left(s^a_t - S^a_t \right), c > d, e > f. \end{aligned}$$

with s^a being the monopolist's ask-rate and the intercept a being equal for both types. The superscripts indicate which type's demand is being described. Seen from the dealer's perspective, customer demand is the same as arriving sell orders.

Competitors' quotations are represented as the average quotation across all dealers in the market - S^a and S^b being the average ask- and bid-rates. The parameters e and f describe the customers' sensitivity to price differentials, with e being HETs' higher parameter and f LETs' lower one. The bigger a positive bracket term the higher is the individual trader's ask-rate relative to the average market ask-rate, and the lower

²An aspect from which we will abstract in this analysis is the real world presence of an interbank market: The interbank market is a market which allows the individual dealer to cover eventually open positions by trading with other dealers. Doing so the dealer acts in the role of a customer which will strengthen competition. The effect of this should be a narrowing of the spread, as was said above, but its effect in an environment of uncertainty about the customer clients' distribution is not clear without thorough analysis.

will be demand for foreign exchange from him. The contrary is true for a negative bracket term.— The parameters c and d, on the other hand, show customers' sensitivity, in the aggregate, to the exchange rate. If sensitivity to price differentials is high it can be assumed that e and f are large relative to c and d, respectively.

Market demand follows to be the sum of the two different demand curves weighted with the respective distributional weights if the number of low elasticity type costumers in the market is given by 1-v, and the number of high elasticity type costumers by v:

$$x_t = v \cdot [a - cs_t^a - e(s_t^a - S_t^a)] + (1 - v) \cdot [a - ds_t^a - f(s_t^a - S_t^a)].$$

Similarly, on the other side of the market the supply functions depend also on HETs' and LETs' sensitivity to price differentials respectively:

$$\begin{aligned} y^h_t &= b + c s^b_t + e \left(s^b_t - S^b_t \right); \\ y^l_t &= b + d s^b_t + f \left(s^b_t - S^b_t \right), c > d, e > f. \end{aligned}$$

The bigger a positive bracket term the higher is the individual trader's bid-rate relative to the average market bid-rate and the higher will be supply of foreign currency to him whereas the contrary holds for a negative bracket term.

Market Supply is then given by:

$$y_t = v \cdot \left[b + cs_t^b + e\left(s_t^b - S_t^b\right)\right] + (1 - v) \cdot \left[b + ds_t^b + f\left(s_t^b - S_t^b\right)\right].$$

It should be remembered that the market demand and supply functions present average arrival rates of incoming orders rather than always present market orders. Once again, high levels of the shift variables a and b represent high levels of demand and supply, respectively.

For every single trader it is assumed that the closed position constraint for the end of the trading day applies, i.e. every existing position has to be reversed during the remainder of the day. The dynamic optimization problem of a dealer facing competition can then be represented

in a similar way to the monopolist's problem in Wuthe (1999):

$$\begin{split} J_t\left[m_t\right] &= \underset{s_t,z_t}{Max} \quad E_t\left\{\pi_t + J_{t+1}\left[m_{t+1}\right]\right\} \text{ (value function)} \\ J_T\left[m_T\right] &= 0 \text{ (terminal value)} \\ m_{t+1} &= m_t - A + s_t \cdot \left[q_t \cdot (\delta + \eta) + (1 - q_t) \cdot (\gamma + \rho)\right] - \\ &\qquad \qquad S_t \cdot \left[q_t \cdot \eta + (1 - q_t) \cdot \rho\right] \text{ (system constraint)} \\ E_t\left(m_T\right) &= m^* \text{ (terminal state constraint)}. \end{split}$$

It is assumed that dealers are aware of there being two different types of clients present in the market, and that they know their demand and supply functions, i.e. all the respective parameters are known to them. However, the dealers have no information about the distribution of high and low elasticity clients, i.e. the value of the parameter v is unknown to them. For his maximization calculus they therefore have to use their subjective prior beliefs q about the true value v: The subjective belief q_t is the belief each trader holds at the beginning of period t conditional on all information available up to that point of time.

Furthermore, dealers are constrained to have their expected foreign exchange positions closed by the end of the day, or to meet some other position target m^* . A position is said to be closed (squared) if the value of assets denominated in a given currency is equal the value of liabilities denominated in that currency; i.e. the dealers' holdings of foreign currencies are hedged against any unexpected change in the environment which determines the customers' average buy and sell orders. Since for every foreign exchange transaction there are always two currencies involved a dealer's position can be regarded as closed if net sales of these two currencies are equal to zero by the end of the trading day (or whatever period under consideration).

The change in each trader's foreign currency inventory, m, during one trading session can be described by the amount of net sales of that period:

$$m_t - m_{t+1} = x_t - y_t,$$

where m_t is the inventory at the beginning of period t, and m_{t+1} is the inventory at the beginning of period t+1 (which is the same as the inventory at the end of period t).

In order to describe the dealer's maximization problem the ask- and the bid-rate are redefined in terms of the mid-rate and the half-spread: The mid-rate is given by $s_t = \left[s_t^a + s_t^b\right]/2$, and the half-spread by $z_t = \left[s_t^a - s_t^b\right]/2$. The profit function of the dealer is then given by (using conventions A = a - b > 0, B = a + b > 0, $\delta = 2c > 0$, $\gamma = 2d > 0$, and $\eta = 2e$, $\rho = 2f$):

$$\begin{split} \pi_t &= \left[q_t \cdot x_t^h + (1 - q_t) \cdot x_t^l \right] \cdot s_t^a - \left[q_t \cdot y_t^h + (1 - q_t) \cdot y_t^l \right] \cdot s_t^b \\ &= \left[\begin{array}{c} q_t \cdot (a - cs_t^a - e\left(s_t^a - S_t^a\right)\right) + \\ (1 - q_t) \cdot (a - ds_t^a - f\left(s_t^a - S_t^a\right)) \end{array} \right] \cdot (s_t + z_t) - \\ \left[\begin{array}{c} q_t \cdot \left(b + cs_t^b + e\left(s_t^b - S_t^b\right)\right) + \\ (1 - q_t) \cdot \left(b + ds_t^b + f\left(s_t^b - S_t^b\right)\right) \end{array} \right] \cdot (s_t - z_t) \\ &= q_t \cdot \left[s_t \cdot (A + \eta \cdot S_t) + z_t \cdot (B + \eta \cdot Z_t) - (\delta + \eta) \cdot \left(s_t^2 + z_t^2\right) \right] + \\ (1 - q_t) \cdot \left[s_t \cdot (A + \rho \cdot S_t) + z_t \cdot (B + \rho \cdot Z_t) - (\gamma + \rho) \cdot \left(s_t^2 + z_t^2\right) \right]. \end{split}$$

In words: The trader's profit of one period is given by the value difference between his foreign currency acquisitions and sales where the net supply quantities are weighted with the period's belief about the population's distribution, respectively.

Solving backward in time the sequential pricing rule and spread are obtained to be: 3

$$s_{t} = \frac{A + S_{t} \cdot [q_{t} \cdot \eta + (1 - q_{t}) \cdot \rho]}{q_{t} \cdot (\delta + \eta) + (1 - q_{t}) \cdot (\gamma + \rho)} - \frac{1}{q_{t} \cdot (\delta + \eta) + (1 - q_{t}) \cdot (\gamma + \rho)} (m_{t} - m_{\bullet}^{\bullet}) / (T + 1 - t),$$

 $^{^3}$ The solution procedure closely follows the one described in the monopoly article.

$$z_t = \frac{B + [q_t \cdot \eta + (1 - q_t) \cdot \rho] \cdot Z_t}{2 \cdot [q_t \cdot (\delta + \eta) + (1 - q_t) \cdot (\gamma + \rho)]}.$$

The expression for the quotation can be split into two parts: The first one (up to the minus sign) is the one-period equilibrium rate which also depends directly on the average quotation in the market and, hence, also on other traders' period beliefs. The second part describes the impact of an eventual open position a fraction of which shall be closed during the following periods. The mid-rate will be below the equilibrium rate if the current inventory positions falls short of the target, and it will be above in the opposite case. Note that the coefficient attached to the open position increases as t approaches the last trading session T. With a zero open position the mid-rate becomes equal to the one-period equilibrium rate.

