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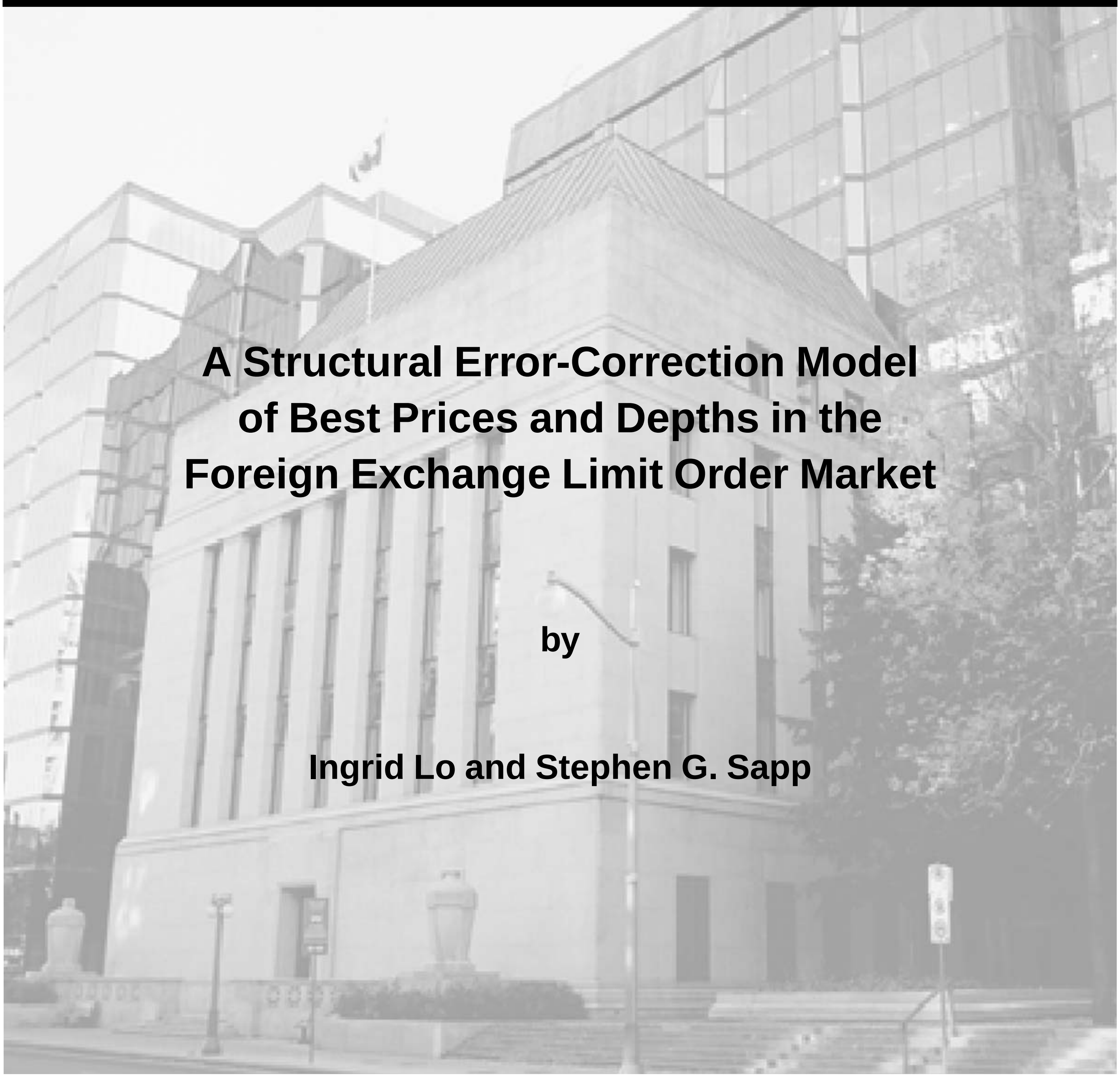

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Abstract

Traders using the electronic limit order book in the foreign exchange market can watch the posted price and depth of the best quotes change over the day. The authors use a structural error-correction model to examine the dynamics of the relationship between the best bid price, the best ask price, and their associated depths. They incorporate measures of the market depth behind the best quotes as regressors. They report four main findings. First, best prices and their associated depths are contemporaneously related to each other. More specifically, an increase in the ask (bid) price is associated with a drop (rise) in the ask (bid) depth. This suggests that sell traders avoid the adverse-selection risk of selling in a rising market. Second, when the spread—the error-correction term—widens, the bid price rises and the ask price drops, returning the spread to its long-term equilibrium value. Further, the best depth on both sides of the market drops, due to increased market uncertainty. Third, the lagged best depth impacts the price discovery on both sides of the market, with the effect being strongest on the same side of the market. Fourth, changes in the depth behind the best quotes impact both the best prices and quantities, even though those changes are unobservable to market participants.

JEL classification: C3, D8, F31
Bank classification: Exchange rates; Financial markets

Résumé

Les cambistes qui ont accès à un carnet électronique d’ordres à cours limité peuvent observer les variations intrajournalières des prix et de la profondeur affichés aux meilleures limites. Les auteurs ont recours à un modèle à correction d’erreurs structurel pour étudier la dynamique de la relation entre le cours acheteur le plus élevé, le cours vendeur le plus bas et la profondeur associée à chacun. Ils incluent parmi les variables de régression des mesures de la profondeur totale du marché aux meilleures limites. Quatre grandes conclusions se dégagent de l’étude. Premièrement, il existe une relation contemporaine entre les meilleures offres et leur profondeur : une hausse du cours vendeur (acheteur) s’accompagne d’une baisse (augmentation) de la profondeur correspondante. Ce résultat donne à penser que les placeurs d’ordres de vente souhaitent éviter le risque d’antisélection lié à une vente sur un marché haussier. Deuxièmement, lorsque l’écart acheteur-vendeur — le terme de correction d’erreurs — se creuse, le cours acheteur s’accroît et le cours vendeur diminue, de sorte que l’écart retourne à sa valeur d’équilibre de long terme. En outre, la profondeur effective aux meilleures limites recule des deux côtés du carnet en raison de l’accentuation de l’incertitude sur le marché. Troisièmement, les valeurs passées de cette profondeur influent sur le processus de découverte des prix tant chez les acheteurs que chez les vendeurs, mais l'effet est plus marqué du même côté du carnet. Quatrièmement, les variations de la profondeur totale aux meilleures limites ont une incidence à la fois sur les meilleures offres et sur les quantités disponibles même si elles ne peuvent être observées par les acteurs du marché.

