The WMR Fix and its Impact on Currency Markets

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Abstract

One of the most widely used benchmarks for FX trading is the so-called London WMR 4pm Fix. This study empirically examines intraday liquidity as well as the returns-flows relationship around the London 4pm Fix and for other intraday points in time using four years of high-frequency data for multiple currencies for both the spot and the futures market. Our results indicate that the behaviour of liquidity and prices around the London 4pm Fix are quite unlike that observed at other points in time. One major finding of this study is that inter-dealer order flow is completely uninformative for spot returns at the Fix window.

Preliminary and Incomplete

Keywords: Currency Markets; Exchange Rates; WMR Fix; Market Microstructure; Order Flow.

JEL Classification: F31; F33; G12; G15.

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1 Introduction

In the summer of 2013, the London WMR 4pm Fix moved from the fine print of foreign exchange contracts to the headlines of newspapers. The London WMR 4pm Fix (or just the "Fix" hereafter) is a key reference rate in the spot foreign exchange market used extensively by market participants.[1] Given the high degree of reliance that investors place on benchmarks, the 2013 news reports revealing widespread manipulation of the Fix threatened the integrity of this benchmark and resulted in a large-scale investigation from various regulatory bodies from the US, UK, EU, Switzerland and Hong Kong among others. According to regulators, traders at some of the world's largest banks colluded in manipulating the spot benchmark rates on a large scale over a period of at least five years. These investigations resulted in fines in excess of $11bn for the banks involved in the story.[2]

Apart from questioning our belief that the more liquid a market the less susceptible it is to manipulation, this incident also revealed that our understanding of forex trading around the Fix is not well understood.[3] Our paper contributes by examining the institutional details of the Fix and the price and liquidity dynamics around it. We extend the the earlier work of Evans (2016) first by considering inter-dealer order flow and second by also considering returns and flows in the futures market.

Although the Fix is the most important institutional feature of the FX market, these dynamics were disregarded in academic literature up until recently. In this paper we examine intraday forex trading patterns around fixes and we contribute towards a better understanding of the role of fixes in the operations of the FX market. We consider currency futures trading as well as spot since these two markets are linked by arbitrage relations and, as we shall see, there is important information content in the flows of both markets.

[1] Other extensively used FX benchmark rates include the 1:15 London local time ECB benchmark rate and the 10am JST Tokyo fixing (GMT 1:00).

[2] More details can be found in Appendix B.

[3] The global FX market is the world's largest financial market with an estimated average daily turnover of approximately 5.1 trillion U.S. dollars in 2016 (Bank of International Settlements (2016)). However, this figure is down from 5.4 trillion U.S. dollars in 2013.

More specifically, in this study we empirically examine the intraday foreign exchange rates and inter-dealer order flow relationship around the Fix for both spot and futures markets for various currencies by using four years of high-frequency data. We compare and contrast intraday liquidity and price behaviour with other fixing points, such as the 3pm London fix and the ECB fix, as well as with other major points in the trading day, such as 9:30am London time when macroeconomic indicators are published. Our analysis indicates that the behaviour of prices and flows at the London 4pm Fix is quite unlike that observed at other points in time.

Our main findings are summarized as follows: (1) During the 60 second calculation window of the Fix, there is an extreme concentration of interbank trading activity not present during any other point in time of the day generating order flow spikes for both the spot and the futures markets. (2) There is a small price reversal in the one minute after the 4pm Fix for both markets that is not observed at other fixing points. (3) More obviously, in the spot market there is a clear reversal during the Fix of positions accumulated in the pre-Fix window. This suggests that during the pre-Fix window dealers accumulate larger positions than necessary to fulfil their customers' Fix orders and liquidate these excess proprietary positions for profit during the Fix. (4) The price impact of interbank order flow during the one-minute Fix is essentially zero, and bid-ask spreads are much narrower than usual, due to the extremely high levels of liquidity seen at the Fix. Liquidation of proprietary positions during the Fix is therefore extremely cheap. (5) Price discovery temporarily migrates from the spot to futures markets at the Fix since futures order flow maintains price impact. (6) Positions accumulated in the futures market during the pre-Fix are also reversed, though over a significantly longer time interval than in the spot market probably due to the more consistent price impact seen in the futures market. This reversal of futures positions is common across all 'extreme' intervals in the trading day.