Also the spread depends no longer on the individual dealer's price making power as in the monopoly case but also on the average spread in the market. It thus fluctuates not only due to belief updates but also to period-to-period changes of other traders' spread.

For the duopoly case the Nash-equilibrium solutions are obtained by replacing S_t and Z_t with the respective opponent's expressions and solving for s_t and z_t :

$$s_t^{N.E.} = \frac{(A-m_t) \cdot \left\{ \left[p_t \cdot (\delta + \eta) + (1-p_t) \cdot (\gamma + \rho) \right] + \left[q_t \cdot \eta + (1-q_t) \cdot \rho \right] \right\}}{\left\{ \begin{array}{l} \left[p_t \cdot (\delta + \eta) + (1-p_t) \cdot (\gamma + \rho) \right] \cdot \\ \left[q_t \cdot (\delta + \eta) + (1-q_t) \cdot (\gamma + \rho) \right] \\ \left[q_t \cdot \eta + (1-q_t) \cdot \rho \right] \cdot \left[p_t \cdot \eta + (1-p_t) \cdot \rho \right] \end{array} \right\} \cdot (T+1-t)^2}$$

$$\begin{split} z_t^{N.E.} &= \frac{B \cdot \left\{2 \cdot \left[p_t \cdot (\delta + \eta) + (1 - p_t) \cdot (\gamma + \rho)\right] + \left[q_t \cdot \eta + (1 - q_t) \cdot \rho\right]\right\}}{2 \cdot \left\{\begin{array}{l} \left[q_t \cdot (\delta + \eta) + (1 - q_t) \cdot (\gamma + \rho)\right] \cdot \\ \left[p_t \cdot (\delta + \eta) + (1 - p_t) \cdot (\gamma + \rho)\right] \end{array}\right\} - \\ & \left[q_t \cdot \eta + (1 - q_t) \cdot \rho\right] \cdot \left[p_t \cdot \eta + (1 - p_t) \cdot \rho\right] \end{split}$$

4 Learning and Belief-Updating

In the course of the trading process traders use the indirect evidence from the order flow to infer what the value of the unknown parameter is. The learning problem is then solved via the application of specific learning rules.⁴

We specify as the information each trader receives a client's reaction to his quoted price. At the beginning of each trading session traders quote bid- and ask-rates upon request. When a trader's quotation gets rejected by a client the trader can infer that a HET client had been calling. In the monopoly case in Wuthe (1999) this procedure of information extraction had been motivated by the fact that the expected demand and supply curves always lie above the HET's respective curves which renders the optimal quotation too high for a HET.

This interpretation becomes disputable in the present setting since it is no longer clear whether a quotation is rejected because of a HET calling or because of too high a price differential for a LET (who is able to call around and get an idea about the market average). However, the reaction to his quotations remains the trader's only potential source of information in order to learn the population's true distribution. In the following it is therefore assumed that the individual trader continues to interpret phone calls the same way as he would do as a monopolist.

After the interpretation of the outcome of the phone call the traders, at the end of each period, update their prior beliefs according to some updating rule. The resulting posterior then becomes their new prior. Observing new data in the following periods the updating process continues.

The choice of the updating rule is of considerable importance since the movement of beliefs over time is determined by it. The dynamics of the updating process and its convergence properties will be reflected in

⁴In what follows we basically summarize the presentation and motivation of the different learning rules introduced in Wuthe (1999).

the movement of prices. Hence, knowing those properties of the learning rule allows to determine what aspects of price behavior follow from the nature of the learning rule, and which reflect other factors such as dealer-specific preferences or market structure constraints.

While all asymmetric-information microstructure models essentially solve a Bayesian learning model we propose here the application of less sophisticated learning rules. The reason for this procedure is that the chaotic and volatile behavior of intra-day exchange rates together with the negligible impact of news of minor importance ⁵ suggest the possibility of a less smooth learning process on behalf of the traders. As will be discussed further below applying less sophisticated learning rules does not necessarily imply a lower level of rationality. This argument is relevant in the context of a market where professional traders try to optimize their behavior in order to extract maximal profits.

Following the taxonomy of learning of Milgrom and Roberts (1991) we will make use of 'unsophisticated learning' behavior as opposed to 'sophisticated learning'. The rules associated with this type of learning are 'adaptive learning' rules. I.e.: Individuals take decisions on the basis of past observations only. ⁶ We will concentrate on this type of learning behavior in the following and present three specific updating rules that fall into the class of adaptive learning behavior. The order of presentation is not by chance; the learning rules are chosen such as to require a decreasing level of sophistication.

⁵See Guillaume, D.M., M.M. Dacorogna and O.V. Pictet (1994a)

⁶Milgrom and Roberts (1991) define adaptive in the sense that every strategy played by a player must not violate a minimum rationality requirement with respect to opponents' previous play. A sophisticated player, on the other hand, would also be forward-looking by anticipating his opponents' past behavior.

4.1 Fictitious Play

Fictitious play is a well known type of adaptive learning behavior. While originally introduced as a method of solving normal form games ⁷ it later on became applied in modeling learning processes.⁸ Its mathematical method is rather intuitive and simple: Taking the empirical frequencies of opponents' past strategies agents are supposed to learn about the future choices of their opponents. Translating this concept into the context of our model the updating algorithm, basically, is of the following shape:

$$Prob(Acpt)(T+1) = \sum_{t} (Acpt_{t})/T,$$

where *Acpt* refers to a client's acceptance of the quote. In words: The probability of next period's customer being a LET type is equal to the sum of all acceptances up until now over the total number of periods.⁹

Being backward-looking only an important characteristic of this learning rule is its long memory: The set of all past events is perfectly recalled and influences each new probability calculation. The longer history lasts the less weight a single new event attains. This leads to a smoothening of the series of frequencies over time. In the limit, as $T \to \infty$ the Prob(Acpt)(T) converges to the true parameter value v.

4.2 Evolutionary Play

Evolutionary play is a theoretical approach that is being used for problems of equilibrium selection and justification in games. Typically, evolutionary models are not considered as describing proper learning processes

⁷See Brown (1951), Robinson (1951).

⁸For examples of applications see e.g. Fudenberg-Kreps (1993 a.1995). However, they justify ficticious play in terms of Baysean learning (Fudenberg-Kreps (1993)) which is not the line of argument we are persuing here.

⁹An explicit specification of initial move properties is omitted here, but will be dealt with in the simulation part.

since no specific learning rule is introduced. Yet, through the evolutionary process some sort of learning is taking place. ¹⁰ In the context of adaptive learning it has to be noticed, however, that in evolutionary models opponents change at each stage which renders the record of past plays non-homogenous.

In our model with competing traders evolutionary learning is applied in the following way: Two different groups of traders will play against each other using different strategies or learning rules respectively. According to each groups' relative success members will then switch to another group. Increments of adjustment are given.

The two strategies the groups will make use of are fictitious play and simplistic learning (which will be described in the following section); i.e. the most and the least sophisticated learning rules on our scale are going to play against each other. Convergence should occur if one of the strategies is dominant. The speed of convergence depends on the change of weights given to each strategy. However, if the change is too rapid the end of game could be reached too quickly, i.e. before one strategy really has proven to be fitter in the long-run.

4.3 Simplistic Learning

The third learning rule we introduce is the least sophisticated one. In fact, the rule reveals little insight on behalf of an agent in a learning process' sensitivity to the degree of adjustments being used in the updating process. It is for this reason that we call it "simplistic". It is introduced here as a reference point at the lower end of the scale of sophistication.

