Microstructure effects, bid-ask spreads and volatility in the spot foreign exchange market pre and post-EMU

by

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Abstract

This article examines how microstructure effects, evident in high frequency data, influence bid-ask spreads and volatility in transaction price series. It uses the event of European Monetary Union (EMU), and the upheaval that this entailed, as an opportunity to empirically investigate these relationships in the electronic inter-dealer spot FX market. The microstructure effects relate to both price and time. There are two price effects, namely price discreteness and price clustering, and two time effects, namely the time elapsed between sample periods and the time-gap between successive trades or quoted price submissions. Strong evidence emerges that all four factors are important in the determination of bid-ask spreads.

This study uses a unique and rich foreign exchange (FX) dataset of global inter-dealer electronic transactions to examine microstructural effects in the spot foreign exchange market. This dataset enables us to shed new light on the debate surrounding the observations that trading volumes have fallen and bid-ask spreads have widened in inter-dealer spot FX markets following European Monetary Union (EMU). Our work provides a more detailed account of the changes that actually occurred at this time, because our data is more comprehensive than has previously been available. Our four-technical-feature explanation is in contrast to the hypothesis of market maker response to exogenous changes in volume as proposed by Hau, Killeen and Moore (2000 and 2002).

Price discreteness means that prices or exchange rates are not an infinite number of digits long, but rather they are truncated to a small number of digits. In the case of the FX market, exchange rates are specified to five digit accuracy. Price clustering refers to the fact that traders may not use all available exchange rates uniformly. In practice, rates ending in 0 or 5 tend to be used more than other rates. The time elapsed between the sample periods is important for a very obvious reason - price levels can differ radically if data is sampled from periods that are far apart in time. On the other hand, the time-gap between successive individual prices is also important because it allows these prices to drift apart. When the successive prices are transaction prices, this effect increases volatility. When they are successive bid and ask prices, the bid-ask spread is increased.

EMU brought widespread change to financial markets. Much of this change is directly due to the re-denomination of certain instruments from Deutschemarks (DEM) to euros (EUR). Since these currency units are of different values, the nature of the price discreteness affecting instruments which are now denominated in EUR will be different from what it was under DEM denomination. This point is exemplified by our finding that the smallest sized bid-ask spread and smallest price increment for the EUR are both 74% greater than that for the DEM, after controlling for drift in currency values.

Our four proposed factors are successful in explaining the observed changes in bid-ask spreads, but are less able to explain the observed changes in price volatility. Also, our results overwhelmingly accept the price resolution hypothesis explanation for price clustering behavior in the spot FX market and overwhelmingly reject the price attraction hypothesis. In the case of the EUR(DEM)/USD bid-ask spread, we provide a deeper understanding of the technical market features that caused this to increase. We show that the widening of the USD/JPY bid-ask spread seems primarily due to the inter-temporal change in currency value. We also show that the narrowing of EUR(DEM)/CHF bid-ask spreads seems largely due a near 50% decrease in the pricing increment used. We find that increased volume has reduced the time-gap for traded and quoted prices for USD/CHF. Finally, in the case of EUR(DEM)/JPY, we find that market practice caused wider bid-ask spreads. The bid-ask spread data evidence suggests that the advent of EMU seems to have strengthened the USD's position as the dominant international vehicle currency. We consider this surprising because we believe that part of the intention in launching the single currency must surely have been the opposite.

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1. Introduction

This study uses a unique and rich foreign exchange (FX) dataset of global inter-dealer electronic transactions to examine microstructural effects in the spot foreign exchange market. This dataset allows us to shed new light on the debate surrounding the observations that trading volumes have fallen and bid-ask spreads have widened in inter-dealer spot FX markets following European Monetary Union (EMU). Our work provides a more detailed account of the changes that actually occurred at this time, because our data is more comprehensive than has previously been available. However, this is more than just an empirical study. We also introduce new theoretical explanations and new methodologies to this debate. These enable us to demonstrate that much of the change in bid-ask spreads and some of the change in price volatility can be explained by four technical features of high-frequency data, namely price discreteness, price clustering, the time elapsed between sample periods and the time-gap between successive traded or quoted prices. This explanation is in contrast to the hypothesis of market maker response to exogenous changes in volume proposed by Hau, Killeen and Moore (2000 and 2002).

It is widely acknowledged that volumes decreased in the inter-bank spot FX market after EMU (see BIS, 2001). It also became increasingly accepted that the EUR/USD bid-ask spread widened at the same time. Hau et al. (2000 and 2002) suggested that lower FX trading volumes and wider bid-ask spreads observed since EMU, are both due to a decrease in “market transparency”. The latter hypothesis centers on the idea that the availability of fewer currency pairs after EMU makes risk management harder to implement. Hau et al. suggest that this causes market makers to quote wider bid-ask spreads, which in turn results in lower volumes.

One part of our argument has been made previously by Goodhart, Love, Payne and Rime (2002). They argued that “price granularity” could account for the observed fall in inter-dealer bid-ask spreads and that reduced volumes are a coincidence due to unrelated structural changes in the industry. What they call “price granularity” is more usually called “price discreteness” in the literature. Price discreteness means that prices are not an infinite number of digits long, but rather they are truncated to a small number of digits. In the case of the FX market, exchange rates are specified to five digit accuracy by convention. The Goodhart et al (2002) view was also echoed by Detken and Hartmann (2002) who used lower frequency data. We believe that Goodhart et al (2002) were broadly on the right track, but they did not uncover the full story. In addition, Goodhart et al (2002) only focused on the USD/DEM and EUR/USD exchange rates. We are able to analyze many more currency pairs over the period of EMU convergence.

The price clustering and time arguments that we present are new to this debate. Price clustering refers to the fact that traders may not use all available exchange rates uniformly. In practice, rates ending in 0 or 5 tend to be used more than other rates. The time elapsed between the sample periods is important for a very obvious reason - price levels can differ radically if data is sampled from periods that are far apart in time. On the other hand, the time-gap between successive individual prices is also important because it allows these prices to drift apart. When the successive prices are transaction prices, this effect increases volatility. When they are successive bid and ask prices, the bid-ask spread is increased. These new perspectives reveal that volumes and bid-ask spreads are not unrelated as Goodhart et al (2002) had argued, but are in fact inextricably interwoven. However, our arguments suggest the opposite causality to that proposed by Hau et al. (2000 and 2002). In short, we find that smaller volumes cause larger bid-ask spreads for technical reasons to do with measurement, whereas Hau et al. (2000 and 2002) had argued that larger bid-ask spreads had caused smaller volumes due to trader behavior.

The remainder of this paper is organized as follows. Section 2 discusses the importance of price discreteness and price clustering and reviews that literature. Section 3 similarly explores the role of time and duration. Section 4 reviews market structure and our unique dataset, while Section 5 discusses the empirical methodology. Section 6 presents the results and Section 7 concludes.

2. The Importance of Price Discreteness and Price Clustering

Prices move in discrete units. The exact size of these discrete units may be imposed by a regulator or an exchange, or it may arise as a market convention. Price discreteness is clearly important for bid-ask spreads because the minimum price increment, or "tick size", places a lower bound on the size of the bid-ask spread. It also determines volatility since it determines the minimum increment by which price can change.

Gottlieb and Kalay (1985) found that "…the variance and…the higher order moments of the rate of return of stocks are upward biased due to the discreteness of observed stock prices". Harris (1990) compounded the latter result by showing that discreteness induces negative serial correlation in high frequency data. Campbell, Lo and MacKinlay (1997, p.113) provide an insight into how this occurs by using a sequence of stock return plots with progressively finer scales to illustrate graphically how discreteness imposes structure on the sequence of returns. This effect is only evident at the highest data resolutions and is more pronounced for larger increment sizes. More recently, Osler (2003) found that discreteness in FX rates can contribute to excess kurtosis.

Until recently, price clustering studies on FX markets were rare and primarily used Reuters indicative quotes data. Goodhart and Curcio (1991) was the only widely cited paper. The main reason for the paucity of research is the lack of appropriate FX data, a situation which has recently begun to ease. Besides Goodhart et al (2002), Sopranzetti and Datar (2002) also examine price clustering in the FX market, using data from the Federal Reserve Bank of New York. Using Royal Bank of Scotland data, Osler (2003) found that the clustering of "stop loss" and "take profit" orders at certain price points explained why certain technical analysis forecasts have predictive power. However, none of these studies have the richness of data that the present paper offers. This is because we have been able to explore global inter-dealer electronic transactions, which are the largest source of trade volume in the spot foreign exchange market.

The vast bulk of previous research on price clustering focuses on the equity markets. The most notable contributions include Harris (1991), Christie and Schultz (1994), Christie, Harris and Schultz (1994), Kleidon and Willig (1995), Aitken, Brown, Buckland, Izan and Walter (1996), Grossman, Miller, Fischel, Cone and Ross (1997), Woodward (1998), Weston (2000), Kandel, Sarig and Wohl (2001) and Brown, Chua and Mitchell (2002). Additionally, some prior work focuses on futures markets, including papers by Ball, Torous and Tschoegl (1985), Brown, Laux and Schachter (1991), ap Gwilym, Clare and Thomas (1998a and 1998b) and ap Gwilym and Alibo (2003).

Over the past decade, most papers which address the subject of price clustering cite Christie and Schultz (1994). In the early 1990s, these researchers caused a stir with a price clustering study, when they suggested that widespread NASDAQ market makers avoidance of odd-eights quotes could amount to tacit collusion to maintain wider bid-ask spreads. As they put it themselves, "[they] are unable to envision any scenario in which 40 to 60 dealers who are competing for order flow would simultaneously and consistently avoid using odd-eighth quotes without an implicit agreement to post quotes only on the even price fractions", and they consider this evidence of an "…apparent lack of competitiveness of the NASDAQ market". This collusion hypothesis has gathered huge support, largely because the use of odd-eight quotes increased following the publication of their results and increased again after subsequent rule changes (see Christie et al, 1994).

Several competent and convincing rebuttals of the Christie and Schultz (1994) result have emerged since their paper was published. These include Kleidon and Willig (1995), Grossman et al (1997) and Woodward (1998). On the other hand, other sources like the US Securities and Exchange Commission (1996) and Weston (2000) seem to support the Christie and Schultz (1994) case. The debate is still open.