The existing literature related to the Fix focuses exclusively on describing price dynamics and does not consider order flow. It is surprising that the only strong (proximate) determinant of exchange rates has not received attention. Further, as Melvin and Prins (2015) and Osler and Turnbull (2016) point out, "price dynamics around fixes are not well accounted for in existing microstructure models." Our paper contributes by extending the analysis to included inter-dealer order flow behaviour around the Fix, together with order flow and price dynamics in the related FX futures markets. Our focus is also on highlighting the uniqueness of the 4pm Fix. In short, this is the only period of the trading day where trading activity, order flows and return volatility are much higher than usual yet liquidity in the form of bid-ask spreads and price impact are much lower than usual. Compared with other fixes or informational event periods, the 4pm Fix is the only one to reveal significant spot flow reversals (though all such extreme events are characterised by futures flow reversals). By examining spot and futures flows we shed light on a puzzle in the Fix literature. While Evans (2016) documents statistically significant price reversals around the Fix, the associated magnitudes are rather small until he narrows down to just end month observations. Osler and Turnbull (2016) present a model of optimising dealer behaviour that, even in the absence of collusive activity, shows that in the pre-Fix window dealers have an incentive to build proprietary positions that exploit their knowledge of Fix orders. These positions are liquidated at the Fix. The puzzle is that while the incentives for proprietary trading are clear (and can be maximised under conditions of active collusion between dealers) the observed price effect is relatively small. Our analysis shows that interbank flows data are much more supportive of the model - active liquidation of positions at the Fix is apparent but we show that this is masked from prices by the extraordinary low price impact of trades during the Fix. Futures flows, similarly, reveal that positions built up during the pre-Fix window are gradually reversed after the Fix. This pattern though is common to many fixes, not just the 4pm Fix, and also to other extreme intervals in the trading day. The spot market flow activity at the 4pm Fix is, however, unique.

The rest of the paper is set up as follows. We first detail the history of benchmark fixes in the foreign exchange market and outline the literature in the area. We describe our data in Section 3 before presenting our results in Section 4. After a graphical presentation of the key series we present results in three subsections. We discuss price-flow dynamics around the 4pm Fix in Section 4.1 and associated regression results in Section 4.2, before broadening the analysis to other important events within the trading day in Section 4.3. We conclude in Section 5.

2 Background and Literature Review

Reliable benchmark rates in highly fragmented or bilateral over-the-counter markets characterized by the absence of a centralized exchange can increase matching efficiency, decrease search costs and increase participation by less-informed or less-sophisticated investors (Duffie and Stein (2015)). Once a reliable and publishable benchmark is established, concentration of trading activity is then expected to take place for two reasons. First, market participants face a strong incentive to reap the information-related benefits from the introduction of the benchmark and in order to achieve these benefits, investors must choose to trade at the benchmark rate. Second, this concentration of trading activity is usually associated with higher liquidity, i.e. smaller spreads, increased depth, faster execution and, potentially lower price impact for larger trades. These benefits could potentially further attract trades as there is an incentive to substitute from less-actively traded instruments towards instruments that reference the benchmark.

In the FX market, such a benchmark was introduced in 1994 by the World Markets Reuters (WMR) Company. It covers 155 spot currency benchmark rates and benchmark forward rates for 80 currencies. The rates are intended to cover the currencies for those countries that are included in a global or regional stock market index or where there is sufficient liquidity in the currency market to provide accurate fixings. The benchmark rate is calculated on a daily basis at an hourly frequency (half-hourly rates are provided for the most heavily traded currencies). Over a one-minute fix period, bids and offers of actual trades executed for each currency pair are sampled every second from 30 seconds before to 30 seconds after the fixing point (e.g. 4pm London time) and median bid and offer rates are calculated.[4] Publication of the fixing rate takes place 15 minutes after the fix time.