The simplistic rule simply says, depending on the last observation, to adjust one's belief half the distance between the belief currently held

¹⁰For a discussion of the connections between learning and evolution see Selten (1991). Weibull (1995) gives a survey of the work in evolutionary game theory.

and the maximum (minimum) parameter value possible. I.e.:

$$q_2 = \frac{1}{2} \pm \frac{q_1}{2}.$$

To be more specific, if in our model a trader meets a high elasticity type (HET) (=no deal took place) he increases q_1 , his subjective prior belief about the fraction of HET in the market, by

$$q_2 = q_1 + \frac{1 - q_1}{2}$$
$$= \frac{q_1 + 1}{2};$$

if he met a low elasticity type (LET) he decreases q_1 such that

$$q_2 = \frac{q_1}{2}.$$

The same happens at the end of each period.

It is obvious that with this learning behavior belief revisions take place in relatively big jumps. With a series of equal observations (i.e. acceptances or rejections only) beliefs quickly adjust towards the respective extreme points. One contrasting observation, instead, makes the new belief immediately jump to the vicinity of the opposite extreme. This jump will be the bigger the closer the last prior has been to the other extreme point. While giving such a big weight to the last observation renders this learning process extremely volatile and non-convergent its expected value, however, converges to the true parameter value:

$$E(q_t) = v \cdot (\sum_{i=1}^{t-1} \frac{1}{2^i}) + \frac{q_1}{2^{t-1}}$$

$$\lim_{t \to \infty} E(q_t) = v \cdot \frac{\frac{1}{2}}{1 - \frac{1}{2}} + \frac{q_1}{2^{\infty}} = v.$$

5 Single Trading Day Simulations

5.1 The Simulation Setup

As in the monopoly case in Wuthe (1999) the dynamic simulation system consists of three periods for the shorter trading day. At the end of the day any open position has to be closed. Several traders are now present in the market. They differ in their subjective prior beliefs which are generated in the following way: q(i) = i/N. I.e.: Each trader's i prior is equal to the ith fraction of the total number of traders N present in the market.

As for the computation of the average quotation of the market against which everybody is playing - each trader is initially given the same arbitrary value which stands for the average quotation. With this value all traders' mid-rates are then determined. I.e.: Each trader is playing against this arbitrary average value. The resulting quotations are then taken to compute a new market average for the mid-rate which, in a new loop, replaces the initial value. This process is repeated until it converges to a stationary value for the average market mid-rate. In order to compute the Nash equilibrium of the duopoly case the same procedure is being applied: The number of traders reduces to N=2 and the average market value is defined as the average of both players' mid-rate.

The above described computations should not be confused with the simulation of the learning process: Each trader's updating takes place at the beginning of each period, following the mechanics lined out above. Only then, with this period's new belief, the quotations are determined in dependence on the market average quotation.

As for the single-day simulations three different variance measures have been used: The first one computes the variance of all possible third period quotations of one single trader (VET). This measure corresponds to the one applied in the monopoly simulations and allows. hence, di-

rect comparison of results. The second measure computes the variance between all traders' differing third period quotations (VAT). This out-of-sample computation is being done for every possible history of events. I.e.: With this method there are as many variances computed as there are possible histories. The third and last measure is the out-of-sample variance of all traders' quotations of all periods (VAAT). Being an out-of-sample measure once again there are as many possible outcomes as there are histories.

For reasons of comparability the parameters' ceteris paribus values are identical to the monopoly case, i.e.:

$$a = 2$$
, $d = 1.2$, $g = 0.6$, $v = 0.4$, $q1 = 0.5$.

As for the two new parameters of LET's and HET's sensitivity to price differentials the ceteris paribus values are as follows:

$$\eta = 5, \, \rho = 0.9.$$

(Later simulations will give a justification of this choice.)

5.2 Volatility Behavior with Different Degrees of Competition

The first set of simulations deals with the impact of different degrees of competition. For this purpose the number of traders has been varied while all other parameter values remained constant. The simulations start with the duopoly case, the number of traders is then increased up to six. This maximum number is relatively low but computational effort grows exponentially with every additional trader: With six traders the number of possible histories amounts already to $2^{2 \cdot N} = 4096$. The results, however, reveal a clear trend.

With the presence of competition a trader whose quotation has been rejected cannot be sure anymore for which reason this has happened: Was it because a HET client had called, or was it because a LET client had called for whom the mid-rate was too high relative to the market average? Since it is impossible for the trader to find a solution to this

riddle he has to make up his own rule of interpretation with subsequently differing updating behavior. In the following simulations the impact of such different rules on the spot-rate's volatility has been taken into consideration.

Case 1: Same Updating Behavior As In the Monopoly Case In this first simulation over the number of traders it is assumed that each trader does his updating as if there was no competition. I.e., if his quotation becomes rejected on the phone he will believe that a HET client called - although there is the possibility that his quotation became rejected by a LET client who found his quotation too high relative to the market average. The advantage of this interpretation for our purposes is that it eases comparisons with the monopoly simulation results where updating followed the same rule.

Observation 1 The variance of all possible third period quotations (VET) is continuously decreasing in the number of traders. It remains excessive, though, for the whole spectrum of 2 to 6 traders.

The mean and the upper limit of the range of VAT (the variance between all traders' differing third period quotations) is increasing in the number of traders. Excess volatility is negative for a majority part of histories, but this part is becoming smaller with growing competition.

Contrasting, the mean and the upper limit of the range of VAAT (the variance of all traders' quotations of all periods) is decreasing with a higher degree of competition. Although the range's lower limit is slightly growing the percentage of histories with positive excess volatility is declining.

In the first graph the variances of each trader's possible third period quotations (VET) are depicted as small circles - each circle representing one single trader's value of VET. On the horizontal axe the number of

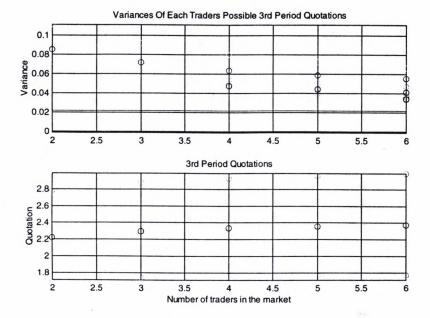


Figure 1:

traders in the market, i.e. the degree of competition is measured. The range of VET values is continuously decreasing in the number of traders, but bands do overlap. I.e., in a market with five traders one trader's VET can be higher than another trader's VET in a market with three traders only. However, one and the same trader's VET is continuously decreasing with tenser competition. Furthermore, the smaller a trader's prior belief the higher is his variance. The explanation for this observation is rather intuitive: A trader with a small prior believes that a small fraction of HETs only is present in the market. The range and mean of his quotations will, hence, be higher causing the variance to grow.

The decrease in VET is continuous but diminishingly so. Throughout this simulation excess volatility remains positive. From the results it is not obvious whether and where the VET values would cross the fundamentals (dashed line) or whether excess volatility would converge and remain positive at an infinite degree of competition.

Why is volatility decreasing with this variance measure? This outcome may seem surprising at first sight: In the quotation's graph - where maximum and minimum values are represented as grey circles, the mean of all possible quotations as black circles instead - it can be seen that with a growing number of traders the mean and the extreme quotations are both increasing (the range of quotations is widening since the increase of the lower bound values is less strong than the upper ones), suggesting an increase in VET. However, it must be remembered that with six traders the number of possible histories is 4096, but with, say, three traders only 64 histories are possible. With more histories there are more values very close to each other which reduces the weight of the more extreme quotations and lowers thus the variance.

The out-of-sample variance VAT (see graph above) is *increasing* in competition. While the lower bound of VAT's range remains constant at 0.0002 its upper bound and mean are growing in a decreasing fashion:

$$Mean(VAT) = \{0.0055; 0.0085; 0.0102; 0.0114; 0.0122\},\$$

where entries are respective to the five different degrees of competition.

The mean lies below the fundamentals' value always. But the percentage of histories with positive excess volatility is growing with the number of traders.- How can this result be explained? The VAT values are considerably smaller than the VET ones since VAT is a measure which computes the variance between outcomes of a Nash equilibrium. In a competitive context a Nash equilibrium tends to pull results together. However, with a growing number of traders more contrasting quotation constellations are possible, depending on the beliefs the traders hold. This leads to an increase of VAT's mean and upper bound.