There are other plausible reasons, besides collusion, that could give rise to cluster patterns in price data. Yule (1927) observed that numerical clustering arose systematically from errors that people made when asked to read numbers from a scale. In the 1960s, a series of papers (Osborne, 1962; Niederhoffer, 1965; Niederhoffer, 1966; Niederhoffer and Osborne, 1966) began to explore the issue of clustering in the context of financial prices. Niederhoffer (1966) argued that price clustering could even be at odds with market efficiency. Niederhoffer and Osborne (1966) went on to specify profitable trading rules based on cluster frequencies.

Utilizing rules laid out by Harris (1991) for NYSE stocks when price increments of $1/8 were in place, Goodhart and Curcio (1991) compare "attraction" with "price resolution" as possible explanations of observed price clustering in the FX market, where the price increment is 1 and the full range of ten final digits is available. The attraction hypothesis focuses on the kind of rounding behavior that Yule (1927) identified. The price resolution hypothesis, put forward by Ball et al (1985), asserts that price clustering is a natural occurrence in a market which has reached "the optimal degree of price resolution". This arises from the trade-off between increased price accuracy on the one hand, and the inconvenience of longer prices on the other.

Aitken et al (1996) found evidence of attraction-type clustering in the Australian stock market. Kandel et al (2001) found the same effect in the Israeli IPO market. ap Gwilym et al (1998b) also find it for international bond futures. Ball et al (1985) not only proposed the price resolution hypothesis, but they also found evidence for it in the gold market. Goodhart and Curcio (1991) find evidence in favor of price resolution in their FX data and of attraction in their bid-ask spreads data. Harris' (1991) results for NYSE stocks are consistent with the price resolution hypothesis, and this is also supported by Grossman et al (1997) for a variety of global markets.

Harris (1991) and Brown et al (1991) both suggest another explanation for price clustering, namely the negotiation hypothesis. This suggests that there could be a two-tier price system, which would give the appearance of resolution-type price clustering when combined. The idea is that large trades result in harder bargaining and progressively more finely tuned trade prices, while small trades are transacted with cruder pricing from a reduced grid of prices.

Grossman et al (1997) demonstrate that price clustering is a both a common and a variable feature across global financial markets. These authors argued that, instead of NASDAQ being out of step with NYSE as Christie and Schultz (1994) had alleged, it is actually NYSE that is anomalous for its lack of price clustering compared with other markets. They go on to show that a wide variety of factors contribute to price clustering. Market structure can play a part. Also, whether the quotes are binding or not matters. Once again, these conclusions do not contradict the final-digit price clustering pattern associated with price resolution, but are attempts to explain why this occurs.

3. The Role of Time and Duration

Price levels can move substantially when there is a lengthy interval between the periods being studied. This is consistent with the idea of price being a random walk with drift, whereby drift components grow to different levels over time. The price level is an important factor in computing both the bid-ask spread and price volatility because both are calculated as a percentage of the price level. If price discreteness and clustering cause minimum bid-ask spreads or the price increments to be rigid, then a jump in the price level can account for observed changes in percentage bid-ask spreads and price innovations.

The other reason that time is important in the context of price volatility and bid-ask spreads relates to the non-synchronicity of quoted bid and ask price arrivals, and the closely related time-gap between successive transaction prices. These are very similar in spirit to the non-synchronous pricing effects described by Lo and MacKinlay (1999). This time-gap is often referred to as "duration" in the market microstructure literature. In essence, if the underlying price evolution process is a random walk with drift, the drift component will grow as the time-gap between trades grows. Hence the innovations in transaction price will appear larger, which makes volatility appear larger.

In the case of bid-ask spreads, it is tempting to assume that bid and ask prices are perfectly synchronous. This may be true of a quote driven market where bids and asks often come from the same market maker at the same time. However, in an electronic, order-driven market, like the electronic, inter-dealer, spot FX market studied here, the bid-ask spread is made up of the most competitive bid and ask limit order prices at every instant. When a more competitive price comes in on either side, the bid-ask spread is updated. It is also updated when a limit order price disappears through execution. Decreases in market volume slow the arrival rate for both new market orders and new limit orders. As a result, a decrease in market volume will increase the average time-gap between the arrival of the prevailing best limit-order bid and ask prices. We can define ask prices as being a mid-price plus a half-spread and bid prices as being a mid-price minus a half-spread. From this perspective, the increased time-gap expands the drift component of the mid-price, which drives up the observed bid-ask spread. This argument does not seem to have been considered previously in the literature as a potential explanation of wider post-EMU spot FX bid-ask spreads.

The arguments in the preceding paragraphs hinge on the underlying price evolution process being a random walk with drift. Meese and Rogoff (1983) made the definitive case for the random walk part of this argument. The conventional view is that the drift component is governed by differentials in international interest rates or longer term bond rates, in the form of the uncovered interest rate parity condition (UIP). This is explained by MacDonald (1999). Garber and Svensson (1995) survey a number of random walk with drift exchange rate models in the context of fixed exchange rate mechanisms. On the other hand, there is a vast empirical literature documenting the phenomenon of forward rate bias (see Engel (1996) for a survey). This says that UIP does not hold, which means that the forward rate is not an unbiased predictor of the future spot rate. If the forward rate does not act as a guide for the future spot rate, the possibility arises that the drift component might not actually exist. However, recent research papers by Mark (1995), Flood and Taylor (1996) and Froot and Ramadorai (2002) find evidence of a link between spot exchange rate changes and future interest rate differentials, but only over very long time horizons (e.g. 4 years). Nonetheless, this is evidence of a robust drift component.

4. Market Structure and Data

There is one further feature of the inter-dealer spot FX market that is important in the determination of volatility, bid-ask spreads and especially volumes. This is cross exchange rate arbitrage and the associated phenomenon of vehicle currencies. The best way to explain this feature is by example. Consider an exchange rate system with three currencies: A, B and C. This gives three exchange rates: A/B, A/C and B/C. Suppose an exogenous shock causes A/C to rise. If there is no change in the other two rates, a riskless arbitrage opportunity arises. Currency A could be used to buy currency B and then currency B could be used to but currency C. Here, B is being used as a vehicle currency. This would enable holders of currency A to buy currency C at the old (cheap) rate. At the same time, they could buy back currency A and sell currency C via the new (higher) exchange rate, A/C. Such trading would continue until supply and demand pressures lowered the rate A/C and/or raised the rates B/C and perhaps A/B, thereby extinguishing the riskless profit opportunity. This will transfer an exogenous shock affecting one exchange rate to other exchange rates. In reality, exogenous shocks are probably rooted in the currency itself and are merely reflected in the exchange rates to which that currency is a part. However, we can not be sure that vehicle currencies would be immune to such shocks. If they are not, the forces driving price volatility will be complicated enormously. The indirect exchange rate using vehicle currencies matters for the bid-ask spread because that the combined indirect (A/B + B/C) bid-ask spread could be lower than the direct (A/C) bid-ask spread. If that happens, volume will move away for A/C and into the cheaper A/B - B/C combination, possibly obliterating A/C as a directly traded currency pair on the inter-dealer market[1].

In 1998, the Bank of International Settlements estimated that the total volume of spot foreign exchange trading was worth almost US$1.5 trillion per day. After EMU, the total value of FX transactions fell. However, the FX market remains the largest financial market in the world, by many orders of magnitude. BIS (1998) and BIS (2001) both show that spot FX transactions account for a little under half of all trading activity in the FX market. In turn, inter-dealer trading accounts for about two-thirds of total global spot FX volume. Over the past decade, the importance of electronic trading venues in the inter-dealer market has risen sharply. BIS (2001) estimates that between 85% and 95% of inter-bank trading occurred over electronic trading systems in 2000. This compares with only 50% in 1998 (BIS (1998)).

Even these large volumes understate the importance of the electronic inter-dealer market. This is by far the most transparent part of the spot FX market and, as such, it sets mid-price exchange rates across the entire market. Figure 1 helps to illustrate this point. Transactions between FX banks and their customers are bilateral and are not visible to other banks. So, the other banks can not use the buy/sell information of this trade to update their prices. However, customer transactions give rise to inventory imbalances. The bid-ask spreads on the inter-dealer market are tiny compared with those that banks charge their customers. Banks can (and do) take on inventory from their customers and rapidly offload that inventory on the inter-dealer market at near mid-market rates. (see Lyons (2001) for greater detail on FX market structure.)

[1] Vehicle currencies and indirect trading are strictly a feature of the inter-dealer spot FX market, as the wider spreads quoted to banks' customers would preclude any arbitrage opportunities.

There are two electronic venues in the inter-dealer spot FX market, namely EBS and Reuters 2000-2. EBS is the global leader in foreign exchange broking and is dominant in the large currencies involving the USD, EUR and JPY. Reuters 2000-2 dominates the Commonwealth and Scandinavian currencies. Killeen, Lyons and Moore (2003) provide a detailed description of how the EBS market works.

EBS provided the data for the present study, and this dataset that has not previously been available to academic researchers. It contains spot FX quote and trade price data for eight currency pairs from the EBS electronic inter-dealer market. The quotes data comprises the best bid and ask quote prices per second (Greenwich Mean Time (GMT)). Trade data is also time-stamped to the nearest second (GMT). No information about the size of each transaction is provided. Also, there are no identifiers of the parties to each trade. The data consist of two separate sample periods with five exchange rates in each. The first covers the period 01/08/98 to 04/09/98 and consists of the currency pairs USD/DEM, USD/JPY, USD/CHF, DEM/JPY and DEM/CHF. The second covers 01/08/99 to 03/09/99 and contains data on EUR/USD, USD/JPY, USD/CHF, EUR/JPY and EUR/CHF. Each sample contains 20 days of per second observations. In this study, the EUR is taken to be the linear successor to the DEM on the grounds that, pre-EMU, the DEM was a pan-European vehicle currency (see Hartmann (1998)).

5. Empirical Methodology

The first part of the empirical analysis consists of a comprehensive table of summary statistics which provides evidence of exchange rate behavior, in terms of volume, volatility and bid-ask spreads. It also reveals the price discreteness properties of each rate and how the average time-gap between trades has changed. Subsequently, we consider whether changes in currency levels could have contributed to the observed changes. Deeper investigation of data characteristics involves comparing the traded volumes pre-EMU and post-EMU at successive bid-ask spread increments.

In the later analysis, focus shifts to the phenomenon of price clustering. The standard way to establish the presence of price clustering is to apply a χ^2 goodness-of-fit test statistic to the observed set of final digits. If clustering is absent, we would expect to see an equal number of observations at each available final digit which would give a χ^2 value of 0. In the spot FX data, rates can take on any final-digit integer value from 0 to 9. The formula for the χ^2 statistic in this case is:

$$\chi^2 = \sum_{i=1}^{10} \frac{\left(n_i - \frac{\sum_{j=1}^{10} n_j}{10} \right)^2}{\frac{\sum_{j=1}^{10} n_j}{10}} \qquad (1)$$

where
$n_{i(j)}$ = number of observations at final digit i(j)

The χ^2 critical value at the 1% significance level with 9 degrees of freedom is 21.7.