Classification JEL : C3, D8, F31
Classification de la Banque : Taux de change; Marchés financiers

1. Introduction

In a limit order market, the market depth at each price determines the cost of trading. A steeper price schedule means that the cost of trading for any given order is higher. Despite there being two dimensions to the price schedule, most researchers focus on the price side, studying how prices react to changing market conditions (i.e., the price-discovery process). This paper empirically examines the dynamics of both prices and depth for the best quotes in a limit order market. Understanding which factors influence both of these characteristics for best quotes is important, because the best quotes are, by definition, the ones that are the next to be executed in the market. Since these quotes represent the current marginal value that the market is assigning to the asset, the best prices are the focus of most existing studies. Nevertheless, the actual marginal cost of trading is determined by both the price *and* the depth.

This paper extends the existing literature by modelling the best prices and the market depth jointly by using the structural error-correction model (ECM) proposed by Kim, Ogaki, and Young (2003). We model the changes in the best bid and ask prices and their associated depth in an electronic limit order market. In particular, we recognize that traders choose both price and quantity in placing a limit order. Thus, in aggregate, changes in price and depth can be contemporaneously related to each other. At the same time, past changes in price and depth on both sides of the market could also convey information and impact the current prices and depths. Therefore, we model both the contemporaneous and time-series relationships of best bid prices, best ask prices, and their associated depths in the structural ECM. Further, the model enables us to examine how prices and depth react to past changes in the price/depth on both the bid and ask sides of the market. We can therefore examine whether the information from the two sides of the market has an asymmetric impact on prices and depth. In addition, the model explicitly accounts for the cointegration between the best bid price and best ask price by incorporating the best bid-ask spread as the error-correction term. Thus, the system of equations allows us to examine how the prices/depth on each side of the market react to a shock in the equilibrium spread, and whether there is any asymmetry in the speed of adjustments. The model also includes measures of the market depth behind the best quotes, allowing us to examine whether such changes in the price schedule contain information relevant for changes in price and depth.

The most similar empirical studies to this work are Hasbrouck (1991), Dufour and Engle (2000), Engle and Patton (2004), and Kavajecz and Odders-White (2001). We extend Hasbrouck (1991) and Dufour and Engle (2000) in several ways: as in most existing studies, they focus on how the quoted midpoint price changes over time, and therefore they do not consider differences in how the prices develop to buy or sell the asset. We model both the current best bid and best ask prices from limit orders, and consider the corresponding depth. We model both sides of the market because it has been demonstrated that markets react differently to bid and ask orders (e.g., Chan and Lakonishok 1993, 1995; Saar 2001). We extend Engle and Patton (2004), who model both the ask and bid price dynamics of equities in the New York Stock Exchange (NYSE), in two ways: first, our model is structural, and so we are able to examine the contemporaneous relationships between the endogenous variables—the best prices and their associated depths. Second, we model the best bid and ask depths on both sides of the market. Kavajecz and Odders-White (2001) were the first to study the price and quantity choices of dealers on both sides of the market. Our analysis extends theirs by allowing lagged information to impact the price and depth dynamics. Our model also explicitly models the cointegration between the bid and ask prices.

For our analysis, we use data from the electronic order book for the Deutsche Mark/U.S. dollar currency pair from the Reuters D2000-2 electronic brokerage system. This complements the existing microstructure work using equity markets. The Reuters D2000-2 system is a limit order book, so it is not subject to the unknown impact on the price schedule of a specialist standing ready to buy and sell unknown quantities at different prices. Our study contributes to the literature by being the first to model both price and depth dynamics in the limit order book in the foreign exchange (FX) market; 85 per cent of FX interdealer trades go through the limit order book, and the Reuters D2000-2 is the only data set to give complete information[1] on it in the most liquid currency. Our modelling of the best price and the associated depth is directly related to the structure of the market. Only the best bid and ask prices, along with their depths, are shown on the Reuters D2000-2 system, so the depth of orders behind the best prices is not known to market participants. Thus, by incorporating measures related to the depth of orders behind the

[1] The Reuters D2000-2 data set is described in detail in section 3.

best prices as explanatory variables, our model allows us to examine whether market participants have private information correlated with the behind best quotes.

Our main findings can be summarized as follows. First, there are significant contemporaneous relationships between the best prices and their associated depths. More specifically, an increase in the concurrent best ask depth is associated with a significant drop in the best ask price. The willingness of more traders to sell indicates that the currency is overpriced, so the best price adjusts downwards. Contrary to the ask side of the market, an increase in the concurrent best bid depth is associated with a significant rise in the best bid price. The willingness of more traders to buy indicates that the currency is underpriced, so the price rises. Alternatively, when the price is rising, there is less adverse-selection risk in buying at too high a price, so traders place larger orders. For the impact of changes in prices on the corresponding depth equations, we find that a higher current bid price or deeper current bid depth causes a negative change in the current best ask depth. The intuition is that higher bid prices or more buyers in the market are positive signals for the value of the currency, so sellers withdraw from the market to avoid being picked off.

Second, both best prices and depth react to a disturbance in the error-correction component, the best bid-ask spread. We find that, consistent with the findings in Engle and Patton (2004), a widening spread in one period leads to a subsequent decrease in the best ask price and an increase in the best bid price. The speed of adjustment is roughly the same for both sides of the market. This suggests that the spread reverts to the long-run equilibrium value after shocks occur, increasing the spread. More interestingly, we find that a wider spread is associated with a negative change in depth on both sides of the market. Traders appear to interpret a widening of spreads as an increase in uncertainty, so they stop submitting orders or withdraw their existing orders.

The information in the lagged depth at the best and off-best prices affects the price-discovery process for both the bid and the ask sides of the market. More lagged depth at the best bid price leads to upward price movement, while more lagged depth at the best ask price leads to downward price movement. Further, the effect on the same side of the market is stronger.

Changes in the depth behind the best price impact changes in both ask and bid prices, although they are not observable to the market participants. A positive change in the bid depth more than 3 pips away from the best price leads to a rise in the best ask price. The opposite holds for the best bid price. This suggests that market participants, who are major dealers in the foreign exchange market, have an information source (e.g., a private customer order base) that is correlated to the depth deeper down/up in the order book. At the "closing" of the market,[2] best depths on both sides of the market rise, confirming the experimental asset market in Bloomfield, O'Hara, and Saar (2005).

This paper is organized as follows. Section 2 describes the structural error-correction model used to estimate the best bid and ask prices and their associated depths. Section 3 describes the data set and defines the elements of the empirical models that we estimate. Section 4 reports the results of the empirical analysis, and section 5 concludes.