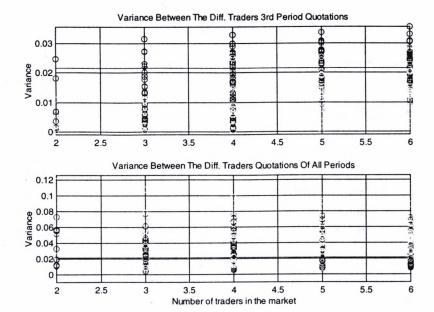


Figure 2:

The picture becomes reversed looking at the out-of-sample variance of all observable quotations of one entire day, VAAT. Here, the mean and the range's upper limit is *decreasing* with a higher degree of competition, in a diminishing fashion:

$$Mean(VAAT) = \{0.0443; 0.0341; 0.0292; 0.0264; 0.0245\}.$$

Mean-volatility is excessive throughout; for every number of traders in the market volatility is excessive for the majority of possible equilibria. Their share - after an initial increase - is slowly getting smaller with more

fierce competition, though:

 $Share(VAAT > Fund) = \{0.6250; 0.6562; 0.6250; 0.5645; 0.5159\}.$

Where does the difference between VAT and VAAT stem from? While it is true that customers' sensitivity to price differentials minimizes the impact of traders' different beliefs on their quotations within one period the same does not hold for price differences between periods: Changing beliefs from one period to another are reflected in different levels of quotations. In a new period the different traders' quotations will again be very similar to one another but now on a new level (since beliefs are different from the previous period). Thus, considering all periods of one trading day (VAAT), the quotations' variance should be considerably higher than the variance of one single period only (VAT).

VAAT's decrease with stronger competition is due to the growing sample size which reduces the weight of extreme values: For two traders there are six quotations observed over an entire trading day, for six traders, instead, there are already eighteen observations.- In the case of VAT the number of observations increases from to two to six only which is not sufficient to outweigh the variance increasing impact of the more and more extreme quotation-constellations which become possible with tenser competition.

Case 2: With Two Rejections A LET Must Have Called The Second Time In this case traders are aware that their quotation may have been rejected by a LET client who found the price too high relative to the market average. They include this possibility in their updating behavior by assuming that a second rejection during one day must be attributed to a LET client. I.e.: While a first rejection leads to an increase in the believed share of HETs in the market the opposite is true for a second rejection. This change in the updating behavior leads to the following results.

Observation 2 All three variance measures react in the same fashion to an increase in competition as in Case 1. The magnitude of VET and VAT, however, is relatively lower. In the case of VAT this leads to more cases of negative excess volatility.

The mean size of VAAT is bigger which implies more instances of positive excess volatility.

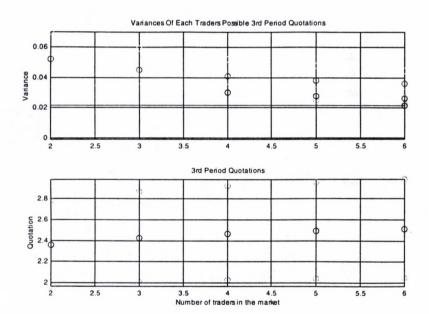


Figure 3:

A look at the 3rd period quotations graph helps explaining these observations: As could be expected from the new updating rule there are more cases with higher quotations now. Whatever the outcome of the

2nd period phone calls the traders will believe that a LET client has called. In fact the quotations' mean moves up by around 1/10th. Furthermore, the lower value of their interval is higher while the upper one did not change so that the length of the interval is shortened altogether. VET becomes thus smaller than in a situation with a broader range of quotations: While quotations' maximum peaks are similar to the ones of Case 1 minimum values are higher. More important, the distribution of quotations is smoother since many histories are identical: All those when a HET called a second time with the ones when a HET called the first time and a LET the second time. Overall this leads to a lower variance of all possible third period quotations. Excess volatility remains positive in this simulation though (or equal to zero in one case).

As well the VAT graph looks similar to the respective graph of Case 1 but moves on a lower scale. The mean values of VAT are increasing in the number of traders but are around 1/4th smaller:

```
mean(VAT_{Case2}) = \{0.0037; 0.0056; 0.0067; 0.0074; 0.0080\}

mean(VAT_{Case1}) = \{0.0055; 0.0085; 0.0102; 0.0114; 0.0122\}.
```

And while the minimum values of VAT do hardly differ between the two cases maximum values are around 1/4th lower this time:

```
\max(VAT_{Case2}) = \{0.0180; 0.0228; 0.0235; 0.0247; 0.0259\}
\max(VAT_{Case1}) = \{0.0246; 0.0316; 0.0329; 0.0336; 0.0355\}.
```

The range of the VAT values is thus shortened from above which, once again, can be attributed to the smaller distance between the quotations' extreme values and their smoother distribution. Consequently there are relatively more cases of negative excess volatility.

As for the ranges of VAAT the upper values are identical for the two cases, the lower ones do not differ significantly. The mean, however, is higher by around 1/5th than in Case 1:

```
Mean(VAAT_{Case2}) = \{0.0549; 0.0419; 0.0355; 0.0317; 0.0293\}

Mean(VAAT_{Case1}) = \{0.0443; 0.0341; 0.0292; 0.0264; 0.0245\},
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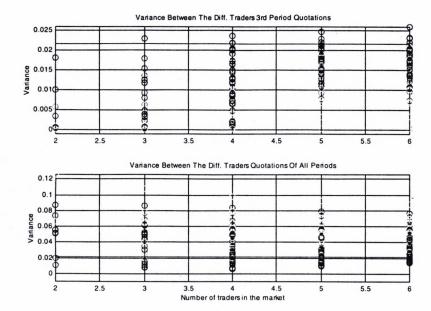


Figure 4:

which implies more cases of positive excess volatility:

$$Share(VAAT_{Case2} > Fund) = \{0.7500; 0.7500; 0.6641; 0.6953; 0.6665\}$$

 $Share(VAAT_{Case1} > Fund) = \{0.6250; 0.6562; 0.6250; 0.5645; 0.5159\}.$

This outcome is once again due to the updating process: In Case 1 two rejections with the respective updating lead to an always lower quotation. But the difference between period 1 and period 2 quotations is bigger than the one between period 2 and period 3. This is so since the updating process halfens an always smaller distance between the current belief and the maximum possible number of *one* (in the case of rejections

only). In Case 2, instead, a second rejection leads to a much bigger jump of the quotation in the opposite direction since a relatively high belief now becomes halfened towards zero. The range of the observed quotations and their mean becomes thus higher. Consequently, the mean of VAAT increases with the number of those cases in which a second rejection is interpreted as a LET client calling.

Case 3: A Rejection Of The First Quotation means That A LET Has Called, For Period Three Everything Remains Equal To Case 1 Again the traders are aware of the possibility that a LET client can reject their quotation. But its integration in the updating process is different now in that a rejection of the *first* quotation is interpreted as a LET client phone call. A second rejection or a first rejection in the second period, instead, are interpreted as a rejection from a HET client.

Observation 3 The new updating rule does not change the direction of competition's impact on the different variance measures but only their magnitude. VET is slightly smaller than in Case 1. Excess volatility remains positive throughout.

While the range of VAT is almost identical to Case 2 its mean is slightly bigger - however, the number of cases of positive excess volatility is smaller.

VAAT 's mean is higher than in the first two cases. There are no instances of negative excess volatility at all.

With the new updating rule every trader will believe in a bigger number of LET clients at the beginning of period 2, no matter whether his previous period quotation was accepted or rejected. Period 2 quotations will thus be higher than before. Only in period three price movements in the opposite direction are possible. As a consequence third period quotations can never be as low as in Case 1. While maximum and minimum values are identical for Cases 2 and 3 the quotations's mean moves now

up again and lies even higher than in Case 2. Obviously the reason for this observation is that there are more possibilities to reach at a low 3rd period belief - and hence a high quotation - with the 2nd period belief always being below the prior than with a 2nd period belief which sometimes exceeds the prior (a subsequent belief then can never become as low as with two updates in the same directions).

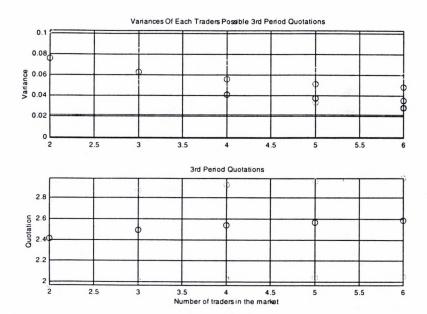


Figure 5:

The updating rule has a dampening effect on VET: Its curve lies slightly below the one of Case 1 but is notably higher than in Case 2. The explanation for this result is simple: As in Case 2 there are now identical stories possible which smooth the quotations' distribution, and

quotations at the lower end of the possible range can only take on less extreme values. The VET values of Case 3 are closer to the ones of Case 1 since the quotations' mean is higher than in the previous case.- Excess volatility in the current simulation remains strictly positive.

Looking at the VAT measure it is not surprising to see that contrary to Case 2 the new updating rule leads to a *higher* mean, exceeding even the one of Case 1 by 1/10th:

```
mean(VAT_{Case3}) = \{0.0065; 0.0098; 0.0117; 0.0130; 0.0138\}

mean(VAT_{Case1}) = \{0.0055; 0.0085; 0.0102; 0.0114; 0.0122\}
```

This, once again, can be explained by the 3rd period quotations' higher mean. However, the share of constellations with positive excess volatility here is higher in two instances only, for three and four traders:

```
Share(VAT_{Case3} > Fund) = \{0.0000; 0.1250; 0.1250; 0.0938; 0.0781\}

Share(VAT_{Case1} > Fund) = \{0.0625; 0.0938; 0.1016; 0.1123; 0.1123\}
```

This result is due to the higher VAT-peaks that are possible in Case 1 with the original updating rule which implied a wider quotations interval.

VAAT, the out-of-sample variance of all traders' all period quotations, has a significantly higher mean than the two previous cases, and excess volatility is always positive. This outcome is due to the updating rule which leads to only one single possible 2nd period quotation, the highest one possible, since all traders update their beliefs in the direction of a higher share of LET clients in the market. VAAT can thus never take on values as low as in the first two cases while the range's upper limit does not change. As a result excess volatility is always positive for the present parameter constellation; even at its lowest value at N=6 traders it exceeds the fundamentals' variance by more than one half.

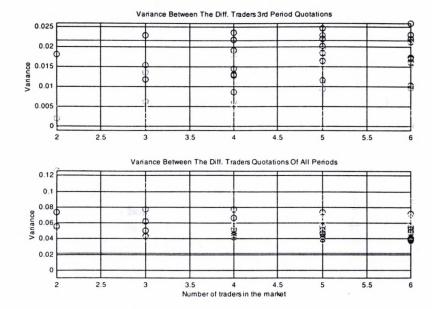


Figure 6:

5.3 Volatility Behavior under Changing Parameter Values

The Impact of the Size of the HET's and LET's Parameter of Sensitivity to Price-differentials e and r In order to choose ceteris paribus values for the two parameters of sensitivity to price differentials both have been simulated simultaneously: The Het parameter of sensitivity, e, takes on values between 5 and 60, the LET parameter, r, values between 0.5 and 4.5. All remaining parameters remain fixed at their ceteris paribus values.

Observation 4 For all realizations of e the quotations are falling in the LET parameter r. Contrasting, quotations are growing in the HET parameter e. The variance measure VET is falling in r but growing in the HET parameter e when r > 0.5. Excess volatility is always positive for the present parameter values.

VAT is falling in both parameters - the stronger in e the smaller is r- VAAT, too, is continuously falling in r, the stronger the smaller is e. But it is growing in e. Excess volatility, in the case of VAT, is positive only for small values of e and r. In the case of VAAT the picture is different: Excess volatility is falling in r but growing in e.

It should be noted that for dimensional reasons the quotations' graph as well as VAT and VAAT are represented for one specific history only, namely history 28 of trader 1. This history has been chosen since it leads to average sized quotations and variances and, at the same time, exhibits an interesting feature of the quotations. It is characterized by the following telephone experiences of the three traders in the first and second period, respectively:

011 in period 1

on period 2.

I.e. trader 1 experienced two acceptances while the other two traders' quotations were rejected in each of the first two periods.

One would expect quotations to fall in both parameters under consideration but interestingly this is not the case for all possible history constellations. While for, say, the extreme case of rejections only the quotations' behavior is perfectly 'normal', here and for most other histories quotations are increasing rather than falling in e, HET's parameter of sensitivity to price differentials. The intuition for this surprising outcome is the following: A trader who has experienced two acceptances believes already in a high presence of LETs in the market and is thus willing to

quote relative high a price. But the higher his quotations are the more he minimizes his chances to make a deal with a HET client. This is true the more the higher is HET's sensitivity to price differentials. Thus, for our trader it is perfectly rational to quote an even higher price when HET's sensitivity is higher since the likelihood to make a deal with this type of client is so small that it pays to raise the price and have an even bigger profit in case a LET client calls.- Note that for the two other traders of this history quotations are also increasing in e but doing so for small values of r as well. The reason is that believing in a higher presence of HETs in the market quotations are already relatively low even if LETs parameter r is very small.

The first graph shows VET, the variance of all possible third period quotations (of the first trader only for clarity of exposition) and the fundamentals' variance which is given by the lower plane. The latter variance is not dependent on e or r and remains invariant. VET is decreasing in r and growing in e for r > 0.5. The shape of VET reflects the quotations' behavior, i.e. falling in r and for the majority of histories growing in e when r is bigger than some number. Excess volatility is significantly positive always for the present set of parameter values.

As for VAT a continuous decrease in both parameters can be observed. This is true although quotations are increasing in e since all three traders' quotations behave in a very similar way. The biggest differences are observable for small values of r and e: Here, as has been described above, trader 1 quotes relatively high prices whereas the other two traders start out with relatively low quotations. With increasing parameter values quotations tend to become more and more similar.- Excess volatility is thus present for small values of e and r only.

VAAT as well is falling in r but growing in e. This difference stems from the nature of this variance measure: Looking at all periods the quotations' growing size in e weighs more than one period differences between relatively low quotations.- Excess volatility thus grows in the HET parameter but falls in r. It can reach a bigger size than in the VAT

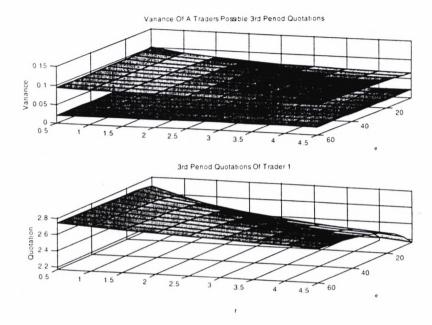
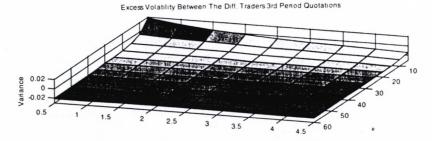


Figure 7:

case and it is present for more parameter constellations.

As for the following simulations ceteris paribus values have been chosen that lie in a range which is sensitive to small variations and that are small enough to guarantee some instances of excess volatility. The parameters will be fixed at the following levels: e=5 and r=0.9.

The Impact of the Size of the Intercept A In this simulation the intercept is taking on values between 1 and 5. All remaining parameter values are fixed at their ceteris paribus level.



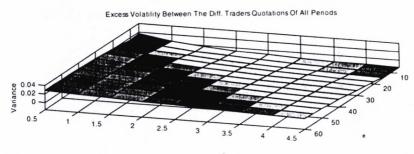


Figure 8:

Observation 4 All three variance measures are increasing in the intercept as are the quotations. Volatility of VET is excessive - as was the case for the monopolist - except at A=1. However, the variances are only half as big and their increase is less steep than in the former case.

Excess volatility of VAT is in most of the cases negative and can become extremely high for low values of A.

VAAT's excess volatility is almost always positive, except at A=1, and becomes extremely high: At its maximum VAAT exceeds the

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fundamentals' variance more than 31 times.

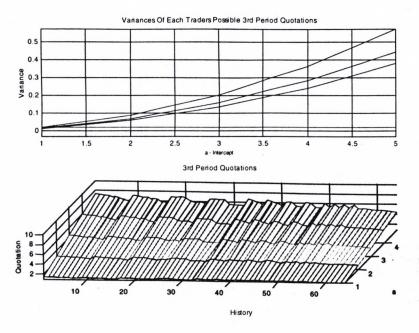


Figure 9:

VET is continuously increasing in the intercept A, the shape of its curve being similar to the one of the monopoly case. Its increase, however, is less steep than without competition and its scale is more than halfened. As a result at A=1 the variance lies below the fundamentals' one. With tenser competition excess volatility can thus become negative even with a bigger trading volume (A>1). Here as in the monopoly case the VET curves' increase is due to the quotations' continuous increase which leads to a higher mean and a bigger difference between the realizations and their mean.

VAT is increasing in the quotations and, hence, in the volume of trade. History-to-history differences in the magnitude of VAT become more pronounced when the quotations are higher. E.g.: History 28 leads to the maximum variance for all parameter values for A. But the maximum values grow considerably with the intercept: At A=1 VAT is equal to 0.0079 while at A=5 the variance equals 0.1976 which exceeds the fundamentals' variance almost twenty times (Var(Fund)=0.0216). A closer look at the 3rd period quotations reveals that VAT has its maximum at history 28: This extreme quotation constellation (the history profile is given by two rejections for two traders: 011 for period 1 and 011 for period 2) becomes enlarged enormously with growing A and, hence, growing rates.