While the χ^2 statistic addresses the existence of price clustering, it does not evaluate or compare its level. Grossman et al (1997) proposed the standardized range (SR) as a measure of the level of clustering for comparison across different instruments. The formula for the standardized range is:

$$SR = (Max(\omega_i) - Min(\omega_i)) / x_i \qquad (2)$$

where
ω_i = percentage of observations at final digit i
Min( ) = minimum value of set
Max( ) = maximum value of set
x_i = percentage at each final digit i, if no clustering

The absence of clustering would lead to a value of zero for SR. For the ten final digit data range analyzed in the present study, 100% concentration would give an SR value of ten.

The χ^2 and SR tests address the existence of price clustering but reveal nothing about its cause. Our next sets of results reveal the price clustering patterns in traded and quoted prices. Goodhart and Curcio (1991) provide two ordered final digits groupings which align with the attraction hypothesis and the price resolution hypothesis respectively. For the attraction hypothesis, the following final-digits should occur in descending order of frequency: 0, 5, {7=3}, {8=2}, {4=6} and {1=9}. In other words, if the attraction hypothesis is correct, 0 and 5 should be the most frequent, followed by the pairs 7 and 3, 8 and 2, 4 and 6, and, in last place, 1 and 9. We compare the differences between these groupings with the differences within each group, thereby developing this expected ordering into a newly devised test statistic:

$$A = \frac{Min\left(\left(Av\left(\phi_{3,7}\right) - Av\left(\phi_{2,8}\right)\right), \left(Av\left(\phi_{2,8}\right) - Av\left(\phi_{4,6}\right)\right), \left(Av\left(\phi_{4,6}\right) - Av\left(\phi_{1,9}\right)\right)\right)}{Av\left(\left|\phi_3 - \phi_7\right|, \left|\phi_2 - \phi_8\right|, \left|\phi_4 - \phi_6\right|, \left|\phi_1 - \phi_9\right|\right)} \qquad (3)$$

where

ϕ_i = number of observations at final digit i

$\phi_{i,j}$ = set of numbers of observations at final digits i and j

$\text{Min}(\ )$ = minimum value of set

$\text{Av}(\ )$ = mean value of set

$|\ |$ = absolute value

An "if" condition statement is used to check whether 0 and 5 are the two most frequent final digits in equation (5)[2]. If they are not, then the pattern does not conform to the conventional forms being tested and the test value is set to zero. Otherwise, the numerator of equation (5) takes the average of the observations for each sequential pair and then detects the minimum difference between each of these averaged pairs. The denominator calculates the average of the absolute difference within each ordered pair. The smallest difference between the pairs is divided by the average difference within the pairs. Note that the denominator will always be non-negative, so that a negative number on the numerator can never be made positive by the denominator. An attraction test score of greater than 1 denotes strong evidence in favor of the attraction hypothesis, for it shows that, not only are the sets of numbers of observations in the required order, but the difference between the set means dominates the internal differences within each set. To put it another way, the magnitude of the statistic measures the degree to which the between groups difference dominates the within group difference. Positive values below 1 also

[2] In the original Goodhart and Curcio (1991) specification, 0 was required to be strictly greater than 5. We relax this requirement, but still require that 0 and 5 both be greater than the other final digit numbers.

identify series with the appropriate rank ordering but differences within at least one of the groupings dominates the difference between the groups. Non-positive values denote that the set means do not exhibit the ordering required by the hypothesis. In other words, non-positive test values reject the hypothesis , while positive values show increasing levels of acceptance.

The second hypothesis we consider is the price resolution hypothesis. Once again, Goodhart and Curcio (1991) provide an ordered set of final digits groupings. In descending order the resolution hypothesis groupings are: 0, 5, {2=3=7=8} and {1=4=6=9}. Again, we develop a new test statistic from their expected ordering:

$$R = \frac{Av\left(\phi_{2,3,7,8}\right) - Av\left(\phi_{1,4,6,9}\right)}{Max\left(Max\left(\phi_{2,3,7,8}\right) - Min\left(\phi_{2,3,7,8}\right), Max\left(\phi_{1,4,6,9}\right) - Min\left(\phi_{1,4,6,9}\right)\right)} \quad (4)$$

where

ϕ_i = number of observations at i

$\phi_{i.j,k,l}$ = set of numbers of observations at final digits i, j, k and l

Min( ) = minimum value of set

Max( ) = maximum value of set

Av( ) = mean value of set

Like equation (5), equation (6) depends on 0 and 5 being the two most frequent end digits. The numerator of equation (6) subtracts the average of the set that should have the lower rank from the higher ranked set. The denominator computes the largest deviation between values within each of the two sets and selects the larger one. As with the previous test, the denominator will always be non-negative, so it can never offset a negative numerator. As with the attraction test, a price resolution test statistic greater than 1 denotes strong evidence in favor of the resolution hypothesis. Positive values below 1 suggest the right ordering but a weak fit. Once again, non-positive test values show that the hypothesis is rejected, while a positive number shows acceptance. The higher the value, the better is the fit.

6. Empirical Results

6.1 Price Granularity, Bid-Ask Spreads, Volume and Volatility

Tables 1, 2, and 4 present the summary statistics for the spot FX data from EBS. These table presents a series of variables that were used by Goodhart et al (2002) to evaluate 'price granularity' as a source of wider bid-ask spreads in the EUR/USD compared with the USD/DEM, using data from Reuters 2000-2. Price granularity is the same concept as price discreteness. As in Goodhart et al (2002), we compute series for percentage bid-ask spreads and for 'pip' bid-ask spreads.[3] Our computation method differs from Goodhart et al (2002) in some minor respects. First, we use the occurrence of a trade to define points in time which are of interest. Then we compute the prevailing bid-ask spread at the time of that trade by selecting the most recently preceding bid and ask prices, but only where these are less than 1 minute old.[4] Trades that do not have both bid and ask value less than one minute old are excluded. In tables 1 and 2, we emulate Goodhart et al's (2002) practice of restricting datasets to between 06:00 and 16:00 GMT. Statistics derived from the full 24-hour day are presented in tables 3 and 4. All tables tell the same broad story.

The pip bid-ask spread is defined as:

$$\text{pip} = (\text{ask} - \text{bid}) * \text{scaling factor} \quad (5)$$

The percentage bid-ask spread formula is:

$$\%\ \text{bid-ask spread} = 100 * (\text{ask} - \text{bid}) / \text{traded price} \quad (6)$$

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[3] The term 'pip' is commonly used in the foreign exchange market in place of the word 'tick'. It may be worth acknowledging the distinction that pips arise as a matter of convention, whereas ticks are formally enforced, usually by an exchange. However, in the present paper we use the two terms inter-changeably. A pip usually refers to the incremental value in the fifth non-zero digit position from the left. Note that it is not related to the position of the decimal point. For example, one pip in a USD/JPY value of 113.57 would be 0.01, while one pip for EUR/USD of 1.0434 would be 0.0001. The fact that the decimal place does not occupy a fixed position necessitates the introduction of a 'scaling factor' with the purpose of bringing the pip to the left of the decimal point. For example, the scaling factor for the USD/JPY is 100 and that for the EUR/USD is 10,000.

[4] Huang and Stoll (1997) discuss using a 2 minute interval, although they ultimately use an alternative method. Since our volume far exceeds that in their data in every case, we decided a shorter interval would be appropriate. However, the choice of 1 minute is essentially arbitrary.

Goodhart et al (2002) chose to remove non-positive bid-ask spreads "which primarily represent the matching of market orders on the Reuters 2000-2 system". However, for the tables we present here, we adopt the view that, in an order-driven regime, zero-spreads are neither erroneous nor irrelevant.[5] Zero-spreads comprise between 20% and 50% of observed spreads in our data, depending on exchange rate and sample period (see table 5). The proportion of zero spreads is clearly higher in the higher volume period and clearly higher for the more heavily traded currency pairs. This is consistent with the prediction of Cohen, Maier, Schwartz and Whitcomb (1981) that, in the absence of exogenous market order transactions costs, the bid-ask spread should collapse to zero as volume increases in an order driven market such as the spot FX inter-dealer market.

Goodhart et al (2002) computed nine summary statistics, encompassing both the unadjusted and time-weighted average bid-ask spreads, which we follow here. The summary statistics are: average bid-ask spread in basis points (AS), time weighted average bid-ask spread in basis points (TWAS), average bid-ask spread in pips (ASPIP), time weighted average bid-ask spread in pips (TWASPIP), total number of trades (TRAD), absolute imbalance between number of buy trades and number of sell trades (ABIM), return volatility over 5-minute intervals (VOLAT) which uses the method outlined by Andersen, Bollerslev, Diebold and Labys (2001), the standard deviation of the bid-ask spread in basis points (STDSP), and the standard deviation of the bid-ask spread in pips (STDSPPIP). For TWAS and TWASPIP, each bid-ask spread is weighted by the amount of time that it persists in the market. Time weighting should give a truer measure of the bid-ask spread facing traders, as it increases the weight of long-lived spreads and decreases the weight of short-lived ones. Finally, we include an additional row to our table to show the average time-gap (ATG) in seconds between successive trades, in order to compare how these have changed between the two sample periods.

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[5] The general arguments for removing bid-ask spreads of zero are that they are due to synchronicity problems, mismatches in bilateral credit or that they arise from automatic electronic order matching between dealers. None of these arguments suggest that these data are corrupt or misrecorded. Also, there is no reason to believe that non-zero spreads are unaffected from the first two influences. Table 5 shows that zero spreads represent a significant proportion of trades. We believe it inappropriate to simply exclude so much data as though these trades never occurred. We believe that it is unlikely that the true prevailing spreads for these trades are very far away from zero. Therefore, assuming that the range of other (i.e. non-zero) spread levels are wholly representative seems more wrong than permitting zero spreads, especially for an intertemporal comparison where the proportion of zero spreads is not constant (as table 5 shows).