The most widely used fix is the one calculated at 4pm London time. The popularity of the 4pm Fix can partially be explained by the fact that the

[4] On February 15, 2015, WMR adopted a five-minute window to calculate currency benchmark rates (i.e., a five minute window from +/- 2.5 minutes either side of the fix), in an attempt to discourage further dealer misconduct. For a more detailed discussion of the calculation methodology, please refer to Appendix A.

foreign exchange market activity is mostly concentrated around the overlap of US and European business hours and partly because it may be seen, in a sense, as the end of the European trading day and as such is typically the price reported in the European financial press. The 4pm Fix is used for constructing indices comprising international securities (e.g. the MSCI stock index, the Barclays Global Bond Index and Markit's credit index), to compute the returns on portfolios that contain foreign currency denominated securities (e.g. country tracking funds and ETFs) as well as the value of foreign exchange securities held in custodial accounts (Evans (2016)). Melvin and Prins (2015) show that trading activity in the spot market is particularly high around the time of the Fix, especially at the month-end. This is because fund managers often rebalance their portfolios at the end of the month to ensure that their currency exposure is in line with their benchmark indices. Because the same rate is also used for the benchmark index the fund manager is measured against, the manager's currency risk is eliminated. Moreover, multinational companies may have an interest in valuing their currency holding using a common reference rate. Trading at the currency Fix rate is often seen as transparent, because the transactions are executed at an official reference rate. It also saves companies from putting resources into monitoring the market and enables them to eliminate the currency risk relative to internal benchmarks that use the Fix rate. Both commercial and financial players thus have an interest in linking orders to currency fixes. This generates large orders and extensive transactions for banks ahead of the times the reference rate are set.

The desire of market participants to trade at the benchmark rate results in a concentration of trading activity and the introduction of a specific order type designed to facilitate trading at the Fix by bank customers. A "fill-at-fix order" is an order given by customers to banks to buy or sell a given amount of currency at the fix rate, which is unknown to either party at the time the order is placed. According to Melvin and Prins (2015) and Evans (2016), market practices dictate that fill-at-fix orders must be submitted to dealer banks before 3:45pm London time. Fix orders to buy or sell a specified volume of a currency pair at the Fix rate are submitted by customers and banks' spot desks guarantee that their customers receive the agreed volume of the currency pair at the as yet unknown and still to be determined Fix rate. Currency risk has now been transferred from the customer to the bank as the bank is exposed to rate movements at the Fix. The bank needs to hedge its own currency risk and can achieve that by buying the currency needed ahead of the actual Fix from other market participants. The bank will make a profit if the average rate at which it buys the currency pair in the market is lower than the Fix rate at which it sells to the client. In isolation, the bank's purchase of the quantity needed will serve to push up the value of the currency, which means that a fill-at-fix order can affect pricing in the period leading up to the Fix. This mechanism implies that the bank's and the customer's interests may not necessarily be aligned towards moving the price in the same direction in the period before the Fix. Thus in the pre-Fix window we could argue that the role of the bank's spot trading desks role shifts from that of a risk-neutral market-maker to a mix between a trader informed about order flow and a market-maker. Given also that dealers shared information during this period according to the manipulation story the informedness of the bank dealers may be even higher.

Our paper relates to three strands of literature on foreign exchange market microstructure. The first and most established strand considers the impact of order flow on currency returns, initiated by Lyons (1995) and Evans and Lyons (2002). They provide the first estimates of the foreign exchange market's response to interdealer order flow by regressing the base currency's daily return on order flow as well as on macroeconomic variables. Their results reveal a strong and statistically significant positive relationship between order flow into a currency and contemporaneous returns on that currency. Evans and Lyons (2002) argue that the importance of interbank order flow in the determination of spot foreign exchange rates is attributable to the information it conveys about (non-dealer) customer trades. At the start of each day, uncertain public demand for each currency pair is realized (stemming from shocks to hedging demands, liquidity demands as well as speculative demands). These demand realizations produce orders (i.e. each trader receives a number of orders from his/her customers) that are not publicly available, so any information they convey must be aggregated through inter-dealer order flow. Even though each trader has a private signal of the currency's payoff, information is not concentrated, but rather it is dispersed among a large number of separate dealers. Order flow is therefore the proximate determinant of exchange rates as it is the transmission mechanism through which all the dispersed pieces of information in the economy are aggregated and incorporated into price.