Excess volatility is always negative or equal to zero for A < 3. For some histories VAT then exceeds the fundamentals' variance. But when most of the traders were rejected twice excess volatility remains negative even at A = 5

VAAT as well is increasing in the intercept. At A=1 all possible VAAT realizations - apart from the very first one - lie below the fundamentals' variance. But excess volatility is less negative than for VAT and becomes immediately positive for almost all histories when A>1, exceeding the fundamentals by far. VAAT's mean at A=3 equals $Mean_{VAAT}=0.0768$, at A=5 it reaches $Mean_{VAAT}=0.2133$.

The VAAT graph repeats the movements of the 2nd period quotations and tends to be high where the 2nd period quotations are high and thus more distant to the 1st period ones. These relative peaks of VAAT are further enforced or dampened by corresponding high variances of the 3rd period quotations.

The different size of VAT and VAAT has already been explained in the description of Case 1: VAAT measures the variance of prices whose level changes from period to period due to different beliefs.

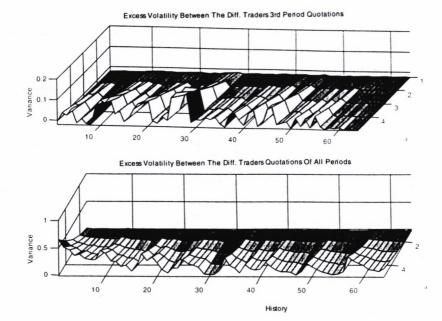


Figure 10:

The Impact of the Size of the HET's Parameter of Price Sensitivity d In this simulation the parameter d takes on values between 0.7 and 4 as in the monopoly case. All other parameter values remain fixed at their ceteris paribus values.

Observation 5 The VET curves - first slightly increasing in d and then slowly decreasing again - are fairly flat compared to the monopoly case. Excess volatility is, thus, present for low values of d only.

The VAT and VAAT curves are both continuously increasing in d. However, due to the much stronger increase of the fundamentals

in d excess volatility is positive in some instances only, when d is small. It then becomes highly negative.

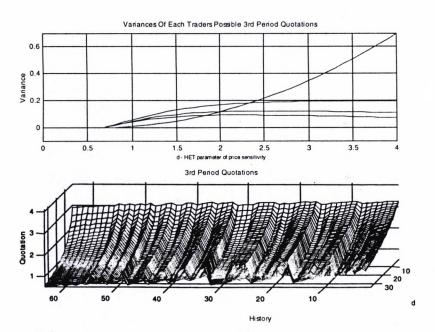


Figure 11:

3rd period quotations decrease with an increasing price sensitivity of HET clients. But the distance between the possible realizations and their mean is growing with a growing difference between the HET's and LET's price sensitivity. In other words: With increasing d the quotations range widens considerably.

The VET curve (its shape has already been analyzed in the respective section of the monopoly chapter) is thus initially still increasing but it

is lowered and flattened by competition which allows for 64 rather than 4 different histories. Consequently, the fundamentals' variance exceeds VET now already at parameter values of $d \in \{1.8; 2.3\}$ rather than at d=3 in the absence of competition.

For most of the histories VAT is continuously increasing in the HET parameter of price sensitivity. For small values of d the minimum values of VAT are very close to zero. Maximum values of VAT are quickly increasing and reach their peak with 0.1221 at d=4. Excess volatility, however, realizes small positive values only for d<1.4 and is then quickly becoming highly negative. This behavior is due to the fundamentals' strong increase in d that has been depicted in the VET graph. (Note that the d-axis in the VAT and VAAT graphs show the three numbers 0, 2, 4 only where the latter number is d's maximum value.)

VAAT is first increasing in d and then, for some histories, decreasing again. For all parameter values the smallest variance realization never exceeds 0.0089. Maxima of VAAT grow with the parameter and reach their highest value at d=2.7 with 0.2039.- The fundamentals' variance, on the other hand, again quickly exceeds VAAT; for d>2.4 excess volatility is negative for all histories. It reaches its negative peak below -0.65.

The Impact of the Size of the LET's Parameter of Price Sensitivity g The parameter g has been simulated here with values ranging from 0.1 to 1.1. All other parameters stayed fix at their ceteris paribus level.

Observation 6 The VET curves are strongly decreasing in g as in the monopoly case. But initial values are considerably smaller than beforehand. The fundamentals' variance is relatively small and its decrease flatter in g. Excess volatility, thus, is decreasing sharply but remains positive or equal to zero throughout.

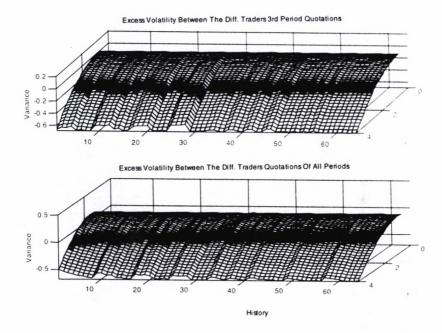


Figure 12:

The VAT curves are also continuously decreasing in g. But initial values can be relatively high before they start falling sharply. VAAT follows the same pattern with initial values being extremely high. Excess volatility for both variance measures can be positive for low values of g but turns negative then for most of the histories.

As has been discussed in the monopoly case quotations differ between histories the more the bigger is the difference between the LET and HET parameter, i.e. the lower is g for a given d. When both parameters are equal quotations do not differ any more. Furthermore, quotations fall with g approaching d since LET's price sensitivity is increasing.

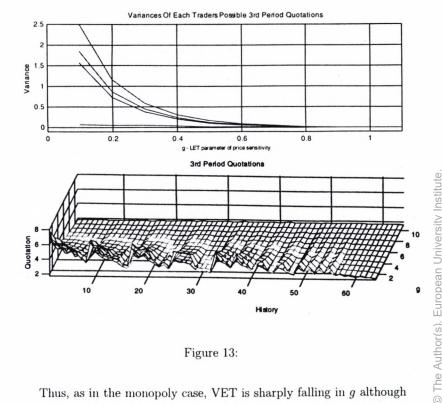


Figure 13:

Thus, as in the monopoly case, VET is sharply falling in g although competition flattens the curve considerably. Excess volatility initially is extremely high, falls quickly, and is then equal to zero at g = 1.1 for the two traders with the higher prior beliefs and close to zero for the third trader.

When LET's parameter is very small and the distance to the HET parameter big then the impact of differing histories on 3rd period quotations is huge. VAT reaches here a maximum of 0.3733, but at the same time, with similar histories it can become as small as 0.00056. VAT then is not only falling, the stronger the higher were the first realizations, but

also history-to-history differences almost completely disappear.- For high values of VAT excess volatility is positive and sometimes very high, but for low ones it can already be negative at g=0.1. Interestingly, excess volatility is then *increasing* in g (although remaining negative) since the fundamentals' variance decline is faster than the one of VAT. On the other hand, if initial values of VAT are high, first, a strong decline can be observed which then changes into a small increase for the same reason (excess volatility remaining negative here as well).

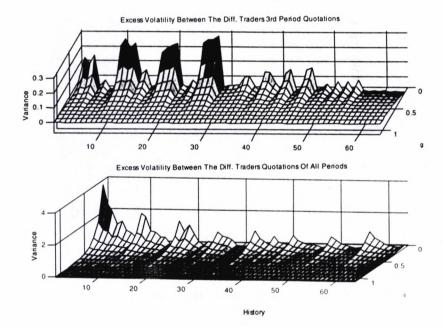


Figure 14:

The decrease of VAAT is even more dramatic. At the smallest value of g it has a peak of 3.8024, and its mean of 0.6137 exceeds the maxima of

VAT by far. The size of VAAT is due to the possible strong increases of quotations over one trading day which is reflected in this measure since it takes account of all three periods. Its values are highest where 3rd period quotations are very high, i.e. for the first history constellations where all traders believe in a small market presence of HETs and quotations are very high, hence.

Initially, excess volatility is extremely high and becomes negative for small values of VAAT only. Its decrease changes into a small increase when values of g are high. But for no history constellation it turns positive again.

The Impact of the Real Distribution of the Population v In this simulation the parameter v takes on values between 0 and 1. All other parameter values remain fixed at their ceteris paribus levels.

Observation 7 The shape of the VET curves is identical to the one of the monopoly case. Volatility is excessive as long as both types of clients are present in the market.

Since quotations do not differ with the distribution parameter v the variance measures VAT and VAAT do not vary with changing parameter values. Excess volatility, though, changes proportionally reversed with the fundamentals' variance and has thus its minimum at v=0.5 for both variance measures. As for VAT it is negative for most of the history constellations. The contrary holds for VAAT.

The quotations themselves are unaffected by a change in v. Only the variance VET is influenced by changes in the probability weight. Its three curves have a similar shape as in the monopoly case, but they are rescaled to around 1/3rd of that size and their maximum has moved to the right: It is at the point where the fundamentals' variance reaches its maximum too, at v=0.5, the point of equal distribution of HET and LET clients in the market. All three trader's variance reaches its