A number of differences compared with Goodhart et al's (2002) findings should be noted. Our bid-ask spreads are narrower than those reported by Goodhart et al (2002). Excluding the non-zero spreads in our data remedies much of this difference. However, the percentage changes we see in bid-ask spreads between 1998 and 1999 give the same overall story in our data for all exchange rates when zero spreads are included or excluded. Comparison of the changes in the EUR/USD with the USD/DEM reveals a marked increase in average percentage bid-ask spread but only a very slight increase in average pip bid-ask spread. This is consistent with Goodhart et al (2002). In addition, both studies also reveal a large decrease in volume, as approximated by the average number of trades (TRAD) and a large decrease in absolute order flow (ABIM). Goodhart et al (2002) conclude that the "price granularity" resulting from rigid "pip" bid-ask spread quoting practices combined with the re-denomination of the currency pair, is responsible for the sharp increase in the bid-ask spread for EUR(DEM)/USD. Our results broadly support this conclusion.

The evolution of EUR(DEM)/USD volatility is a lot less clear. In contrast to Goodhart et al (2002), who found that EUR(DEM)/USD volatility increased by 22%, we find that volatility for all currency pairs has actually fallen since EMU. This finding also conflicts with the majority of other studies, including Hau et al (2000, 2002), Galati and Tsataronis (2001), and BIS (2001). Two likely contributory factors are that our samples come from different time periods and that our data source, EBS, is dominant in the EUR(DEM)/USD inter-dealer market in contrast to their Reuters 2000-2 data which has only a minor role in this particular market. The TRAD results also suggest that Reuters 2000-2 lost significant market share to EBS after EMU.

More generally, tables 1 and 2 clearly show that bid-ask spreads have not widened across the board, despite a widespread fall in volumes. Volume (TRAD) is significantly lower for all exchange rates, except USD/CHF which rose by a steep 59%. It is interesting to note also that absolute order flow (ABIM) fell drastically everywhere, except for the USD/CHF. The USD/CHF bid-ask spread might have been expected to remain unperturbed by EMU, since it was not re-denominated. However, the average bid-ask spread in pips (ASPIP) shows a sharp fall of 26%. This is closely reflected in the percentage bid-ask spread (AS) decreasing by 27%. The average time-gap between trades reduced by 38% after EMU. This throws suspicion on a larger drift component as the culprit for higher bid-ask spreads.

We believe that the alternative explanation of market makers widening bid-ask spreads in the face of lower volume, proposed by Hau et al. (2002), is not credible because we perceive no evidence to support the idea that any participants in the electronic inter-dealer spot FX market are acting as conventional market makers. Indeed, only the largest banks would have the capital required to provide such a service and they are precisely the ones who could get a better return on it by providing a market making service to their (bigger spread paying) customers.

One striking finding in Tables 1 and 2 is that the average percentage bid-ask spread for USD/JPY increased by more than a quarter after EMU, but the average pip bid-ask spread exhibited no change at all.

Volatility is lower across the board after EMU. The fact that the changes in volatility for USD/JPY and for USD/CHF do not mirror the changes in their bid-ask spreads indicates that other factors play a determining role. While it is true that volatility is comprised of the incremental move between successive prices, it must be remembered that the continuity or reversal rates of successive increments over the series also play a major part in forming the volatility value. In addition, cross exchange rates mean that each rate is not free to react unfettered to the forces acting upon it. In addition, we must recognize that a non-zero bid-ask spread can exist over periods where price does not move. Such a period will provide very different results for bid-ask spreads and price volatility. Similarly, bid-ask spreads may be stable over periods of substantial price moves.

The fall in EUR(DEM)/JPY volume since EMU could be attributed to a change in vehicle currency behavior. The DEM/JPY might have been seen as a viable currency pair for direct trading, while the subsequent EUR/JPY may be considered less cost effective. Instead, the USD may be being used as a vehicle in the latter case, i.e. a combination of EUR/USD and USD/JPY may be used in place of direct EUR/JPY trades. However, the puzzling picture that emerges from these tables is that for both of these currency pairs, indirect trading via the USD was more cost effective than direct trading. However, the saving on indirect trading over direct for the EUR/JPY was twice that for the DEM/JPY. By contrast, the rise in USD/CHF volume closely mimics the fall in EUR/CHF volume. If this is caused by vehicle currency activity, then the USD appears to have taken over much of the vehicle role previously played by the DEM in CHF trades, i.e. third party currencies now appear to be converted into USD and then to CHF, whereas previously the DEM had been the intermediate currency.

6.2 The Effect of Quoting Practices

There are two obvious potential sources of difference between EUR/USD and USD/DEM: unit change and inversion. EUR units are almost twice the size of DEM units and the quoting conventions for these two exchange rates are the inverse of each other, i.e. the new rate is "EUR/USD" whereas if the format of "USD/DEM" had been preserved, it would have been "USD/EUR". In order to explore the respective effects of re-denomination and inversion, independent of exchange rate fluctuations, we need to control specifically for intertemporal fluctuation in currency level, which is the purpose of Table 6. In this table, the observed minimum price increment is divided by the concurrent average exchange rate (over each of the two 20 day sample periods). This gives the percentage value of the minimum tick for each currency pair for each sample period. However, simply comparing pre-EMU data with post-EMU data masks the denominational (minimum tick size) change, as well as any change in price level. In order to separate out these changes, we first compute the 1999 EUR average exchange rates and percentage bid-ask spread values. We then convert the 1999 EUR rates to DEM at the official European Central Bank (ECB) fixed conversion rate of 1.95583. The result is a set of DEM exchange rates that have no drift in value compared to the EUR rates. For EUR/JPY and EUR/CHF, we divide the average EUR rate by 1.95583. In the case of the EUR/USD, we divide 1.95583 by the rate to reverse the inversion. We divide the minimum tick size observed in 1998 and 1999, by their "constant price" 1999 exchange rates expressed in DEM and EUR respectively. The percentage difference between the actual DEM exchange rates and the "constant price" exchange rates is the percentage change in currency value.

The results presented in Table 6 show the percentage change in the currency value between the sample periods. Panel A shows that, for the EUR(DEM)/CHF and EUR(DEM)/JPY, re-denomination of these rates from DEM to EUR increased the minimum bid-ask spread by a mere 2%, when exchange rate fluctuations are removed. If the USD/DEM had been quoted inversely, i.e. as DEM/USD, whereby the constant price average FX rate would have been 0.54260 rather than 1.8430, and if traders had only used final-digits 0 and 5 in the fifth digit position, this re-denomination change would also have been 2%. However, the USD/DEM was quoted as USD/DEM and the isolated impact of re-denomination on the inverted exchange rate is a startling 74% increase in the bid-ask spread. The change in currency value has a minor offsetting affect, as it tempers the increase to 67%. This vindicates Goodhart et al's (2002) conclusion that the change in price discreteness was the principal cause of the observed rise in EUR/USD bid-ask spreads after EMU. However, it establishes that it was the inversion in the way the rate was quoted which increased the bid-ask spread, rather than simply the redenomination.

Panel B of Table 6 acts as a control. The same procedure applied to the non-EUR(DEM) based currency pairs shows that the percentage value of their one-tick-spread is unchanged in 1999 compared with 1998, in spite of big changes in trading volumes and the market environment. However, the 21% fall in value for the USD/JPY between the two sample periods comfortably explains the 26% rise in the average bid-ask spread noted above. The fact that the USD/JPY pip bid-ask spread is completely unmoved by such a large change in exchange rate suggests that the size and use of pip bid-ask spreads are probably quite rigid. The time difference between the two sample periods means that we are looking at two very different price levels for USD/JPY.

Goodhart et al (2002) consider whether the market practice relating to pip quoting could have been changed to add a decimal place and so facilitate a reduction in bid-ask spreads, i.e. traders could use 6 rather than 5 significant digits. They conclude that this could have introduced complications as other researchers found that trade size and market depth fell when policy induced smaller tick sizes were imposed (e.g. Jones and Lipson, 2001; Goldstein and Kavajecz, 2000). However, Goodhart et al (2002) only considered the case of using a full range of 10 final digits in an additional decimal place. As is evident for DEM/JPY and DEM/CHF in Panel A of Table 6, the spot FX market has used half-points in the past. The introduction of a half-point (0 and 5 only in the sixth decimal place) could have dissipated the increase in bid-ask spreads without introducing the complications outlined by Goodhart et al (2002).

The reason that this half-point option for the EUR was not applied is probably due to the spot FX market convention of having prices that consist of 5 significant digits. USD/JPY, which has three digits to the left of the decimal point, is quoted to two decimal places. DEM/CHF had zero to the left of the decimal point and so could have five decimal places. The half-points that were observed for DEM/JPY and DEM/CHF were in the fifth digit position. The half-point option for the EUR/USD would entail the use of a sixth significant digit. However, if this path had been taken, the percentage one-tick bid-ask spread would have been 13% lower for EUR/USD compared with USD/DEM, according to our constant prices methodology. This is in stark contrast to the 74% increase actually recorded.

6.3 Traded Volume at Successive Bid-Ask Spread Levels

In the next part of the analysis, the pre-EMU DEM exchange rates and bid-ask spreads are compared with the post-EMU EUR figures. It is quite common in the literature to compare the legacy DEM with the successor EUR because the DEM was acting as a pan-European vehicle currency prior to currency convergence. This means that a transaction from outside Europe coming in to a non-DEM European currency would first be converted into DEM and then into the local currency.[6] The upshot of this is that the currency flows associated with DEM were much greater than could be explained by trade and investment alone. Hence, this provides the justification for comparing the DEM directly to the EUR. Alongside the DEM-EUR rate comparisons are two rates which were not re-denominated during the move from pre-EMU to post-EMU regimes. These are USD/JPY and USD/CHF. We then analyze the percentage of trading volumes at each different bid-ask spread level (measured in ticks) for all currencies. This reveals the distribution of trading at successively higher bid-ask spread levels in each of our two sample periods.

[6] For example, an amount of JPY to be converted into FRF would first use DEM/JPY and then DEM/FRF. This path would be used because DEM/JPY and DEM/FRF were both very liquid, whereas FRF/JPY was not. While a bank's customer would engage in a direct FRF/JPY trade with the bank, the vehicle currency behavior described relates to what happens in the inter-dealer market when the bank converts the inventory arising from that transaction back to the optimal holdings it held prior to the trade (see Hartmann (1999) for an in-depth discussion of vehicle currencies).