A growing literature has further examined this hypothesis with longer or more recent datasets, covering more currencies, at daily and higher frequencies, with brokered, interdealer and customer trades (e.g. Evans and Lyons (2005a); Evans and Lyons (2005b); Marsh and O'Rourke (2005); Killeen et al. (2006); Danielsson and Love (2006); Berger et al. (2008)). The estimated coefficients for order flow are always statistically significant providing substantial empirical support for the validity of the contemporaneous relationship between inter-dealer order flow and exchange rate returns. Our work builds on this literature, and examines the power of both interbank order flow and futures market flows in determining exchange rates. We do so using intraday data, and show that both flows contribute to price discovery in both markets. Furthermore, we reveal significant intraday shifts in the contribution to price discovery of these two markets. Specifically, while the spot market leads quite consistently throughout the trading day, exactly at the 4pm Fix price discovery entirely migrates to the futures market as spot flows become completely uninformative. This is quickly reversed after the Fix. We also show that price impact coefficients (the correlation between flows and rates) in both markets deviate from normal levels at various points in the trading day besides the 4pm Fix. The Fix, however, is the most extreme intraday event of all.

The second strand is that of time-of-day patterns in foreign exchange markets. The foreign exchange market could be considered as the closest analogue to the concept of a continuous time global market. When intra-daily data of trading activity became available, a large number of studies emerged examining intraday seasonalities of trading activity. In relation to trading volume in the spot market Bollerslev and Domowitz (1993), Hartmann (1999), and Ito and Hashimoto (2006) report that trading activity and bid-ask spreads of major currency pairs increases during London and/or New York opening hours and that trading volume and volatility is highest during the overlap period when both New York and London are open. Baillie and Bollerslev (1991), Andersen and Bollerslev (1997), and Andersen and Bollerslev (1998) document the existence of a distinct U-shaped pattern in return volatility over the trading day. In addition, they report intraday volatility calendar effects, Daylight Saving Time, Tokyo Opening and Tokyo Lunch time effects, and examine the dynamics of intraday volatility clustering and other properties. Harvey and Huang (1991) report similar results for the currency futures market.

Our analysis reveals the impact the regular fixes - particularly at 4pm but also at other times - and scheduled macroeconomic news announcements have on both spot interbank and futures markets. We focus then less on the general trends within the trading day and more on the extreme outlier events caused by these institutional arrangements. We show that the various market fixes and announcement periods look very different from more standard trading intervals and that these extreme intervals also look very different from each other.

The third, and the more recent strand, relates to forex trading around the London WMR 4pm Fix. The majority of these studies stem from the spot rates manipulation scandal and concentrate on empirically examining activity around the Fix during the period of alleged manipulation (e.g. Michelberger and Witte (2016); Evans (2016); Ito and Yamada (2015)). While our paper does not aim to establish empirical red flags concerning the alleged manipulation of forex benchmark rates we do examine trading behaviour around fixing periods. We extend the literature by incorporating order flow to the analysis and simultaneously examining the currency futures market.

A common finding of the empirical studies is that market dynamics around the Fix can be distinguished from other times during the day. The fixing period is characterized by high concentration of trading activity and it is believed that market dynamics around the Fix are most probably caused by the compression of a large number of trades into a narrow time window (Michelberger and Witte (2016); Melvin and Prins (2015); Ito and Yamada (2015)). Moreover, the fixing period is associated with increased volatility and there is a significant probability of observing extreme price movements within the Fixing period, as compared to other trading intervals within a day, consistent across all investigated currency pairs (Michelberger and Witte (2016); Evans

(2016)). Ito and Yamada (2015) and Evans (2016) further examine price dynamics around the Fix and provide some evidence of spikes in prices around the fixing window. Evans (2016) provides evidence of negative autocorrelation of the spot rate between the pre- and post-fixing periods, particularly at the end-of-month trading days and identifies very small reversals during the first minute after the Fix (on the order of one basis point) for intra-month days and sizeable reversals in prices in the end-of-month days. Ito and Yamada (2015) provide evidence that liquidity provision at the fixing time is larger than other times, which makes the price impact of any trade smaller. They also examine trading behaviour around the Tokyo fixing and show that price spikes in the Tokyo fixing are more frequent than in London. Melvin and Prins (2015) test the hypothesis that currency hedging trades by international equity portfolio managers, generated by outperformance of a country's equity market over the course of a month, relative to other markets, will lead to selling of that country's currency prior to the last Fix of the month. They report a statistically significant and negative effect suggesting that currency returns in the lead-up to the Fix on the last day of the month are predicted by relative moves in country equity markets. They also provide evidence that equity hedging flows are responsible for higher exchange rate volatility, specifically around the end-of-month Fix.