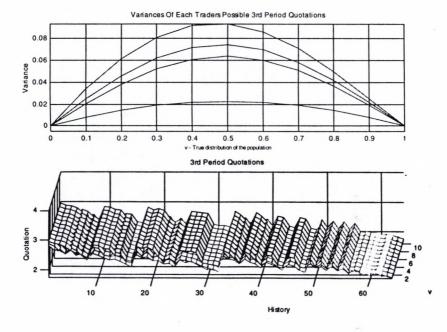


Figure 15:

maximum here since the possible sequences of histories are the same for all of them. The difference in the curves height stems solely from the different subjective priors.

Since VET's increase is stronger than the fundamentals one excess volatility reaches its maximum at v = 0.5, too.

The variances VAT and VAAT do not change with v since they are out-of-sample measures which are not affected by the size of the probability weight. The respective excess volatility measures thus change reversed proportionally with the fundamentals' variance: When the latter reach their maximum the former are at their minimum. Due to the

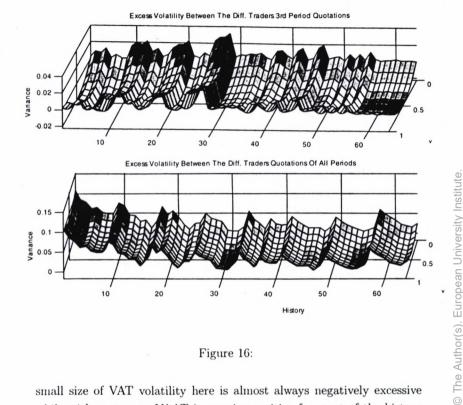


Figure 16:

small size of VAT volatility here is almost always negatively excessive while with respect to VAAT it remains positive for most of the history constellations.

Conclusions of the Single Trading Day Simula-5.4 tions

The foregoing simulations showed that the impact of increasing competition on volatility is not a clear one: Depending on which measure of volatility is being used the effect of an increase in the number of traders on price volatility can be everything between negligibly small and strongly positive. Although surprising at first sight this result is quite intuitive: On the one hand side a growing number of traders, each with a different subjective prior, allows for a growing number of possible history constellations and therefore quotations for each trader. Depending on which beliefs traders hold in a given period - which are a function of their respective histories - a trader's quotation will be a different one each time. The number of possible constellations in every period thus grows exponentially with the number of traders. This effect becomes more than outweighed, though, by the growing number of similar history constellations. Volatility, measured by the variance of a trader's possible quotations, thus decreases with growing competition.

On the other hand, volatility measured empirically over all quotations of a single period increases with competition since a growing number of traders allows for more quotation constellations where individual histories differ significantly. (Imagine, e.g., some traders experiencing HET calls only over a longer number of periods, others LET calls only, and still another group some experience in between those.)

Expanding the variance measure to comprise all quotations of all periods, again, the growing sample size is more than outweighing the impact of more extreme quotation constellations, and volatility is decreasing in competition.

As for the different parameters' impact on the variance measures the findings have been similar to the monopoly case.

6 Analysis of the System's Long-run Behavior with Competition

In this section increasing competition's impact on volatility in the long run is investigated. I.e.: We want to see how the different volatility measures change with more traders being in the market, and how this impact differs from learning rule to learning rule. However, the learning process itself is not influenced by the presence of competition since for his updating each trader takes into consideration his personal phone experiences only. Volatility, then, can change as a result of different quotation levels due to different degrees of competition and/or due to the construction of the different variance measures.

All results of the following three sections stem from simulations of 1000 trading days. Every learning rule has been simulated with 2, 3, and 5 traders in the market. The resulting volatilities under the three different variance measures are presented in a summarized way, i.e. as the *Mean* of the respective 1000 variances. As for the monopolist the variance measure introduced in Wuthe (1999) is being used. Parameter values stayed fixed at their ceteris paribus values.

6.1 Volatility Behavior and Convergence with Simplistic Learning

In this set of simulations each trader is using the above defined learning rule of simplistic updating. More specifically, use is made of the variation presented in Case 1 of the previous section: I.e. in his updating process the trader does not take into consideration the possibility that a rejection may have come from a LET client for whom his quotation was too high relative to the market average.- The traders' initial beliefs are given by the fraction 1/N, one over the number of traders in the market. The monopolist's prior belief is given by 1/2.

The results of the simulation set are presented in the following table. On the left the different variance measures and the means of 3rd period quotations are listed. As for the first variance measure there is one row for each trader's respective outcome. The columns indicate the degree of competition, reaching from the monopolist case up to 5 traders in the market. The table construction implies that for the first variance measure there is one entry for the monopoly case, two for the duopoly,

etc.. Means of 3rd period quotations are listed in the same fashion.- All reported numbers are means over the 1000 days vectors of the respective variance measures or quotations.

By construction beliefs never converge with this updating rule as has been demonstrated earlier. However, the different volatility measures now exhibit trends due to competition's impact. The first measure reported in the table, the variance of a single trader's quotations of all periods of one trading day, does not correspond directly to VET of the previous section but has been chosen for comparability reasons with the monopolist.

The variance of a single trader's quotations of all periods of one trading day is continuously decreasing in competition where the downward movement is the steepest between the monopoly and duopoly cases and then slowly becomes flatter. Differences between different traders are negligible and do not show any specific pattern. This is not surprising considering the number of simulated trading days which renders insignificant any potential impact of differing priors.

The variance between all traders' all period quotations of one day which corresponds to the VAAT measure from the previous section - is diminishingly decreasing in competition as well. The variance between all traders' 3rd period quotations, instead, - corresponding to VAT - is growing in competition.

These results should not be surprising. In terms of trend of competition's impact they seem to confirm the observations of Case 1. Running a simulation over 1000 trading days should result in something close to the mean of all possible out-of-sample-variances which have been reported there. It seems striking, however, that here the mean values of all observed variances and quotations are considerably higher than they are there, although parameter values are fixed to the same ceteris paribus values. The explanation for this riddle lies in the value at which the parameter of the true distribution of the population has been fixed: v=0.4. Telephone calls follow this distribution of nature, and the simulation pro-

gram's respective random device has been designed accordingly. Since on average more LET than HET clients are calling the quotations's mean is going to be higher than was the case for a single day where the mean of all possible quotations has been computed. But with higher quotations on average variances are going to be higher on average while preserving the trend of competition's impact.

Excess volatility is positive for the first two variance measures but decreasing in competition. Applying the VAT corresponding measure excess volatility is negative but increasing in competition. It is not clear though whether it will become positive eventually since its increase is diminishing.

	Monopolist	2	3	5 Traders	
VARIANCE MEASURES					
Variance of a single trader 1	0.0886	0.0513	0.036	0.025	
traders quotations of trader 2		0.051	0.035	0.0258	
all periods of a day truder 3			0.0352	0.0252	
trader 4				0.025	
trader 5				0.0249	
Variance between all traders'					
all period quotations of a day		0.0567	0.0432	0.0345	
Variance between all traders					
3rd period quotations		0.0086	0.0124	0.0143	
Variance of Fundamentals	0.0216	0.0216	0.0216	0.0216	
QUOTATION MEANS					
Quotations' Mean trader 1	2.4958	2.5346	2.5567	2.5598	
trader 2		2.5392	2.5597	2.5536	
trader 3			2.5546	2.5601	