Table 7 reveals the percentage volume at each bid-ask spread level (in ticks). The 1999 data is shown beneath that from 1998. The widest bid-ask spread shown, 6+ ticks, is a catch-all category containing not only the observations at 6 ticks but also all those observed at tick values greater than 6. The table is calibrated in half-ticks. For the USD/JPY, USD/CHF, EUR(DEM)/USD, EUR/JPY and EUR/CHF, half-ticks do not exist and the cells are blank for these rates. However, the half-tick categorization has relevance for the DEM/CHF and the DEM/JPY. These pre-EMU exchange rates were quoted to 5 significant digits, like the others, but they only ever used 0 and 5 in the final digit position in the data analyzed in this study. In addition, recognizable price cluster patterns can be discerned in their penultimate digits, i.e. in their fourth significant digit positions. None of the other exchange rates exhibit a recognizable price cluster pattern in their penultimate digit positions. The half-tick category is introduced as a device to facilitate the analysis of DEM/CHF and DEM/JPY price clustering behavior.

It is clear from Table 8, that in spite of the fact that the mean USD/JPY bid-ask spread has not changed, the mode has changed. Most trades in this currency pair now execute at a bid-ask spread of 1 pip, whereas pre-EMU, most trades were done at a bid-ask spread of zero pips. Table 7 also shows a greater concentration of USD/CHF trading activity in the first three ticks. After EMU, 85% of trading in this currency pair takes place within 3 ticks, as opposed to 72% before EMU. The EUR(DEM)/USD shows another shift in the mode from zero to one pip. Pre-EMU, 47% of EUR(DEM)/USD trades were executed at a zero bid-ask spread compared with post-EMU, when 49% of trades coincided with a one pip bid-ask spread. There is also a very clear fall-off in volumes occurring at spreads with a tick-size greater than 2. However, this understates the shift because EUR/USD tick units are 74% larger in value terms that USD/DEM tick units. As such, it would be more appropriate to compare each EUR/USD tick with every 2 USD/DEM ticks. On that scale, the increased volume at 2 EUR/USD ticks compared with the combined volume at 3 and 4 USD/DEM ticks is stark. This suggests that there are more observations at higher (adjusted) pip bid-ask spread levels after EMU, which could be due to larger time-gaps and increased drift between bid and ask prices.

DEM/JPY and DEM/CHF both show clear usage of half-points which arise because they only used 0 and 5 in the fifth-digit position. The successor EUR/JPY and EUR/CHF rates are denominated such that a full 0 to 9 range of final digits is used. It is clear that DEM/CHF made greater use of this half-point than did DEM/JPY. Like the EUR(DEM)/USD, the values of the EUR(DEM)/JPY and EUR(DEM)/CHF ticks are not equivalent. In value terms, 1 EUR/JPY (EUR/CHF) tick equals 98% of the DEM/JPY (DEM/CHF) half-point, i.e. two EUR/JPY (EUR/CHF) ticks is approximately equal to one DEM/JPY (DEM/CHF) tick. By that comparison, the startling increase in volume that seems to occur at higher tick levels in the EUR/JPY compared with the DEM/JPY is tempered. However, EUR/JPY volumes at higher tick (value) levels are still sharply higher, revealing that the composition of the EUR/JPY bid-ask spread increase is very different from that of the EUR/USD and also different from the smaller increase in the USD/JPY. A pattern that could be consistent with half-point avoidance behavior in the DEM/JPY also seems to apply to the EUR/JPY. Even after allowing for economic value, the shift in mode from 0 for DEM/CHF to 1 for EUR/CHF is stark. The narrowing of the bid-ask spread for this exchange rate arises from the sharp fall in the usage of high value spread levels in the post-EMU period. In other words, there is very little volume at above three EUR/CHF tick spreads, compared with what had existed above the one and a half DEM/CHF point level. Once again, this is evidence that larger time-gaps allow the drift component to expand and push the bid and ask prices apart.

6.4 Price Clustering

Changes in the patterns of price clustering may shed further light on why bid-ask spreads have evolved the way they have. Our attention now turns to these. All currency pairs analyzed in this study consist of 5 significant digits throughout, as is the convention in the spot foreign exchange market. In the second sample period, all rates use the full final digit range of 0 to 9. As noted above, in the first sample period, DEM/JPY and DEM/CHF, only use 0 and 5 in the final digit position. This makes it difficult to apply the Goodhart and Curcio (1991) price clustering pattern tests to all currency pairs and sample periods. However, we found that DEM/JPY and DEM/CHF exhibited visually discernible price clustering in their penultimate digits, so, we apply these tests to the fourth digit patterns in these special cases.

Tables 8 to 10 present summary statistics relating to the price clustering features of these data. In these tables, Panel A is formed using traded price data, while Panel B uses quoted price data from submitted limit orders. Table 8 shows the final digit usage of DEM/JPY and DEM/CHF, and demonstrates that both currency pairs did not use the final-digit 5 very much, but the DEM/JPY used it less than DEM/CHF. Table 9 presents the odd versus even number usage among full price points in spot FX markets. There is persistent evidence that even numbers are weakly preferred to odd numbers. Table 10 presents the chi-squared tests for the presence of price clustering in the spot FX market. In each case, the χ^2 statistics emphatically reject the absence of clustering, and this is consistent across both the trades and quotes data.

In Table 11, the standardized range measure uncovers pronounced price clustering in spot FX rates. The level of price clustering seems to have fallen post-EMU, in both trade and quote data, for currency pairs using the USD, compared with those using the EUR(DEM). The USD rates are the only ones for which a direct comparison is truly meaningful. The fall in USD clustering may be linked to vehicle currency status, since the volumes detailed in both CHF and JPY suggest there has been a shift in spot FX volume from DEM to USD rather than to EUR. Although USD/JPY volume has fallen, EUR/JPY volume has fallen even more. This may suggest that the USD/JPY's role as international vehicle currency for the JPY has been strengthened, at the expense of the EUR/JPY.

Tables 12 and 13 reveal the precise frequency of final digit usage for the spot FX trade price and quoted price data. The detailed breakdown of the USD/JPY data shows that the dominance by final digits of 0 and 5 over the rest of the numbers has declined since EMU. USD/CHF experienced a similar post-EMU decline in the dominance by these final digits. This should decrease bid-ask spreads and price volatility for these exchange rates. For EUR/USD, the decrease in the use of final digits of 0 and 5 counteracts the 74% increase in economic value of the minimum tick size, tempering the effect of the latter on the average bid-ask spread.

EUR/JPY exhibits an increase in the dominance of final digits of 0 and 5, and a more pronounced cluster pattern than its predecessor. It must be remembered that EUR/JPY price clustering is in the fifth significant digit position, compared with the fourth digit position for DEM/JPY. DEM/JPY had half-points and made very little use of them. The economic value of those half points is 98% of the EUR/JPY full point. In this context, EUR/JPY's comparatively full usage of the entire range of final digits is important, as it reveals an almost 50% drop in the pricing increment actually used, implying narrower bid-ask spreads and lower volatility. It is thus surprising that Table 1 showed that EUR/JPY bid-ask spreads are actually 54% higher than those for DEM/JPY. Table 2 revealed an even steeper hike of 58%. However, the very high volumes recorded at EUR/JPY rates ending in 0 and 5 pull in the other direction and are consistent with the larger observed average spreads. These may be sufficient to offset the fuller tick usage. The fuller usage of the final digit range in EUR/JPY would also lead one to expect that volatility would be lower than for the DEM/JPY. Tables 1, 2, 3 and 4 show that volatility is weakly lower.

The price clustering evidence in Tables 12 and 13 for EUR(DEM)/CHF is weaker in both sample periods than for the other currency pairs. However, as with EUR(DEM)/JPY, we need to consider the under-utilized half-point of the DEM/CHF. Like the DEM/JPY, the comparatively full usage of similarly valued EUR/CHF tick units points an almost 50% drop in the value of the pricing increment actually used. However, in this case, the very similar price cluster distribution patterns of the DEM/CHF and the EUR/CHF suggest that this price drop is not offset by very different practical usage of the new pricing increments. The unfettered lower pricing increment points to narrower bid-ask spreads and lower volatility, which were both clearly evident in Tables 1 and 2.

In terms of our formal test for the cause of price clustering, the attraction hypothesis was completely rejected for all rates and sample periods (i.e. all test statistic values were zero) and therefore these results are not presented here. Table 14 presents results for our price resolution hypothesis test statistic. Here, the results fit the final digit usage pattern in the spot FX data. This is evident in both the trade and quotes data. Table 14 reveals that resolution type price clustering has decreased since EMU, except for EUR/JPY which has increased. In particular, EUR(DEM)/USD price clustering has fallen by almost two-thirds. In the case of the EUR/CHF, the apparent 54% fall in resolution type price clustering represents a decrease in a series that exhibited weak resolution characteristics to begin with. The remaining results support the findings from the standardized range.

7. Conclusions

This article set out to document and explain the changes in bid-ask spreads and in volatility in five currency-pairs between pre-EMU and post-EMU periods. The data used shows that volatility fell for all exchange rates, while some bid-ask spreads widened and others narrowed. Four distinct potential explanatory market microstructure factors for these changes were explicitly considered: price discreteness; price clustering; the inter-temporal shift in currency value; and the time-gap between successive observations. The four proposed factors are successful in explaining the observed changes in bid-ask spreads, but are less able to explain the observed changes in price volatility. The combination and influence of each of these four factors varies from exchange rate to exchange rate. In characterizing the source of price clustering behavior in the spot FX market, our results overwhelmingly affirm the price resolution hypothesis explanation and firmly reject the price attraction hypothesis. Our price clustering analysis makes use of new test statistics which we propose to capture behaviors described by Goodhart and Curcio (1991).

In the specific case of the EUR(DEM)/USD bid-ask spread, we broadly concur with the price granularity (price discreteness) hypothesis of Goodhart et al (2002) which asserts that redenomination is the most likely cause of an increase in the spread for this exchange rate. We proceed to show that rigid market quoting practices are critical in this. The switch from USD/DEM to EUR/USD quoting practice caused a 74% increase in the one-tick EUR(DEM)/USD bid-ask spread. If the market had been willing to embrace an additional half point price increment by using 0 and 5 in the sixth digit position, the one-pip EUR/USD bid-ask spread would have been 13% lower than for USD/DEM. The fall observed in EUR/USD price clustering had a dissipating effect on this. So too, did the inter-temporal shift in currency value. On the other hand, the increase in the time-gap between prevailing bid and ask prices exacerbated the rise. However, as we demonstrated above, it was the inversion of this quoting format (i.e. using EUR/USD rather than USD/EUR) that was primarily responsible for this bid-ask spread increase.