2. Model and Hypotheses

2.1 Model

The model we use has four unique features. First, it is structural, so we are able to examine the contemporaneous relationship between best prices and their associated depths. Second, we model best bid prices, best ask prices, best bid depth, and best ask depth as a system, so we are able to more accurately capture any asymmetries in the dynamics between the bid and ask series. Third, as in Engle and Patton (2004), we explicitly account for the cointegrating relationship between the best bid and ask price by incorporating the error-correction component, the bid-ask spread. Fourth, we examine whether behind best depth contains information that impacts price and depth.

The structural ECM that we use can be represented by the following equation:

$$A_0 Y_t = d + b\,spread_{t-1} + A(L)Y_t + C(L)X_t + qTime + E_t, \qquad (1)$$

[2] The Deutsche Mark/U.S. dollar market operates 24 hours a day, but quoting and trading activities drop to a low level after 16:00 GMT, as Figure 1 shows.

where $Y_t = \left[\Delta p_t^{bid}\ \Delta p_t^{ask}\ \Delta d_t^{bid}\ \Delta d_t^{ask}\right]$ is a vector consisting of changes in the best bid price, Δp_t^{bid}, changes in the best ask price, Δp_t^{ask}, changes in the best bid quantity, Δd_t^{bid}, and changes in the best ask quantity, Δd_t^{ask}, at time t. The concurrent relationships between best prices and best depths are represented by the 4×4 matrix A_0, which is non-singular with ones along the principal diagonal. The lag effects of the best prices and best depths are represented by the matrix $A(L)$.

The lag spread, $spread_{t-1}$, is the difference between the best ask price and the best bid price. It is the error-correction component in equation (1), because the best bid and the best ask prices are prices on the same underlying asset and they are cointegrated. We verify this by applying the augmented Dickey-Fuller test to the spread;[3] the null hypothesis that the spread is I(1) is rejected at the 1 per cent significance level.[4] The speed of adjustment towards the long-run equilibrium spread is represented by the 4×1 vector, b.

The set of exogenous variables that we consider, X_t, consists of variables related to the depth at behind best prices in the order book; their effects are given by the coefficient matrix $C(L)$. Two measures of depth behind the best prices are used. The first measure, the *near depth*, is the change in the aggregate depth 1 to 3 pips from the best price on each side of the market from time t-1 to t. This variable measures the changes in depth close to the best prices standing in the book. The second measure, the *far depth*, is the change in the aggregate depth more than 3 pips from the best price on each side of the market from t-1 to t. This variable measures the changes in the depth further down/up the order book.

The final aspect of the model is the time-of-day effects, *time*. Their effects are given by the coefficient matrix, q. This term accommodates the distinct intraday seasonalities of quoting and trading in the foreign exchange market, as Figure 1 shows. The quoting activity of the Deutsche Mark/U.S. dollar exchange rate is most active during two periods: 7:00 GMT–10:00 GMT (hereafter referred to as the London trading hours) and 12:00 GMT–16:00 GMT (hereafter referred to as the New York trading hours). We incorporate six hourly dummies, from

[3] The augmented Dickey-Fuller tests include 10 lags of change in spread.
[4] Both the best ask depth and the best bid depth are I(0) variables. We account for the cointegration between only the best bid price and the best ask price, so there is only one cointegrating vector within the system.

10:00 GMT to 16:00 GMT, to compare the price and depth dynamics of the trading day relative to those in the London trading hours.

The vector, E_t, contains the disturbance terms from equaiton (1).

To estimate the model, we follow the instrumental variables method proposed in Kim, Ogaki, and Young (2003). The set of exogenous variables used in the model (the far depth and near depth) are used as instruments. For each equation, the near depth and the far depth on the same side of the market are excluded for identification purposes. Kavajecz and Odders-White (2001) similarly restrict price and quantity to respond only to information from the opposite side of the market, in order to identity the equations system. We write out the equations system explicitly as follows:

$$\begin{aligned}\Delta p_t^{ask} &= d_1 - a_{0,bid\,price}^{ask\,price}\Delta p_t^{bid} - a_{0,ask\,depth}^{ask\,price}\Delta d_t^{ask} - a_{0,bid\,depth}^{ask\,price}\Delta d_t^{bid} - b^{ask\,price} spread_{t-1} \\ &- \sum_{ii=1}^{5} a_{i,ask\,price}^{ask\,price}\Delta p_t^{ask} - \sum_{i=1}^{5} a_{i,bid\,price}^{ask\,price}\Delta p_{t-i}^{bid} - \sum_{ii=1}^{5} a_{i,ask\,depth}^{ask\,price}\Delta d_{t-i}^{ask} - \sum_{i=1}^{5} a_{i,bid\,depth}^{ask\,price}\Delta d_{t-i}^{bid} \\ &- \sum_{i=1}^{5} c_{i\,bid\,near\,depth}^{ask\,price}\Delta x_{t-i}^{bid\,near\,depth} - \sum_{i=1}^{5} c_{i\,bid\,far\,depth}^{ask\,price}\Delta x_{t-i}^{bid\,far\,depth} \\ &+ \sum_{t=1}^{5} q_i^{ask\,price} time^i + e_{ask\,price,t};\end{aligned} \tag{2}$$

$$\begin{aligned}\Delta p_t^{bid} &= d_1 - a_{0,ask\,price}^{bid\,price}\Delta p_t^{ask} - a_{0,ask\,depth}^{bid\,price}\Delta d_t^{ask} - a_{0,bid\,depth}^{bid\,price}\Delta d_t^{bid} - b^{bid\,price} spread_{t-1} \\ &- \sum_{ii=1}^{5} a_{i,ask\,price}^{bid\,price}\Delta p_t^{ask} - \sum_{i=1}^{5} a_{i,bid\,price}^{bid\,price}\Delta p_{t-i}^{bid} - \sum_{ii=1}^{5} a_{i,ask\,depth}^{bid\,price}\Delta d_{t-i}^{ask} - \sum_{i=1}^{5} a_{i,bid\,depth}^{bid\,price}\Delta d_{t-i}^{bid} \\ &- \sum_{i=1}^{5} c_{i\,ask\,near\,depth}^{bid\,price}\Delta x_{t-i}^{ask\,near\,depth} - \sum_{i=1}^{5} c_{i\,ask\,far\,depth}^{bid\,price}\Delta x_{t-i}^{ask\,far\,depth} \\ &+ \sum_{t=1}^{5} q_i^{bid\,price} time^i + e_{bid\,price,t};\end{aligned} \tag{3}$$