Our key contribution is to bring order flow - both spot interbank and futures - into the analysis of the London 4pm Fix. Evans (2016) details evidence of price reversals at the Fix but these are not economically large despite the obvious incentives for dealers to liquidate proprietary positions built up as a results of customer fix orders. Osler and Turnbull (2016) show how information sharing, free-riding, collusion and risk aversion can each affect the intensity of trading at the Fix but in each setting, the incentive for dealers to acquire proprietary positions during the pre-Fix period and to them liquidate them at the Fix remains. We show that while prices may not reveal this activity, interbank order flow data does. In the 4pm Fix - and only in this Fix - we see clear evidence of spot trading reversals, but these are barely revealed by prices since liquidity at the Fix is so high that price impact of interbank trades is negligible. Conversely, we show that futures market trading across extreme events such as the 4pm Fix, ECB fix or 9:30am data release show common patterns, whereby positions accumulated before the event are slowly unwound afterwards.

3 Data

Our spot data include all GBP/USD, AUD/USD and NZD/USD transactions between January 1, 2010 and December 31, 2013 on the Reuters Dealing electronic inter-dealer trading system. The Reuters platform is one of the two dominant brokered trading platforms used in the inter-dealer spot foreign exchange market and is the primary trading venue for commonwealth (GBP/USD, AUD/USD, NZD/USD, USD/CAD) and emerging market currency pairs.[5]. Data include a millisecond time stamp for every trade, the transaction price, the best prevailing bid and ask quotes and a trade direction flag. The value of each transaction is not available.

During our sample period, the 4pm London Fix was calculated from trades in the interval 15:59:30 until 16:00:30.[6] To match this, we aggregate the irregularly spaced raw data to a one minute sampling frequency. We exclude the first and the last 30 seconds of each trading day such that each observation spans the one minute window of +/- 30 seconds each side of the specified minute. Thus, we construct 1,439 equally spaced 1-minute intervals of trading activity per full trading day, one of which exactly matches the Fix interval. Since the focus of our study is the 4pm London Fix we concentrate our analysis on London trading hours and restrict our sample to London trading hours, i.e. from 08:00:30 to 17:00:30 London time. Weekends and public holidays where trading activity is very thin (typically, Christmas Eve, Christmas Day, December 31st-January 2nd, Easter Friday and Easter Monday) are removed from the analysis.[7]

[5] The BIS reported that in 2000, between 85 and 95% of all interbank trading took place using electronic brokers (Bank for International Settlements, 2001, 71st annual report, section 5, 'Foreign exchange markets'.) EBS is the primary trading venue for EUR/USD, USD/JPY, EUR/JPY, USD/CHF, EUR/CHF and USD/CNH

[6] For a detailed description of Fix calculation methodology, please refer to Appendix A.

[7] Our reported results are based on the full span of the data. We also split the dataset into two subsets, January 1, 2010 - March 31, 2013 and June 1, 2013 - December 31, 2013 since from June 2013 possible manipulation of the Fix attracted significant media attention

The futures database consists trade and quote activity on GBP/USD, AUD/USD and NZD/USD futures contracts listed on the Chicago Mercantile Exchange collected from Thomson Reuters Tick History. We focus on the contract closest to maturity. Each contract has a nominal value of 100,000 US dollars. The raw data give the best prevailing bid and ask prices and associated depths, together with all transactions prices and quantities. Each datapoint comes with a millisecond time stamp. To be consistent with the spot data we ignore traded quantities of futures transactions and simply count trades. Our results are not sensitive to this decision. No information is provided on the direction of each trade so we apply the Lee and Ready (1991) algorithm. We are able to sign 99.64% of all trades in our final futures rates sample. All unclassified trades and trades with no associated trading quantity or time stamp are excluded. Futures data are aggregated in exactly the same manner as the data from the spot market.

For each minute of trading activity we record the bid, ask and midpoint spot price at the end of each minute, the logarithmic spot return (denoted ΔS_t), and the number of buy and sell trades from which the net order flow (X_t^S) is calculated. A positive order flow denotes a flow into the US dollar and a positive return implies an appreciation of the US dollar. We compute log futures returns (ΔF_t), order flows (X_t^F) and the basis, defined as the difference between the spot rate and the futures contract rate ($Basis_t = log(S_t) - log(F_t)$). We use the absolute intra-minutely log return each minute as a proxy for volatility.