The widening of the USD/JPY bid-ask spread seems primarily due to the sharp inter-temporal change in currency value. Price discreteness can explain no part of this change because there was no re-denomination of the USD/JPY from pre-EMU to post-EMU periods. Like the EUR(DEM)/USD, the fall in price clustering should have had a dampening effect on the bid-ask spread. On the other hand, the increased time-gap between bid and ask prices should contribute to the widening of post-EMU spreads. Finally, wider EUR/JPY and EUR/USD bid-ask spreads preclude any possibility that the EUR could act as a vehicle for currency flows between USD and JPY. This means, at the very least, that the threat of indirect trading which previously may have inhibited the widening of the direct USD/JPY bid-ask spread became a less potent influence post-EMU.

The narrowing of EUR(DEM)/CHF bid-ask spreads seems largely due a near 50% decrease in the pricing increment used. Although there is almost no change in the economic value of the usable minimum tick size, implying no change in price discreteness, the price clustering patterns show that the pre-EMU half-points were rarely used in practice. The data show that whole numbers were mainly used and that the price increment used in practice was actually two pips. By contrast, in the post-EMU, EUR denominated world, traders used one pip increments, effectively halving the bid-ask spread. Exchange rate value levels and price clustering patterns over the range of whole numbers were little changed. The large increase in the time-gap will have tempered the narrowing of this bid-ask spread. This explanations tells us that the bid-ask spread change is due to a change in trader behavior but it does not tell us why this change occurred. The rejection of the attraction hypothesis for price clustering suggests that human fondness for round numbers is not a satisfactory explanation. A more plausible reason may be increased competition from USD/CHF. The trend-bucking increase in USD/CHF trade volume closely matches the volume lost by EUR/CHF. If it is the case that USD/CHF has taken over much of the international vehicle currency role of the DEM/CHF, the EUR/CHF could face even more loss of volume if its prices are uncompetitive.

Increased volume reduced the time-gap for traded and quoted prices for USD/CHF. Since there is no change in price discreteness and very little change in the currency value level, it appears that the change in the time-gap is the leading contender to explain the narrower bid-ask spreads evident in this exchange rate. The price clustering data also reveals a spread-reducing influence in that it shows less use of extreme 0 and 5 final digit values. It seems plausible that reduced price clustering reflects more accurate pricing behavior in response to increased USD/CHF volume and to the development of a competitive scenario with EUR/CHF. Note that this is the only exchange rate where we find any evidence supporting the Hau et al (2000 and 2002) assertion that volume changes drive bid-ask spread changes. However, even then, the direction of the volume impetus and the specific exchange rate remain different. Our analysis suggests that higher volume lead to lower bid-ask spreads for USD/JPY, whereas they concluded that lower volume led to higher bid-ask spreads in EUR/USD. In addition, our argument also relies on a competitive vehicle currency scenario.

The fact that CHF/JPY was never a liquid currency pair in the inter-dealer market combined with the fact that the CHF has never been considered as a credible international vehicle currency implies that indirect exchange rates are not a significant determinant of either EUR/CHF or USD/CHF bid-ask spread changes.

Reconciliation of the evidence on the EUR(DEM)/JPY bid-ask spread is perhaps the most complicated. This spread widened by 58% in the period studied. The value of this exchange rate dropped by 24%, which should indeed lead to a wider bid-ask spread, if the minimum tick change remained unchanged. The value of the minimum tick size did indeed remain almost totally unchanged because the increase in currency unit size from DEM to EUR is almost exactly offset by the decrease in economic value of the minimum pip increment in use post-EMU. This means that the change in exchange rate level between the two sample periods accounts for around half of the observed bid-ask spread increase. An increase in the time-gap and price clustering behavior also contribute to the widening of this bid-ask spread, the size of which more than doubled in pip terms after EMU. The time-gap between successive prices almost triples after EMU, which should also widen bid-ask spreads, due to drift. In addition, the price clustering data reveal that extreme 0 and 5 final digit prices are much more pronounced after EMU, suggesting that the market's quoting practice results in wider bid-ask spreads. We must consider why market practice should have changed in this way. One possible reason is that the EUR/JPY may have lost considerable ground to the USD/JPY as an international vehicle currency. The respective bid-ask spread levels clearly show that there is a substantial saving to be made after EMU by trading EUR/JPY indirectly, using the USD as a vehicle. This provides the economic grounds for indirect trading to flourish. In addition, the steeper decline in EUR/JPY trading volume compared with USD/JPY, suggests that a shift from direct to indirect trading has taken place.

This evidence of increased indirect trading from EUR/JPY and the two CHF rates leads to the startling conclusion that the advent of EMU seems to have strengthened the USD's position as the dominant international vehicle currency. Part of the intention in launching the single European currency must surely have been the opposite.

The ubiquitous fall in volatility that we observe is more puzzling, not least because it differs so much from other researchers' observations. We conclude that volatility in FX markets is intrinsically a more complicated phenomenon than bid-ask spreads. Volatility may be influenced by information coming to the market at specific times and by temporary imbalances between supply and demand which may differ greatly between data samples. Furthermore, cross currency arbitrage could dissipate across the market what should be localized shocks. Such issues are beyond the scope of this paper and remain for future research.

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Key for Tables 1, 2, 3 and 4

AS: average bid-ask spread in basis points

TWAS: time weighted average bid-ask spread in basis points

ASPIP: average bid-ask spread in pips

TWASPIP: time weighted average bid-ask spread in pips

TRAD: total number of trades (volume)

ABIM: absolute imbalance between number of buy trades and number of sell trades

VOLAT: return volatility over 5-minute intervals

STDSP: the standard deviation of the bid-ask spread in basis points

STDSPPIP: standard deviation of the bid-ask spread in pips

ATG: average time-gap in seconds

Table 1: Summary statistics (Hourly data, 10 hour day)

Hourly Average	USD/JPY 98	USD/JPY 99	USD/JPY %Δ	USD/CHF 98	USD/CHF 99	USD/CHF %Δ	EUR(DEM)/USD 98	EUR(DEM)/USD 99	EUR(DEM)/USD %Δ
AS	0.72(0.1513)	0.91(0.1689)	26%	1.58(0.456)	1.15(0.2646)	-27%	0.42(0.0964)	0.66(0.081)	57%
TWAS	0.81(0.2363)	0.92(0.2304)	14%	1.75(0.6984)	1.24(0.4316)	-29%	0.41(0.107)	0.65(0.1099)	59%
ASPIP	1.03(0.2082)	1.03(0.1833)	0%	2.35(0.6651)	1.73(0.4003)	-26%	0.75(0.1678)	0.69(0.0847)	-8%
TWASPIP	1.16(0.3281)	1.04(0.2549)	-10%	2.59(1.0205)	1.87(0.6546)	-28%	0.73(0.1864)	0.69(0.1159)	-5%
TRAD	846(520)	507(305)	-40%	148(115)	240(150)	62%	1367(672)	933(465)	-32%
ABIM	67.18(56.4131)	30.37(24.1556)	-55%	17.59(16.5925)	15.98(13.2052)	-9%	89.65(58.7582)	33.03(25.3438)	-63%
VOLAT	0.0456(0.0264)	0.037(0.018)	-19%	0.0363(0.0211)	0.0325(0.0135)	-10%	0.0324(0.018)	0.0308(0.0126)	-5%
STDSP	0.89(0.1829)	0.92(0.1846)	3%	1.29(0.2064)	1.06(0.1628)	-18%	0.49(0.1129)	0.64(0.0854)	31%
STDSPPIP	1.27(0.2432)	1.04(0.2016)	-18%	1.92(0.2859)	1.6(0.2461)	-17%	0.87(0.1955)	0.68(0.0897)	-22%
ATG	0.85	1.42	67%	4.86	3.00	-38%	0.53	0.77	47%

Hourly Average	EUR(DEM)/JPY 98	EUR(DEM)/JPY 99	EUR(DEM)/JPY %Δ	EUR(DEM)/CHF 98	EUR(DEM)/CHF 99	EUR(DEM)/CHF %Δ	Goodhart et al. : EUR(DEM)/USD 97	Goodhart et al. : EUR(DEM)/USD 99/00	Goodhart et al. : EUR(DEM)/USD %Δ
AS	1.32(0.3796)	2.09(0.5914)	58%	0.76(0.219)	0.57(0.1411)	-25%	1.62(0.4783)	2.77(1.2823)	71%
TWAS	1.42(0.5364)	2.27(0.9489)	60%	0.77(0.398)	0.59(0.2482)	-23%	1.45(0.531)	2.67(1.4189)	84%
ASPIP	1.06(0.2982)	2.5(0.7)	136%	0.63(0.1791)	0.91(0.2256)	44%	2.84(0.8339)	2.82(1.2843)	-1%
TWASPIP	1.14(0.4255)	2.72(1.1293)	139%	0.64(0.3303)	0.94(0.397)	47%	2.53(0.9274)	2.71(1.4305)	7%
TRAD	332(193)	117(84)	-65%	237(149)	96(56)	-59%	602.74(313.279)	289.55(146.127)	-52%
ABIM	26.98(24.0536)	16(14.5088)	-41%	22.08(20.5351)	9.9(9.0706)	-55%	51(47)	30(27)	-41%
VOLAT	0.0422(0.0203)	0.0408(0.0193)	-3%	0.0186(0.0096)	0.0065(0.003)	-65%	0.0318(0.05996)	0.0387(0.058)	22%
STDSP	1.53(0.4376)	1.56(0.253)	2%	0.88(0.3264)	0.49(0.1479)	-44%	1.11(0.0566)	2(1.7955)	80%
STDSPPIP	1.23(0.3414)	1.87(0.2935)	52%	0.73(0.268)	0.79(0.2366)	8%	1.93(0.9888)	2.03(1.8531)	5%
ATG	2.17	6.15	184%	3.04	7.50	147%			

Summary statistics for EBS spot FX with the data aggregated into hourly units. Standard deviations are shown in parentheses. Statistics are computed in the same manner as Goodhart et al (2002), using the same 10 hour time window (07:00 to 17:00, London time). The original Goodhart et al (2002) findings are shown at the end. Since all the data comes directly from the original source (EBS), there are no missing data intervals due to system crashes as some previous studies have had to allow for. Average bid-ask spread and volatility measures are shown in basis points.