$$\begin{aligned}\Delta d_t^{ask} = d_1 &- a^{askdepth}_{0,askprice}\Delta p_t^{ask} - a^{askdepth}_{0,bidprice}\Delta p_t^{bid} - a^{askdepth}_{0,biddepth}\Delta d_t^{bid} - b^{askdepth} spread_{t-1} \\ &- \sum_{i=1}^{5} a^{askdepth}_{i,ask\,price}\Delta p_t^{ask} - \sum_{i=1}^{5} a^{askdepth}_{i,bid\,price}\Delta p_{t-i}^{bid} - \sum_{i=1}^{5} a^{askdepth}_{i,ask\,depth}\Delta d_{t-i}^{ask} - \sum_{i=1}^{5} a^{askdepth}_{i,biddepth}\Delta d_{t-i}^{bid} \\ &- \sum_{i=1}^{5} c^{askdepth}_{i\,bid\,neardepth}\Delta x^{bidneardepth}_{t-i} - \sum_{i=1}^{5} c^{askdepth}_{i\,bid\,fardepth}\Delta x^{bid\;fardepth}_{t-i} \\ &+ \sum_{t=1}^{5} q_i^{askdepth} time^i + e_{askdepth,t}; \end{aligned} \tag{4}$$

$$\begin{aligned}\Delta d_t^{bid} = d_1 &- a^{bid\,depth}_{0,askprice}?p_t^{ask} - a^{biddepth}_{0,bidprice}?p_t^{bid} - a^{biddepth}_{0,askdepth}?d_t^{ask} - b^{biddepth} spread_{t-1} \\ &- \sum_{i=1}^{5} a^{biddepth}_{i,ask\,price}?p_t^{ask} - \sum_{i=1}^{5} a^{biddepth}_{i,bid\,price}?p_{t-i}^{bid} - \sum_{i=1}^{5} a^{biddepth}_{i,ask\,depth}?d_{t-i}^{ask} - \sum_{i=1}^{5} a^{biddepth}_{i,biddepth}?d_{t-i}^{bid} \\ &- \sum_{i=1}^{5} c^{biddepth}_{i\,askneardepth}?x^{askneardepth}_{t-i} - \sum_{i=1}^{5} c^{biddepth}_{i\,ask\,fardepth}?x^{ask\;fardepth}_{t-i} \\ &+ \sum_{t=1}^{5} ?_i^{biddepth} time^i + e_{biddepth,t}; \end{aligned} \tag{5}$$

The equations above are estimated using a two-stage least-squares method. White's (1980) method is used in each equation to adjust for heteroscedasticity.

2.2 Hypotheses

2.2.1 Contemporaneous relationship between the best price and its associated depth

When placing a limit order, a trader must specify both the price and quantity for the order. Thus, at the aggregate level, it would seem logical that changes in price and depth should be related to one another. More specifically, we hypothesize that an increase in the depth on the sell side should lead to a drop in both the bid and ask prices, since an increase in the number of traders willing to sell indicates that the currency is overvalued. Similarly, an increase in the depth on the buy side should lead to a rise in both the best bid and ask prices.

Turning to the depth equations, an increase in the best prices should lead to a drop in the best ask depth, because traders want to avoid the adverse-selection risk of selling too low in case the price continues to rise. Similarly, an increase in the best prices should lead to an increase in the best bid depths, since there is less adverse-selection risk to buy when the price is increasing.

2.2.2 Error-correction impact on prices and depths

As Engle and Patton (2004) suggest, the best ask and bid prices should converge back towards their equilibrium values after a shock to the error-correction term, the lag spread. Thus, the best ask price should drop and the best bid price should rise after a widening of the spread. We can also examine whether there is any asymmetry in the adjustment speed of the two sides of the market.

A widening of the spread could be associated with an increase in uncertainty about the currency's value. Thus, both the best bid and best ask depth should drop as the spread widens, because placing a best limit order entails increasing adverse-selection risk under uncertain market conditions.

2.2.3 The impact of past changes in depths

Extending Kavajecz and Odders-White (2001) and Engle and Patton (2004), our model enables us to examine how lagged best depth dynamics affect the best bid and best ask prices and depths. Similar to the intuition for concurrent depths, a previous deeper market on the bid side should lead to upward price movement on both sides of the market. The opposite holds true for a deeper market on the ask side. Further, the effect of the lagged best depth should decline over time, as past information is successively incorporated into prices. The model also allows us to examine whether the two sides of past depth have asymmetric effects on the price-discovery process.

Turning to the effect on depth equations, a deeper market on the same side of the market means longer queues and more competition for placing best limit orders. Consequently, traders should refrain from submitting best orders on the same side of the market. This is the crowding-out effect described in Parlour (1998). Therefore, the best depth should drop following a previous rise in depth on the same side of the market.

2.2.4 The impact of past changes in depth behind the best prices

Depths behind the best price represent the aggregation of individuals with valuations above or below the current best levels, or their expectation of future price movement. As a result, behind best depth should carry price-relevant information. Even though this information is not observable to market participants, we expect that, similar to the case of best depths, more behind best ask depth should lead to a downward movement in the price, and more behind best bid depth should lead to an upward movement in the price. Further, we could examine whether a depth closer to best depth or one deeper down the order book has the strongest impact on the price/depth discovery process. Since Reuters shows only the best price along with the associated depths (depths behind the best prices are not observable), best prices and depths would respond to changes in behind best depths only if individual traders have private information correlated with the dynamics of the depths behind the best prices.

2.2.5 Time-of-day effect

Using time dummies, from 10:00 GMT to 16:00 GMT, allows us to compare the impact of activities for the rest of the trading day with the London trading hours. Bloomfield, O'Hara, and Saar (2005) use an experimental asset market to investigate traders' behaviour at these times. They find that informed traders demand liquidity early in the trading session by submitting market orders, but that those traders start to supply liquidity by submitting limit orders as the day progresses. As a result, we expect to see an increase in the depth of best limit orders as the day progresses, especially at the end of the day.

3. Data

We use the Deutsche Mark/U.S. dollar exchange rate from the Reuters D2000-2 system from the evening of 6 October 1997 to midnight on 10 October 1997. The D2000-2 is an electronic order book to which foreign exchange traders can submit both market and limit orders. Subscribers see the best bid and best ask quotes, the size supplied at these prices, and the most recent transactions. Although we observe all of the orders submitted to the market, traders do not directly observe the complete order book. For example, they cannot observe the off-best limit orders posted, or their cancellation. They do, however, observe information from other sources, such as Reuters' EFX page, as well as their own customer order flow. Because there was an unexpected change in interest rates by the Bundesbank on 9 October 1997, and the change had an unusual impact on the trading activity in the foreign exchange market (see Carlson and Lo 2004), that day is excluded from our sample.