3.1 Summary Statistics

We show summary statistics for the one-minute and daily returns, trades and order flow data of GBP/USD in Table **??** below. Summary statistics for AUD/USD and NZD/USD can be found in the Appendix D.

We observe many more trades per day in the futures market than in the spot

which may have led to a change in the behaviour of market participants. Our results are, however, consistent across both subsamples so are not reported but are available on request.

Table 1: Summary Statistics for Spot and Futures GBP/USD.

	Spot Data			Futures Data		
	Trades	**Flows**	**Returns**	**Trades**	**Flows**	**Returns**
Panel A: Minute (obs: 558,360)						
Mean	12.005	-0.010	1.05×10^{-5}	85.196	-0.141	7.6×10^{-6}
Median	8.000	0.000	0.000	54.000	0.000	0.000
Maximum	718.000	171.000	0.774	3,689.000	975.000	0.753
Minimum	0.000	-142.000	-1.093	0.000	-1,432.000	-1.074
Std.Dev.	16.382	5.940	0.021	107.144	29.311	0.023
Q(5)	3,515.867	2,983.541	734.804	4,904.481	7,745.701	7,680.053
ADF	-327.834	-706.639	-771.063	-301.299	-678.063	-837.964
AR(1)	0.504	0.056	-0.031	0.543	0.097	-0.114
Panel B: Daily (obs: 1,034)						
Mean	6,482	-5.149	0.006	46,005	-76.105	0.004
Median	6,341	0.000	0.019	45,912	-78.500	0.019
Maximum	18,341	768.000	1.465	141,379	3,802.000	1.472
Minimum	661	-758.000	-1.631	176	-3,326.000	-1.625
Std.Dev.	2,313	222.244	0.438	16,844	1,075.749	0.437
Q(5)	948.585	28.280	5.976	482.517	135.700	5.955
ADF	-5.497	-28.490	-31.528	-5.843	-26.672	-31.680
AR(1)	0.506	0.119	0.018	0.458	0.180	0.014

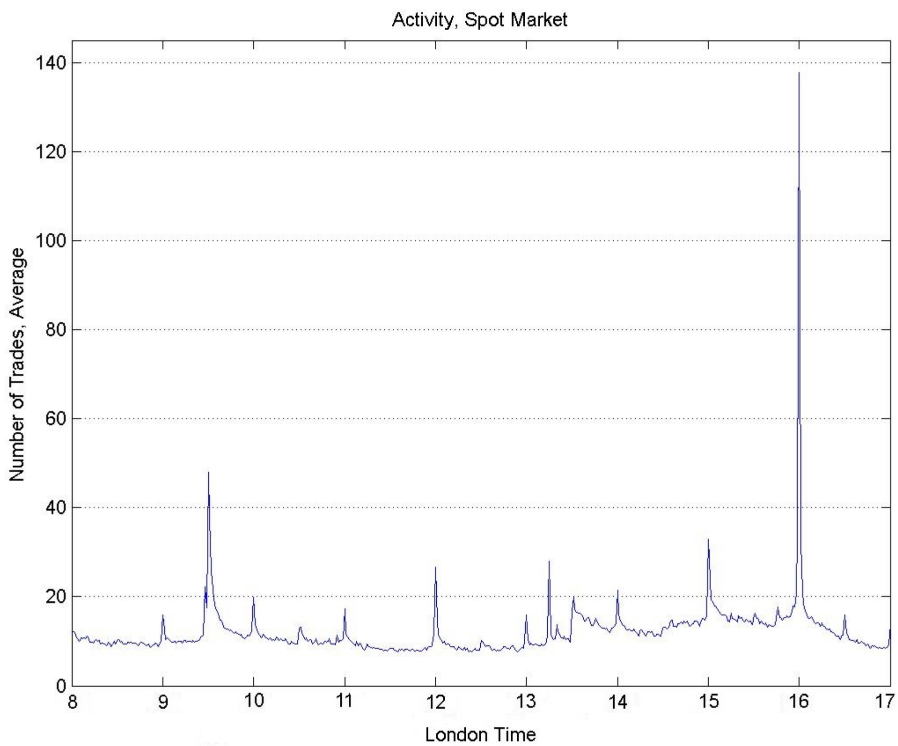
This table presents summary statistics for trades, order flow and returns for both the spot and futures market for the GBP/USD currency pair. Full period statistics are calculated over the period January 2010 to December 2013. Number of observations correspond to each market separately. Q(5) denotes the Ljung-Box Q-test statistic for the first five serial correlations of returns. Under the null hypothesis of no serial correlation, the LBQ statistic is asymptotically distributed as $\chi^2(5)$. ADF denotes an Augmented Dickey-Fuller test for non-stationarity in each series.