Table 2: Summary statistics (Daily data, 10 hour day)

Daily Average	USD/JPY 98	USD/JPY 99	USD/JPY %Δ	USD/CHF 98	USD/CHF 99	USD/CHF %Δ	EUR(DEM)/USD 98	EUR(DEM)/USD 99	EUR(DEM)/USD %Δ
AS	0.71(0.0951)	0.9(0.0876)	27%	1.48(0.2579)	1.09(0.0892)	-26%	0.42(0.0627)	0.65(0.0344)	55%
TWAS	0.81(0.1245)	0.92(0.0901)	14%	1.75(0.3446)	1.24(0.1423)	-29%	0.41(0.0556)	0.65(0.0363)	59%
ASPIP	1.01(0.121)	1.01(0.0877)	0%	2.19(0.3591)	1.64(0.1409)	-25%	0.74(0.1058)	0.69(0.0345)	-7%
TWASPIP	1.16(0.1584)	1.04(0.0911)	-10%	2.6(0.4772)	1.87(0.2198)	-28%	0.73(0.0933)	0.69(0.0368)	-5%
TRAD	8493(3197)	5108(1635)	-40%	1496(676)	2395(655)	60%	13830(3995)	9369(2155)	-32%
ABIM	671.84(283.4645)	303.68(94.1602)	-55%	175.88(61.0535)	159.84(30.6236)	-9%	896.48(349.3857)	330.28(90.225)	-63%
VOLAT	0.0456(0.0197)	0.037(0.0108)	-19%	0.0363(0.0156)	0.0325(0.0058)	-10%	0.0324(0.0132)	0.0308(0.0057)	-5%
STDSP	0.89(0.1426)	0.94(0.1202)	6%	1.31(0.1445)	1.06(0.0796)	-19%	0.5(0.093)	0.65(0.0479)	30%
STDSPPIP	1.27(0.1795)	1.05(0.1265)	-17%	1.94(0.1845)	1.6(0.1201)	-18%	0.89(0.1591)	0.69(0.0499)	-22%

Daily Average	EUR(DEM)/JPY 98	EUR(DEM)/JPY 99	EUR(DEM)/JPY %Δ	EUR(DEM)/CHF 98	EUR(DEM)/CHF 99	EUR(DEM)/CHF %Δ	Goodhart et al. : EUR(DEM)/USD 97	Goodhart et al. : EUR(DEM)/USD 99/00	Goodhart et al. : EUR(DEM)/USD %Δ
AS	1.25(0.2431)	1.93(0.1997)	54%	0.74(0.1248)	0.55(0.0381)	-26%	1.63(0.2917)	2.77(0.6592)	70%
TWAS	1.42(0.3198)	2.27(0.356)	60%	0.77(0.1613)	0.59(0.0688)	-23%	1.44(0.2474)	2.69(0.6654)	87%
ASPIP	1.01(0.1845)	2.3(0.2152)	128%	0.61(0.0987)	0.88(0.0606)	44%	2.86(0.4997)	2.82(0.6264)	-1%
TWASPIP	1.14(0.2472)	2.72(0.4109)	139%	0.64(0.1302)	0.94(0.1097)	47%	2.53(0.4246)	2.74(0.6379)	8%
TRAD	3323(971)	1171(472)	-65%	2375(954)	960(280)	-60%	6027(914)	2864(735)	-52%
ABIM	269.84(85.3511)	160(56.4816)	-41%	220.8(92.6058)	99(28.2297)	-55%	86.6(129.009)	104.16(88.4)	20%
VOLAT	0.0422(0.0149)	0.0408(0.0118)	-3%	0.0186(0.0068)	0.0065(0.0017)	-65%	0.3178(0.2181)	0.3888(0.293)	22%
STDSP	1.5(0.3234)	1.59(0.1088)	6%	0.9(0.2076)	0.51(0.0649)	-43%	1.25(0.411)	2.58(1.2311)	106%
STDSPPIP	1.21(0.2452)	1.9(0.1079)	57%	0.75(0.1666)	0.81(0.1036)	8%	2.19(0.7133)	2.63(1.2682)	20%

Summary statistics for EBS spot FX with the data aggregated daily units. Standard deviations are shown in parentheses. Statistics are computed in the same manner as Goodhart et al (2002), using the same 10 hour time window (07:00 to 17:00, London time). The original Goodhart et al (2002) findings are shown at the end. Since all the data comes directly from the original source (EBS), there are no missing data intervals due to system crashes as some previous studies have had to allow for. Average bid-ask spread and volatility measures are shown in basis points.

Table 3: Summary statistics (Hourly data, 24 hour day)

Hourly Average	USD/JPY			USD/CHF			EUR(DEM)/USD		
	98	99	%Δ	98	99	%Δ	98	99	%Δ
AS	0.78(0.3524)	1.01(0.388)	29%	2.08(0.9521)	1.68(0.7628)	-19%	0.52(0.2085)	0.84(0.3712)	62%
TWAS	0.94(0.5272)	1.02(0.4675)	9%	2.21(1.0981)	1.75(0.9539)	-21%	0.55(0.2762)	0.87(0.4711)	58%
ASPIP	1.11(0.5041)	1.14(0.4344)	3%	3.08(1.4048)	2.54(1.1545)	-18%	0.93(0.3676)	0.89(0.3951)	-4%
TWASPIP	1.34(0.7515)	1.15(0.5241)	-14%	3.27(1.6223)	2.64(1.4425)	-19%	0.97(0.4864)	0.93(0.5011)	-4%
TRAD	646(519)	369(289)	-43%	82(104)	124(146)	51%	786(702)	507(500)	-35%
ABIM	47.35(48.5914)	24.02(21.7034)	-49%	10.7(13.8111)	9.86(10.8552)	-8%	53.14(55.1597)	21.46(21.2729)	-60%
VOLAT	0.0401(0.0256)	0.032(0.0183)	-20%	0.0336(0.0256)	0.0275(0.0147)	-18%	0.0264(0.0182)	0.0237(0.013)	-10%
STDSP	0.94(0.2554)	0.97(0.2695)	3%	1.32(0.453)	1.18(0.3158)	-11%	0.6(0.2049)	0.76(0.246)	27%
STDSPPIP	1.34(0.3524)	1.09(0.301)	-19%	1.95(0.6648)	1.78(0.477)	-9%	1.07(0.3599)	0.81(0.2611)	-24%

Hourly Average	EUR(DEM)/JPY			EUR(DEM)/CHF		
	98	99	%Δ	98	99	%Δ
AS	1.81(1.0362)	2.64(1.0116)	46%	1.15(0.785)	0.88(0.5948)	-23%
TWAS	2.11(1.4978)	2.7(1.2236)	28%	1.25(1.1801)	0.88(0.6852)	-30%
ASPIP	1.46(0.8289)	3.15(1.2053)	116%	0.96(0.6521)	1.4(0.9515)	46%
TWASPIP	1.69(1.1998)	3.22(1.4528)	91%	1.04(0.9779)	1.4(1.0963)	35%
TRAD	211(190)	72(76)	-66%	124(142)	52(56)	-58%
ABIM	19.28(21.4283)	11.64(12.9744)	-40%	13.37(16.6773)	6.33(7.3518)	-53%
VOLAT	0.0384(0.0242)	0.0379(0.0219)	-1%	0.0156(0.0109)	0.0063(0.0037)	-60%
STDSP	1.84(0.6322)	1.55(0.4808)	-16%	1.2(0.6192)	0.63(0.3139)	-48%
STDSPPIP	1.48(0.5007)	1.86(0.5703)	26%	0.99(0.5123)	1(0.5022)	1%

Summary statistics for EBS spot FX with the data aggregated into hourly units. Standard deviations are shown in parentheses. Statistics are computed in the same manner as Goodhart et al (2002), using a full 24 hour day. Since all the data comes directly from the original source (EBS), there are no missing data intervals due to system crashes as some previous studies have had to allow for. Average bid-ask spread and volatility measures are shown in basis points.

Table 4: Summary statistics (Daily data, 24 hour day)

Daily Average	USD/JPY			USD/CHF			EUR(DEM)/USD		
	98	99	%Δ	98	99	%Δ	98	99	%Δ
AS	0.75(0.204)	1.02(0.2814)	36%	1.74(0.5856)	1.47(0.7072)	-16%	0.53(0.2012)	0.83(0.3262)	57%
TWAS	1.11(0.5827)	1.14(0.3911)	3%	2.37(0.6386)	1.73(0.5185)	-27%	0.61(0.2563)	1.04(0.5132)	70%
ASPIP	1.08(0.291)	1.15(0.3185)	6%	2.58(0.8569)	2.22(1.0603)	-14%	0.94(0.3545)	0.88(0.3463)	-6%
TWASPIP	1.59(0.8398)	1.28(0.4427)	-19%	3.51(0.9378)	2.62(0.7949)	-25%	1.08(0.4479)	1.1(0.5473)	2%
TRAD	13304(7380)	7528(3838)	-43%	1534(900)	2431(1285)	58%	16134(8647)	10343(5216)	-36%
ABIM	961.13(530.2018)	488.5(221.6365)	-49%	199.5(100.5502)	192.57(92.0565)	-3%	1084(598.5601)	436.4(208.7687)	-60%
VOLAT	0.038(0.0157)	0.0311(0.0079)	-18%	0.0334(0.0168)	0.0264(0.007)	-21%	0.0261(0.0137)	0.0221(0.0062)	-15%
STDSP	0.97(0.206)	1.04(0.2346)	7%	1.38(0.1905)	1.17(0.1484)	-15%	0.63(0.2058)	0.82(0.2811)	30%
STDSPPIP	1.39(0.2853)	1.17(0.2622)	-16%	2.04(0.268)	1.77(0.2299)	-13%	1.11(0.3602)	0.87(0.2989)	-22%

Daily Average	EUR(DEM)/JPY			EUR(DEM)/CHF		
	98	99	%Δ	98	99	%Δ
AS	1.59(0.6322)	2.29(0.6086)	44%	0.97(0.4225)	0.82(0.6608)	-15%
TWAS	2.43(1.0858)	2.93(0.731)	21%	1.42(0.7985)	0.99(0.6128)	-30%
ASPIP	1.28(0.5124)	2.74(0.7535)	114%	0.81(0.3463)	1.31(1.0545)	62%
TWASPIP	1.96(0.8816)	3.51(0.8731)	79%	1.18(0.6569)	1.59(0.9792)	35%
TRAD	4269(2227)	1425(851)	-67%	2463(1491)	1023(500)	-58%
ABIM	388.87(205.6505)	229.77(120.9658)	-41%	264.27(148.3646)	124.21(57.7862)	-53%
VOLAT	0.0391(0.0207)	0.0365(0.0092)	-7%	0.0151(0.0068)	0.0063(0.0011)	-58%
STDSP	1.81(0.5069)	1.68(0.1829)	-7%	1.21(0.4649)	0.67(0.2784)	-45%
STDSPPIP	1.46(0.4064)	2.01(0.2031)	38%	1.01(0.3808)	1.07(0.4449)	6%

Summary statistics for EBS spot FX with the data aggregated daily units. Standard deviations are shown in parentheses. Statistics are computed in the same manner as Goodhart et al (2002) , using a full 24 hour day. Since all the data comes directly from the original source (EBS), there are no missing data intervals due to system crashes as some previous studies have had to allow for. Average bid-ask spread and volatility measures are shown in basis points.