trader 4				2.5555	
trader 5				2.5544	

6.2 Volatility Behavior and Convergence with Fictitious Play

In this set of simulations each trader is using fictitious play as rule of updating. Prior beliefs are either 0 or 1 and are determined by a random device at the beginning of each simulation. Results are reported in the following table.

Convergence of beliefs, once again, is not affected by the presence of competition since updating behavior considers individual experience only. Individual beliefs do converge to the true value of the population's distribution (this process has been described in Wuthe (1999)). Every trader's quotations as well converge at the same speed as their respective updating does and, finally, converge all to the same value with minor fluctuations.

All variance measures differ significantly from zero during the first days only. Mean values of variance measures are close to zero. No clear trends can be identified with respect to competition. This is true because of the fast belief convergence which pulls each trader's quotations quickly to a specific value which is identical for all. As for differences between the different variance measures only the variance of all traders' quotations of all periods seems to be slightly higher than the other ones - due to the bigger number of observations which cover all the periods of the updating process.

Excess volatility is thus strongly negative. But competition has no impact at all on its size.

	Monopolist	2	3	5 Traders
VARIANCE MEASURES				
Variance of a single truder 1	0.000038152	0.00009435	0.00002645	0.00008025
traders quotations of trader 2		0.00007874	0.00002679	0.00002575
all periods of a day truder 3			0.00007970	0.00002949
trader 4				0.00009936
trader 5				0.00003224
Variance between all traders				
all period quotations of a day		0.00011562	0.000087250	0.00013981
Variance between all traders				
3rd period quotations		0.000033255	0.000038616	0.000091427
Variance of Fundamentals	0.0216	0.0216	0.0216	0.0216
QUOTATION MEANS				
Quotations' Mean truder 1	2.4001	2.3864	2.3880	2.3885
trader 2	190	2.3904	2.3866	2.3901
truder 3			2.3871	2.3843
trader 4				2.3964
trader 5				2.3932

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6.3 Volatility Behavior and Convergence with Evolutionary Play

In this section a market with competition is simulated where evolutionary play takes place between traders. I.e. there are two groups of traders, one updating according to simplistic learning, the other one according to fictitious play. Members of each group play a pure strategy. The evolutionary process then takes place via switching of agents between groups according to relative performance. At the end of every day profits per individual of each updating rule are being compared; if one group has been more successful one trader of the other group will switch to it. Altogether there are 40 traders present.

The following 'mistrust' interpretation has been implemented: If the evolutionary learning process converges to one of the two rules by default one member of the loosing party will survive. Thus, there is a continuous control of the other updating rule's performance. In case of an improvement traders will start to move back to the other rule.

As in the monopoly case convergence occurs with fictitious play being the dominant strategy. But due to the continuous checking of the other rule's potential success this convergence outcome is unstable. In the simulations run here simplistic learning was able to gain back a weight of 0.166 at around 152 days after convergence.

The simulation results resemble the fictitious learning outcome, only that all mean values are considerably bigger than beforehand. This is due to the impact of the early periods with an equally strong presence of simplistic players which averages up the quotation means and the size of the different variance measures.

While at first sight these results seem again to suggest a predominance of fictitious play, a look at the traders' profits reveals that this is not the case: The mean daily profit of a trader under evolutionary play is about 8.56 foreign currency units. This has to be compared to the mean daily profit of a market where all traders are simplistic learners which is

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of e.g. Beltratti and Margarita (1992) and Gode and Sunder (1990), who showed that at some point it may not pay any more to be smart, or that zero intelligent agents are capable of seizing the entire possible surplus of a market. While in our case the simplest learning rule is not identical to the evolutionary dominant strategy it does keep the price process from settling down, and with a Folk theorem type of argument it can be argued that traders will choose to apply the simplistic learning rule.

Regarding competition's impact on exchange rate volatility the set-up presented here gives a rather differentiated picture of the possible effects. The outcome varies with the volatility measure applied: Using those two measures that result into the relative highest levels of excess volatility the impact is decreasing in competition. The opposite is true for the third measure that has been used.

The effects of the introduction or strengthening of competition on spread and price are ambiguous. One of the common findings of the reviewed literature were either a reduction of the spread with increasing competition in inventory models or its remaining at the monopoly level. The spread showed to be independent of the inventory, only its placement was affected by the inventory. (See e.g. Ho and Stoll (1983) and Suvanto (1993).) In our model the spread's independence of the inventory is preserved. But its size changes from period to period due to the belief updating process - the one of the quoting trader as well as the one of the other traders which is reflected in the changing average market spread. The price which adjusts the inventory towards an equilibrium level and then towards a competitive equilibrium shows the same dependence on traders' updating behavior.

All results have been shown to depend in specific ways on customers' price sensitivity, the volume of trade, and the population's true distribution.

The findings of this paper confirm the importance of a market microstructure approach to explaining the phenomenon of exchange rate volatility. given by 9.45 currency units. Following a Folk type argument simplistic learning will become the market's equilibrium outcome.

This result is striking since the competitive process introduces a switch in traders' learning behavior from fictitious play to simplistic learning, thus creating a volatile price structure that does never converge. The reason for this outcome is that with competition prices are pulled together to the market average. Using simplistic learning the average spread becomes considerably bigger than with other learning rules. While this can create big period losses these become outweighed by even bigger period profits. The competitive mechanism of pulling prices together works less strongly with agents that can differ in their prices that much. In other words, the observed instability of the process stems from the fact that it pays to behave simplistically again: Applying the less conservative learning rule of simplistic learning allows for the possibility of higher profits. ¹¹ (Notice, that in this set-up the arbitrage-avoidance imperative is not violated since for customers it is impossible to systematically exploit these big price differences: They are unpredictable.)

Hence, while we originally have introduced simplistic learning as a learning behavior on the lower end of a scale of sophistication it turns out that its followers may prove their full rationality by preferring it to other more sophisticated learning rules.

7 Conclusion

Introducing competition in the foreign exchange market this paper extends the analysis of a monopolistic environment in Wuthe (1999). Trying to explain excess volatility of exchange rates we are able to give a rationale for the use of rather simple learning mechanisms: Their application can be a sign of full rationality since they may allow to seize the relative highest profit. This result goes in line with some recent findings

 $^{^{11}\}mathrm{This}$ finding can be compared to the results of Grossman and Stiglitz (1980).

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