market. Note, however that each futures contract has a monetary value of approximately 100,000 US dollars whereas the minimum trade size in the spot interbank platform is 1,000,000 US dollars. Returns and order flow are serially correlated, consistent with some informed trading models. For example, Easley and O'Hara (1987) model a situation where sequences of large purchases (sales) arise when insiders with positive (negative) signals are present in the market. The positive serial correlation in order flow is also consistent with strategic order splitting, i.e. a trader willing to buy for informational or non-informational reasons and splitting his order to reduce market impact.

4 Empirical Approach & Results

The objective of this section is to increase our understanding of the average behaviour of spot and futures exchange rates and of trading behaviour around the Fix and to put this in the context of the observed behaviour over the rest of the trading day. To do so we first present key aspects of the markets graphically. We focus on results for the GBP/USD exchange rate here. We show that AUD/USD and NZD/USD markets behave similarly in a subsequent section.

Figure 1: Spot Market Intraday Activity GBP/USD



Figures 1 and 2 plot intraday activity levels for the GBP/USD spot and futures markets, as measured by the number of trades executed per minute averaged over the full sample period during London trading hours. Most markets display some intraday pattern, typically related to the effect of the open and close, the regular timing of key public information disclosure. In the case of the interbank spot and futures FX markets, the outstanding features of activity levels are regular abrupt peaks. Most importantly for this paper, as Figure 1 makes apparent, the single most significant spike in interbank trading activity occurs at exactly 4pm London time. On average, there are approximately seven times as many trades during the Fix as there are during all other minutes of trading activity within the day.

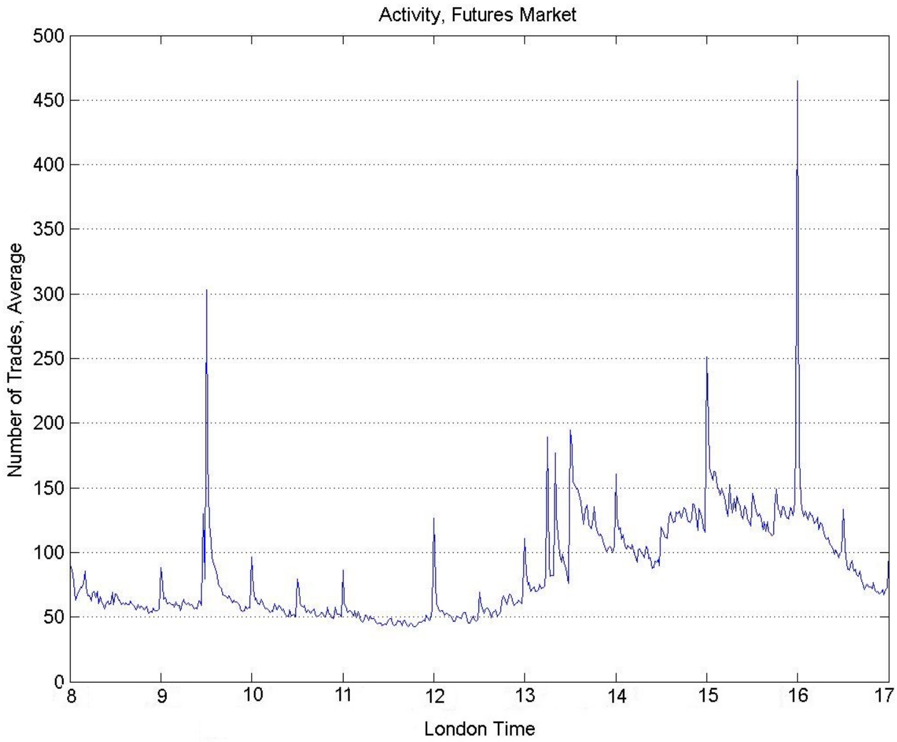
The second highest activity spike is at 9:30am London time when major UK macroeconomic indicators are published. US indicators are often published at 1:30pm or 3pm London (8:30am and 10am Eastern Time) coinciding with other observable but smaller peaks in trading activity.[8] There are smaller peaks in activity at each hour (and to a much smaller extent at some half-hours). These spikes could partly be attributed to trading concentration at the hourly fixing periods and partly to time-based algorithmic trading. Finally, a large spike is observed at the ECB fixing at 1:15pm London time.