Table 5: Percentage of bid-ask spreads which equal zero

Rate	Year	%
DEM/CHF	98	37%
EUR/CHF	99	31%
DEM/JPY	98	39%
EUR/JPY	99	21%
USD/DEM	98	47%
EUR/USD	99	41%
USD/CHF	98	29%
USD/CHF	99	29%
USD/JPY	98	50%
USD/JPY	99	36%

Table 6: Changes in the economic value of the minimum tick size associated with each currency pair at constant prices, and changes in the inter-temporal value of those exchange rates.

	98				99			% Change in	% Change in
(A) EUR & DEM	Min Tick	Av. Rate*	Basis Pts		Min. Tick	Av. Rate	Basis Pts	Min. Tick Value	Currency Value
USD/DEM	0.0001	1.8430	0.5426	EUR/USD	0.0001	1.0612	0.9423	74%	4%
DEM/JPY	0.005	60.957	0.8203	EUR/JPY	0.01	119.22	0.8388	2%	-24%
DEM/CHF	0.00005	0.8181	0.6112	EUR/CHF	0.0001	1.6001	0.6250	2%	-2%
(B) non-EUR(DEM)									
USD/JPY	0.01	112.74	0.8870	USD/JPY	0.01	112.74	0.8870	0%	-21%
USD/CHF	0.0001	1.5075	0.6634	USD/CHF	0.0001	1.5075	0.6634	0%	2%

* 1998 rates are adjusted to 1999 prices to remove fluctuations in the FX rate.

Table 7: Percentage of traded volume occurring at each prevailing bid-ask spread level in ticks.

		0	½	1	1½	2	2½	3	3½	4	4½	5	5½	6+
USD/JPY	98	50%		23%		15%		6%		2%		2%		2%
USD/JPY	99	36%		40%		16%		5%		1%		1%		1%
USD/CHF	98	29%		12%		18%		13%		6%		8%		13%
USD/CHF	99	29%		23%		23%		11%		4%		4%		6%
USD/DEM	98	47%		34%		12%		3%		1%		1%		1%
EUR/USD	99	41%		49%		9%		1%		0%		0%		0%
DEM/JPY	98	39%	6%	27%	3%	12%	1%	5%	0%	2%	0%	1%	0%	3%
EUR/JPY	99	21%		15%		22%		14%		7%		7%		13%
DEM/CHF	98	37%	26%	22%	4%	5%	1%	2%	0%	1%	0%	0%	0%	1%
EUR/CHF	99	31%		51%		12%		3%		1%		1%		1%

The DEM/JPY and DEM/CHF are special cases here. The half-tick level applies only to them and is irrelevant for all other exchange rates. Although these two rates were specified to 5 digit accuracy like all the other rates, they only ever used 0 and 5 in their final digit position. However, a considerable a considerable amount of dispersion of the volume traded is evident in the units of the penultimate digit. In the cases of DEM/JPY and DEM/CHF, the 'tick' spread levels actually refer to the units of their penultimate digit positions.

Table 8: Percentage of spot FX trades and quotes at a final digit of zero

(A) Trade Price Data	
Exch. Rate	**% at 0**
DEM/JPY	93%
DEM/CHF	74%
(B) Quoted Price Data	
Exch. Rate	**% at 0**
DEM/JPY	91%
DEM/CHF	73%

Table 9: Percentage of spot FX trades and quotes (limit orders) at odd final digits

(A) Trade Price Data			
% Odd	Pre	Post	%Δ
USD/JPY	47%	48%	2%
USD/CHF	46%	47%	1%
EUR(DEM)/USD	48%	49%	2%
EUR(DEM)/JPY	48%	46%	-4%
EUR(DEM)/CHF	49%	49%	1%
(B) Quoted Price Data			
% Odd	Pre	Post	%Δ
USD/JPY	48%	49%	2%
USD/CHF	47%	47%	0%
EUR(DEM)/USD	49%	50%	2%
EUR(DEM)/JPY	49%	46%	-5%
EUR(DEM)/CHF	49%	49%	-1%

Table 10: Chi-squared test statistic and number of observations for spot FX trades and quotes (limit orders)

(A) Trade Price Data			
χ^2 (No.of Obs.)	Pre	Post	%Δ
USD/JPY	79,729	15,195	-81%
	(399,187)	(225,825)	
USD/CHF	15,009	13,783	-8%
	(42,952)	(72,939)	
EUR(DEM)/USD	24,658	2,809	-89%
	(484,006)	(310,300)	
EUR(DEM)/JPY	6,025	12,046	100%
	(128,064)	(42,743)	
EUR(DEM)/CHF	464	317	-32%
	(73,898)	(29,654)	
(B) Quoted Price Data			
χ^2 (No.of Obs.)	Pre	Post	%Δ
USD/JPY	77,074	17,116	-78%
	(819,673)	(633,963)	
USD/CHF	90,466	66,874	-26%
	(251,624)	(399,722)	
EUR(DEM)/USD	20,535	3,567	-83%
	(771,614)	(540,868)	
EUR(DEM)/JPY	21,846	103,619	374%
	(495,771)	(329,584)	
EUR(DEM)/CHF	1,516	1,552	2%
	(232,362)	(121,166)	

Table 11: Standardised ranges for spot FX trades and quotes (limit orders)

(A) Trade Price Data			
Std. Range	Pre	Post	%Δ
USD/JPY	1.34	0.79	-41%
USD/CHF	1.81	1.34	-26%
EUR(DEM)/USD	0.71	0.34	-52%
EUR(DEM)/JPY	0.69	1.65	139%
EUR(DEM)/CHF	0.28	0.38	39%
(B) Quoted Price Data			
Std. Range	Pre	Post	%Δ
USD/JPY	0.93	0.52	-44%
USD/CHF	1.82	1.22	-33%
EUR(DEM)/USD	0.53	0.29	-44%
EUR(DEM)/JPY	0.62	1.73	177%
EUR(DEM)/CHF	0.29	0.41	44%

Table 12: Percentage of total traded (i.e. market order) volume at each final digit

	Year	0	1	2	3	4	5	6	7	8	9
USD/JPY	98	18%	5%	10%	10%	7%	18%	7%	10%	11%	5%
USD/JPY	99	14%	6%	10%	11%	9%	14%	8%	10%	11%	7%
USD/CHF	98	22%	5%	10%	9%	6%	20%	6%	8%	10%	4%
USD/CHF	99	19%	6%	10%	9%	6%	17%	7%	9%	11%	5%
USD/DEM	98	13%	7%	10%	10%	9%	14%	9%	10%	11%	7%
EUR/USD	99	10%	8%	10%	10%	10%	12%	10%	11%	10%	8%
DEM/JPY	98	93%	0%	0%	0%	0%	7%	0%	0%	0%	0%
DEM/JPY	*98**	*14%*	*8%*	*10%*	*10%*	*8%*	*14%*	*9%*	*9%*	*10%*	*7%*
EUR/JPY	99	21%	5%	10%	9%	6%	19%	7%	8%	10%	5%
DEM/CHF	98	74%	0%	0%	0%	0%	26%	0%	0%	0%	0%
DEM/CHF	*98**	*10%*	*9%*	*11%*	*10%*	*10%*	*11%*	*10%*	*10%*	*10%*	*8%*
EUR/CHF	99	11%	8%	9%	11%	10%	12%	10%	10%	10%	9%

* Figures for DEM/JPY and DEM/CHF which are listed as 98* are for the penultimate digit.

Table 13: Percentage of total quoted price (i.e. limit order) volume at each final digit.

	Year	0	1	2	3	4	5	6	7	8	9
USD/JPY	98	15%	6%	10%	10%	7%	15%	8%	10%	11%	6%
USD/JPY	99	12%	8%	10%	11%	9%	13%	9%	10%	11%	8%
USD/CHF	98	23%	5%	9%	10%	6%	20%	5%	8%	10%	5%
USD/CHF	99	18%	6%	10%	9%	7%	17%	7%	9%	11%	6%
USD/DEM	98	12%	8%	10%	10%	9%	13%	9%	10%	11%	8%
EUR/USD	99	10%	8%	10%	10%	10%	11%	10%	11%	10%	9%
DEM/JPY	98	91%	0%	0%	0%	0%	9%	0%	0%	0%	0%
DEM/JPY	*98**	*14%*	*8%*	*10%*	*10%*	*8%*	*14%*	*9%*	*9%*	*10%*	*8%*
EUR/JPY	99	22%	5%	10%	9%	6%	19%	6%	8%	10%	5%
DEM/CHF	98	73%	0%	0%	0%	0%	27%	0%	0%	0%	0%
DEM/CHF	*98**	*12%*	*9%*	*10%*	*11%*	*10%*	*11%*	*10%*	*10%*	*10%*	*9%*
EUR/CHF	99	13%	8%	10%	10%	10%	12%	10%	10%	10%	8%

* Figures for DEM/JPY and DEM/CHF which are listed as 98* are for the penultimate digit.

Table 14: Price resolution hypothesis test statistics for spot FX trade and quote (limit order) prices

(A) Trade Price Data			
Resolution	Pre	Post	%Δ
USD/JPY	2.23	1.47*	-34%
USD/CHF	2.49	2.03	-19%
EUR(DEM)/USD	1.33*	0.50*	-62%
EUR(DEM)/JPY	1.34	1.78	33%
EUR(DEM)/CHF	0.52*	0.24*	-54%
(B) Quoted Price Data			
Resolution	Pre	Post	%Δ
USD/JPY	2.06	1.60*	-22%
USD/CHF	2.27	1.97	-13%
EUR(DEM)/USD	1.48*	0.52*	-65%
EUR(DEM)/JPY	1.86	2.05	10%
EUR(DEM)/CHF	0.85*	0.57*	-32%

* - *these values go to zero if the restriction of volume(0) > volume(5) is enforced*

Figure 1: The Structure of the Spot FX Market.