The use of the foreign exchange market has several advantages over the more commonly used equity data. For example, because the market is open 24 hours a day, we can study more clearly how the supply and demand for a highly liquid asset develop as trading activities ebb and flow with the arrival and departure of traders from different geographic regions and the arrival of information over the day. The impact of these changes on trading behaviour can be studied more clearly because this market is open with a consistent trading mechanism over the entire trading day. Despite the fact that the data set has a short time span, it is the only data set available that has complete information on the limit order book in the foreign exchange market. The Deutsche Mark/U.S. dollar was the most heavily traded currency pair before the introduction of the euro, so the liquidity of the market limits potential problems resulting from illiquid trading, information asymmetries, and other errors in the measurement of microstructure characteristics. Most importantly, around 85 per cent of the interdealer trade in major currencies currently goes through the electronic limit order book (Sager and Taylor 2005).

The limit order book in the foreign exchange market therefore provides unique insight into the order submission strategies of dealers in a very liquid market with round-the-clock trading. It enables us to examine more thoroughly how the supply and demand for currencies over the day influence traders' decisions. Further facilitating our analysis is the fact that the submission and cancellation of market and limit orders in the foreign exchange market provide a full picture of the changing state of the limit order book (there is no market-maker or features such as "iceberg orders").

The data set includes the following information on each order: the price at which the submitter stands ready to buy or sell the currency, the quantity to be traded, the exact time it arrived, whether the quote is a limit order or a market order, whether the quote is bid-side or ask-side initiated, and the entry and exit time of the quote. The complete data set consists of 130,526 quotes. Focusing on both order submission activities during the most active trading period—from 7:00 to 16:00 GMT (see Figure 1)—the data set used for the empirical analysis consists of 91,086 submitted quotes.

Each trading day is divided into 5-second intervals. The changes in the best bid and best ask prices and their associated depths are defined as the orders submitted closest to the end of each interval. For example, the change in the price of the best ask (bid) in the market is calculated as the difference between the quoted best ask (bid) price closest to the end of period *t*-1 and the quoted best ask (bid) price closest to the end of period *t*. The same is done for the depth at these prices.

The exogenous variables, as explained in section 2.1, are the changes in the near depth and the far depth on both sides of the market over the last 5-second interval. For example, the change in the depth near the best price on the bid side is defined as

$$\Delta d_t^{bid\ near\ depth} = \sum_{i=1}^{3} d_t^{i^{th}\ pip\ from\ best\ bid\ price} - \sum_{i=1}^{3} d_{t-1}^{i^{th}\ pip\ from\ best\ bid\ price}, \tag{6}$$

where $d_t^{i^{th}\ pip\ from\ best\ bid\ price}$ represents the depth at the i^{th} pip from the best bid price. The change in the ask near depth is defined in a similar way. The change in the bid far depth is defined as

$$\Delta d_t^{bid\ far\ depth} = \sum_{i=4}^{\infty} d_t^{i^{th}\ pip\ from\ best\ bid\ price} - \sum_{i=4}^{\infty} d_{t-1}^{i^{th}\ pip\ from\ best\ bid\ price}. \tag{7}$$

The change in the ask far depth is defined in a similar way.

Table 1 shows the overall means and standard deviations of the changes in best prices and their associated depths, the near depths and the far depths of both sides of the market. The mean changes in the prices and depths of all definitions are close to zero. Standard deviations of changes in depths are higher than changes in prices. Tables 2 and 3, respectively, show the sample means and sample standard deviation through the trading day.

4. Empirical Results

Table 4 shows the results of the estimation of the structural error-correction model. Each of the following subsections will discuss the results shown in the table.

4.1 Contemporaneous relationship between the best price and its associated depth

Rows 2 to 4 of Table 4 report the contemporaneous relationships between the current prices and quantities. We find that an increase in the best ask depth leads to a significant drop in the best ask price. The relevant coefficient in the best ask price equation, -0.1425, is significant at the 1 per cent significance level. This finding confirms the hypothesis that if more traders are willing to sell, then the currency is overpriced, and the price decreases. The effect, however, concentrates on the sell (same) side of the market. The change in the best ask depth has no significant effect on changes in the best bid price.

An increase in the best bid depth leads to a rise in the best bid price, confirming the hypothesis that if more traders are willing to buy, then the currency is undervalued. The respective coefficient in the best bid price equation is 0.0989, which is again significant at the 1 per cent significance level. The effect concentrates on the same side of the market—changes in the best bid depth do not have a significant effect on the equation for the best ask price.

Turning to the depth equations, we similarly find that the corresponding changes in the best depths are consistent with our hypotheses. For the best ask equation, positive changes in best prices are associated with a drop in the best ask depth. Thus, traders try to avoid potential adverse-selection risk in case the price continues to rise: traders do not submit new best ask orders and they withdraw existing ones. The effect stems from the bid side of the market: the coefficient on the best bid price is significantly negative, with a value of -3.4394, while the coefficient for the best ask price is not significant, although the sign is also negative, as hypothesized.

Similar to the relationships for the best ask depth, we find that an increase in the best prices on both sides of the market leads to an increase in the best bid depth. This suggests that buy traders are less worried about adverse-selection risk when placing a best buy limit order in a rising market. Unlike for the best ask depth, the effect of changes in the best prices comes from both sides of the market. The coefficients related to changes in the best ask and bid prices are both significantly positive and they are of similar magnitude.

4.2 Error-correction impact on best prices and depths

In Table 4, as hypothesized, the best ask price drops significantly and best bid prices rise significantly after a widening of the lag spread, returning the spread to the long-term equilibrium value. This finding confirms the results of Engle and Patton (2004). Moreover, the two coefficients are of similar absolute magnitudes, which suggests that the two price series have a similar speed of adjustment. Therefore, the best bid price and the ask price react similarly (but in opposite directions) to a shock to the equilibrium spread.

Extending the results of Engle and Patton, we find that the changes in the spread significantly impact the best depths on both sides of the market. As hypothesized, a widening of spread leads to a negative change in both the best bid depth and the best ask depth. The intuition is that a wider spread represents increased uncertainty about the value of the currency. Thus, traders stop submitting or start withdrawing their existing best orders, to avoid being picked off in an uncertain market. Quite interestingly, the drop in depth across the two sides of the market in response to a change in spread is similar: the spread coefficients in the two depth equations are similar in magnitude. This suggests that the uncertainty created by a widening spread has a similar impact on depth on both sides of the market.

4.3 The impact of past changes in the best depth

The past changes in the depth quoted at the best prices significantly impact both the best bid and best ask prices being submitted (Table 4). Past increases in the best ask depth lead to significant decreases in the best price on both sides of the market. The coefficients are slightly larger and more significant on the ask side of the market. The opposite holds for past changes in the best bid depth—they lead to significant increases in the best prices on both sides of the market. The coefficients are again slightly larger and more significant on the same side of the market. These findings suggest that more traders placing best ask (bid) limit orders in the past conveys negative (positive) aggregate information about the future value of the currency, and best prices on both sides of the market therefore drop (rise). Moreover, the impact of concentrating on the same side of the market can be explained by the fact that traders tend to quote only one side of the market, instead of giving two sides a quote, as described in Sager and Taylor (2005). As a result, the traders react more to information stemming from the same side of the market. Another finding is that the magnitude of the coefficients on the lagged best depth declines over time. Except for the impact of the past ask depth on the best bid price, the lagged best depth coefficients uniformly drop in value for the higher autoregressive orders in both best price equations. This finding confirms the hypothesis that more distant information is less relevant for the price-discovery process.

For the depth equations, the effects of past depth changes on the same side of the market confirm the crowding-out effect suggested in Parlour (1998) and Goettler, Parlour, and Rajan (2005). Past positive changes in the best depth on the same side of the market lead to subsequent negative changes in the best depth. This holds for both the bid and the ask sides of the market. All coefficients on lagged changes in the best ask (bid) depth are significantly negative in the ask (bid) depth equation. Thus, traders appear to refrain from competing with liquidity supply on the same side of the market.

Further, we find that best depths respond to past changes in the best depth on the opposite side of the market. A past positive change in the best depth on the opposite side of the market leads to, in general, a subsequent positive change in the best depth. This indicates that traders submit more best limit orders in response to past increases in liquidity supply on the opposite side of the market. A potential explanation is that a deeper market at the best price on the opposite side of the market indicates that more traders are willing to supply liquidity at that best price. Thus, there is less risk on price uncertainty, and so traders place more orders on the same side of the market. The effect, however, is weaker than for those of the lagged, same-side depth: the coefficients are of much smaller absolute magnitude than those for lagged changes on the same-side depth, and the significance levels are much lower. This suggests that traders are more concerned about competition with liquidity supply from the same side of the market.

4.4 The impact of past changes in unobservable depths behind the best prices

Previous changes in behind best depth, though unobservable, significantly impact the price-discovery process (Table 4). Further, changes in the far depth—the depth accumulated at more than 3 pips from the best price—have a stronger and more significant effect than in the near depth—the depth accumulated between 1 to 3 pips from the best price—on the price-discovery process. In both cases, a positive previous change in the behind best bid depth leads to a subsequent increase in the best ask price, while a positive previous change in the behind best ask depth leads to a subsequent decrease in the best bid price. The intuition is that the changes in the depth behind the best price aggregate the changes in individuals' valuations, or expectations, of future price movements. When more traders place orders deeper down (up) the order book, it signifies that a larger proportion of market participants have lower (higher) valuations for the currency, or that they are expecting downward (upward) price changes. In a market with asymmetric information and no common knowledge, the changes in behind best depth reveal price-relevant information on the value of the currency. In addition, the results show that, although traders could not observe the changes in behind best depth, they must have accessed information correlated with those changes (e.g., a private customer base).

Turning to the depth equations, the behind best depths have a mixed effect on the current best depths. For the best ask depth equation, the effect of changes in the bid near depth is stronger and more significantly positive than in the bid far depth. Thus, traders place more best ask orders in response to liquidity supply close to the best bid price. For the best bid depth equation, the coefficients of behind best ask depth are smaller and less significant than their counterparts in the best ask depth equation.

4.5 Time-of-day effect

Confirming our hypotheses, we find that the best depth at the end of the trading day increases compared with the beginning of the trading day (the London trading hours). In Table 4, the time dummy from 15:00 GMT to 16:00 GMT, *t*16, is significantly positive for both the best bid depth equation and the best ask depth equation. Thus, this study empirically supports the evidence obtained using an experimental asset market in Bloomfield, O'Hara, and Saar (2005).

More interestingly, the time-of-day effect influences the best prices as well. Over the latter part of the trading day, from 14:00 GMT to 16:00 GMT, represented by the time dummies *t*15 and *t*16, the best ask price increases significantly, while the best bid price drops significantly. The best bid price also drops significantly at the end of the London session from 10:00 GMT to 11:00 GMT. This indicates that, at the end of the trading session, traders want to insure themselves against market movement during their later inactive period, and so they place orders at a higher ask price or lower bid price.

5. Conclusions

We have used a structural error-correction model to examine the dynamics of best the bid price, best ask price, best bid depth, and best ask depth. The model includes behind best depth and time dummies as regressors. We find that (i) best prices and their associated depths are contemporaneously related to each other; (ii) when the spread widens, the best bid price rises and the best ask price drops, while depth on both sides of the market drops; (iii) the lagged best depth has an effect on price discovery on both sides of the market, but the effect is stronger on the same side of the market; (iv) depths behind the best quotes move both best prices and quantities, even though these events are unobservable on the Reuters screen; and (v) the best depth on both sides of the market rises at the closing of the market.

Our empirical results have important implications for researchers who are interested in modelling prices and depth. First, the depths in the limit order book are determined jointly with prices. Both current and lagged depth affect the price-discovery process. Models that ignore depth lack an important piece of information. Second, behind best quotes, especially those deeper down/up the order book, have a significant impact on the price-discovery process. Although this fact is unobservable to traders in the FX market, it cannot be ignored in empirical modelling of the limit order book. Finally, the sides of the market from which information arrives and at which orders are submitted are critical in understanding the evolution of the bid and ask prices. Thus, using midquotes, as in much of the empirical literature, may blur potentially important information from the two sides of the market.

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Table 1: Summary Statistics of Variables

This table shows the mean, standard deviation, median, maximum, and minimum for the exogenous and endogenous variables. The data are the Deutsche Mark/U.S. dollar quotes from the Reuters D2000-2 electronic brokerage system for the week of 6–10 October 1997. The data used are from 7:00 to 15:59 GMT.

	Mean	**Std**	**Median**	**Max**	**Min**
Change in ask price*	0.001	1.26	0	26	-19
Change in bid price	0.001	1.21	0	18	-32
Change in ask depth**	0.001	3.43	0	45	-39
Change in bid depth	0.000	3.45	0	78	-82
Ask depth 1 to 3 pips from best price	-0.001	4.53	0	52	-60
Ask depth more than 3 pips away from best price	-0.005	4.52	0	56	-56
Bid depth 1 to 3 pips from best price	-0.001	4.08	0	48	-52
Bid depth more than 3 pips away from best price	0.003	4.33	0	55	-56

* Prices are multiplied by 10,000.
** Depths are in millions.

Table 2: Sample Mean of Variables through the Trading Day

This table shows the sample mean of variables in the model. The trading day is divided into half-hour intervals and we consider the values between 7:00 and 15:59 GMT.

	7:00	7:30	8:00	8:30	9:00	9:30	10:00	10:30	11:00	11:30	12:00	12:30	13:00	13:30	14:00	14:30	15:00	15:30
Change in ask price	-0.0153	0.0076	-0.0021	-0.0298	0.0090	0.0243	-0.0375	0.0090	-0.0285	0.0188	-0.0076	0.0216	0.0639	-0.0305	0.0313	-0.0076	0.0326	-0.0332
Change in bid price	-0.0146	0.0063	-0.0014	-0.0291	0.0097	0.0243	-0.0410	0.0104	-0.0278	0.0174	-0.0118	0.0236	0.0681	-0.0319	0.0334	-0.0076	0.0222	-0.0277
Change in ask depth	0.0042	0.0090	-0.0090	0.0097	0.0076	-0.0146	-0.0028	-0.0028	0.0049	-0.0035	0.0055	0.0049	-0.0056	0.0035	0.0049	-0.0125	-0.0021	0.0214
Change in bid depth	0.0049	0.0007	-0.0049	0.0097	0.0007	-0.0153	0.0035	-0.0007	0.0000	0.0000	-0.0021	0.0000	0.0076	0.0083	-0.0077	-0.0042	0.0021	-0.0062
Ask depth 1 to 3 pips from best price	0.0021	0.0063	0.0083	0.0062	-0.0049	-0.0049	-0.0083	-0.0160	0.0146	-0.0021	0.0236	-0.0174	0.0104	-0.0111	0.0007	-0.0153	0.0146	-0.0221
Ask depth more than 3 pips away from best price	0.0195	0.0396	0.0056	0.0354	-0.0250	-0.0097	0.0083	-0.0180	0.0250	-0.0501	0.0305	-0.0188	-0.0125	-0.0049	-0.0389	-0.0313	-0.0049	-0.0408
Bid depth 1 to 3 pips from best price	0.0021	-0.0035	0.0014	-0.0028	0.0180	-0.0146	-0.0132	0.0173	-0.0125	0.0028	-0.0076	0.0160	-0.0007	-0.0007	-0.0035	-0.0090	-0.0104	-0.0007
Bid depth more than 3 pips away from best price	0.0007	0.0743	0.0430	-0.0208	0.0090	0.0195	0.0612	-0.0735	0.0431	0.0000	-0.0479	-0.0139	0.0222	-0.0485	0.0709	-0.0361	-0.0353	-0.0076

Table 3: Sample Standard Deviation of Variables through the Trading Day

This table shows the sample standard deviation of variables in the model. The trading day is divided into half-hour intervals and we consider the values between 7:00 and 15:59 GMT.

	7:00	7:30	8:00	8:30	9:00	9:30	10:00	10:30	11:00	11:30	12:00	12:30	13:00	13:30	14:00	14:30	15:00	15:30
Change in ask price	1.19	1.22	1.11	1.01	0.75	0.81	0.97	0.99	1.14	1.11	1.29	1.19	1.18	1.16	1.52	1.94	1.69	1.73
Change in bid price	1.27	1.30	1.09	0.84	0.83	0.90	0.85	0.99	1.00	0.94	1.19	1.63	1.47	1.08	1.56	1.49	1.63	1.13
Change in ask depth	3.71	4.30	3.99	3.45	3.23	3.49	2.94	2.55	2.58	3.11	3.17	3.84	4.25	4.78	3.64	2.92	2.26	2.23
Change in bid depth	3.88	3.54	4.00	4.10	3.03	3.42	3.23	2.92	2.92	2.93	3.40	3.67	4.10	4.86	3.89	3.11	2.12	1.59
Ask depth 1 to 3 pips from best price	4.34	5.42	5.05	4.51	4.04	4.88	3.44	3.66	3.52	3.74	3.97	5.08	7.06	6.27	5.04	3.55	2.96	2.57
Ask depth more than 3 pips away from best price	4.33	4.71	5.44	4.72	4.11	4.74	2.91	2.80	4.05	3.75	4.17	5.25	7.85	5.69	5.11	3.16	2.92	2.15
Bid depth 1 to 3 pips from best price	4.50	4.26	5.17	4.83	3.53	3.99	3.57	3.09	4.02	3.16	5.33	4.38	4.57	4.77	4.30	3.62	2.92	1.70
Bid depth more than 3 pips away from best price	4.47	4.25	5.88	5.16	3.34	3.98	3.36	3.35	4.48	3.44	5.66	4.68	4.65	4.62	5.26	3.87	3.29	2.59

Table 4: Estimation of the Structural Error-Correction Model

This table shows the results of the estimation of the simultaneous equation model (equation (1)) using the changes in best prices and quantities from the Reuters D2000-2 electronic brokerage system for the week of 6–10 October 1997.

	Change in ask price	*t* stat	Change in bid price	*t* stat	Change in ask depth	*t* stat	Change in bid depth	*t* stat
Intercept	0.2605	9.23	-0.2460	-10.44	0.1114	2.52	0.0909	2.06
Change in ask price			0.6140	2.21	-0.2611	-0.70	2.3927	3.24
Change in bid price	0.8584	2.55			-3.4394	-4.95	2.9925	5.68
Change in ask depth	-0.1425	-6.27	0.2262	1.35			0.5910	1.27
Change in bid depth	-0.0097	-0.12	0.0989	4.56	-0.5990	-2.18		
Spread, *t*-1	-0.1428	-9.66	0.1319	10.71	-0.0578	-3.81	-0.0555	-3.96
Change in ask price *t*-1	-0.2076	-8.63	0.0669	4.02	0.0488	2.24	-0.0423	-1.85
Change in ask price *t*-2	-0.1187	-6.29	0.0784	5.24	0.0481	2.32	-0.0710	-3.11
Change in ask price *t*-3	-0.0738	-4.05	0.0555	3.78	0.0460	2.39	-0.0157	-0.69
Change in ask price *t*-4	-0.0447	-2.19	0.0405	2.93	-0.0117	-0.58	-0.0442	-1.99
Change in ask price *t*-5	-0.0366	-2.50	0.0244	2.15	0.0121	0.64	0.0225	1.10
Change in bid price *t*-1	0.0582	3.32	-0.2014	-8.88	0.0217	0.88	-0.0232	-0.95
Change in bid price *t*-2	0.0747	4.35	-0.1229	-6.05	0.0355	1.28	-0.0505	-2.37
Change in bid price *t*-3	0.0510	3.02	-0.1001	-5.01	0.0454	1.80	-0.0651	-3.01
Change in bid price *t*-4	0.0458	2.91	-0.0574	-3.43	0.0346	1.38	0.0265	1.35
Change in bid price *t*-5	0.0138	0.95	-0.0367	-1.94	0.0311	1.35	-0.0276	-1.56
Change in ask depth *t*-1	-0.0374	-13.69	-0.0220	-6.65	-0.4519	-34.85	0.0166	2.21
Change in ask depth *t*-2	-0.0234	-8.59	-0.0199	-6.63	-0.3371	-27.22	-0.0018	-0.21
Change in ask depth *t*-3	-0.0189	-6.86	-0.0085	-2.78	-0.2565	-20.88	0.0157	1.72
Change in ask depth *t*-4	-0.0123	-4.44	-0.0131	-4.67	-0.1676	-15.76	0.0203	2.41
Change in ask depth *t*-5	-0.0104	-4.14	-0.0071	-2.68	-0.1028	-10.71	0.0157	2.00
Change in bid depth *t*-1	0.0252	8.67	0.0354	11.43	0.0213	2.83	-0.4633	-24.15
Change in bid depth *t*-2	0.0196	6.86	0.0210	7.51	0.0068	0.92	-0.3476	-24.90
Change in bid depth *t*-3	0.0135	4.66	0.0166	6.21	0.0011	0.14	-0.2660	-22.62
Change in bid depth *t*-4	0.0106	3.79	0.0150	5.79	0.0149	1.97	-0.1999	-18.75
Change in bid depth *t*-5	0.0086	3.17	0.0103	3.81	0.0029	0.41	-0.1160	-12.10

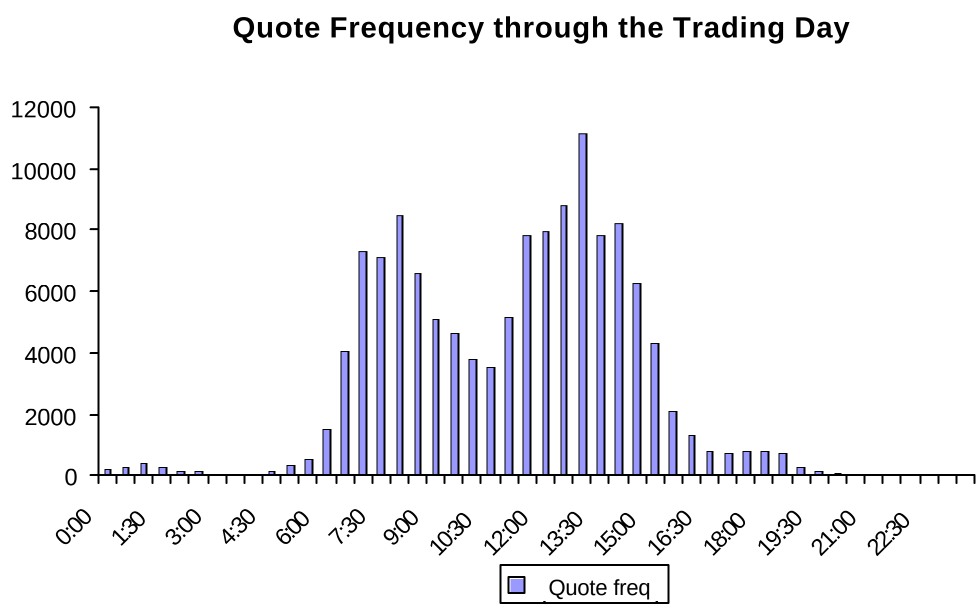
(continued)

Table 4 (concluded)

	Change in ask price	*t* stat	Change in bid price	*t* stat	Change in ask depth	*t* stat	Change in bid depth	*t* stat
Ask depth 1 to 3 pips from best price, *t*-1			-0.0395	-1.61			-0.0443	-0.66
Ask depth 1 to 3 pips from best price, *t*-2			-0.0167	-1.51			-0.0013	-0.04
Ask depth 1 to 3 pips from best price, *t*-3			-0.0140	-1.34			-0.0113	-0.40
Ask depth 1 to 3 pips from best price, *t*-4			-0.0069	-1.76			0.0140	1.37
Ask depth 1 to 3 pips from best price, *t*-5			-0.0062	-1.99			0.0193	2.30
Ask depth more than 3 pips away from best price, *t*-1			-0.0462	-3.59			-0.0598	-1.81
Ask depth more than 3 pips away from best price, *t*-2			-0.0202	-3.87			-0.0260	-1.94
Ask depth more than 3 pips away from best price, *t*-3			-0.0125	-3.31			-0.0003	-0.04
Ask depth more than 3 pips away from best price, *t*-4			-0.0105	-3.01			-0.0133	-1.53
Ask depth more than 3 pips away from best price, *t*-5			-0.0113	-2.63			-0.0130	-1.23
Bid depth 1 to 3 pips from best price, *t*-1	0.0132	1.02			0.1209	2.87		
Bid depth 1 to 3 pips from best price, *t*-2	0.0006	0.09			0.0729	3.65		
Bid depth 1 to 3 pips from best price, *t*-3	0.0021	0.49			0.0385	3.37		
Bid depth 1 to 3 pips from best price, *t*-4	0.0041	1.01			0.0340	3.01		
Bid depth 1 to 3 pips from best price, *t*-5	0.0022	0.73			0.0239	3.08		
Bid depth more than 3 pips away from best price, *t*-1	0.0319	4.37			0.0258	1.23		
Bid depth more than 3 pips away from best price, *t*-2	0.0108	3.03			-0.0044	-0.52		
Bid depth more than 3 pips away from best price, *t*-3	0.0105	3.25			-0.0063	-0.83		
Bid depth more than 3 pips away from best price, *t*-4	0.0041	1.30			0.0149	1.73		
Bid depth more than 3 pips away from best price, *t*-5	0.0052	1.60			0.0185	2.16		
*t*11	0.0072	0.35	-0.0400	-2.03	0.0080	0.13	0.0114	0.18
*t*12	0.0254	1.13	-0.0338	-1.63	0.0178	0.29	0.0118	0.19
*t*13	0.0392	1.61	-0.0143	-0.53	0.0198	0.29	0.0128	0.19
*t*14	0.0290	1.24	0.0168	0.68	-0.0093	-0.11	0.0276	0.34
*t*15	0.0996	3.15	-0.0619	-2.09	0.0269	0.41	0.0272	0.40
*t*16	0.2442	6.77	-0.2257	-6.96	0.1172	1.89	0.0947	1.72
R square		0.10		0.10		0.19		0.21

Figure 1

This graph shows the average number of orders submitted in each half-hour interval using the data from the Reuters D2000-2 electronic brokerage system for the week of 6–10 October 1997.



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