Underlying these spikes there is a more smooth evolution of activity levels. In general, trading activity in both spot and futures markets is highest when both London and New York are open (the New York trading session begins at around 1pm London time). Activity levels clearly decline after the 4pm fix as London closes.

Given the decentralised structure of the foreign exchange market and the heterogeneity of market participants, the foreign exchange market is characterized by informational asymmetries and so dealers and market-makers gather disperse and private information from the orders placed by their customers (Lyons (1997)). Thus, although Thompson Reuters database is mainly an interdealer trading platform, underlying customer order flow is a key driver of interdealer flow through "hot potato" trading after a customer trade (Lyons (1997)). As the top panels of Figures 3 and 4 make clear, on average, the size and direction of this order flow measure for both markets does not have an obvious predictable pattern and seems on average to converge to zero. This masks a much more obvious pattern that is revealed if we consider absolute order flows (lower panels of Figures 3 and 4). Interbank order flows

[8] The 3pm spike could also be partly driven by 10am Eastern Time options expiry and the regular hourly fix.

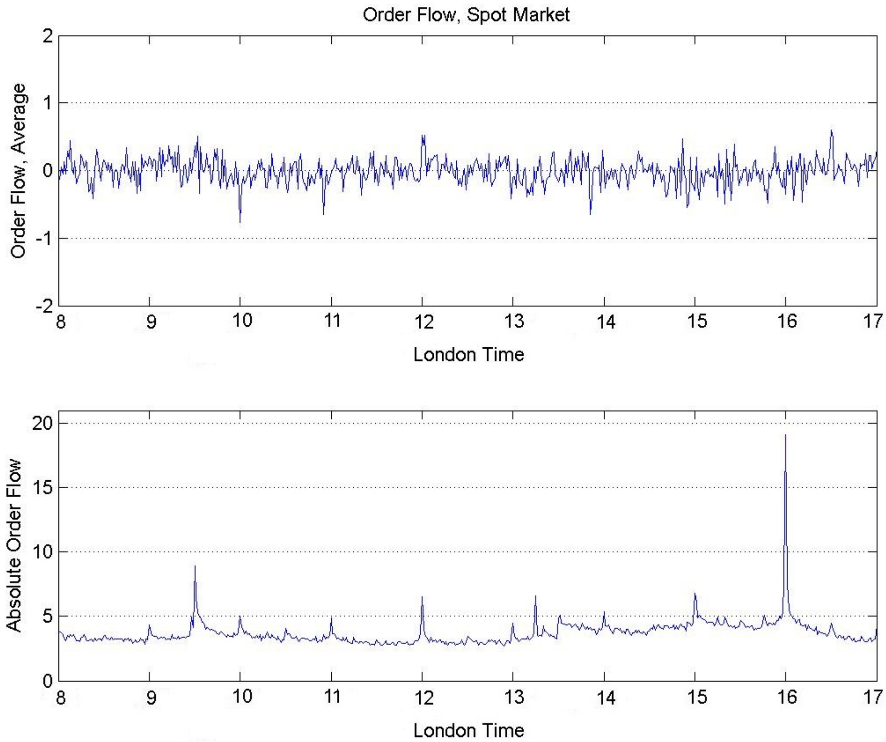
Figure 2: Futures Market Intraday Activity GBP/USD



are typically much less balanced at the points already identified as most active. In particular, at the 4pm Fix order flow is four times as large as that observed in most active minutes. As the imbalance may be into or out of the dollar, however, averaging of signed order flow over our long sample averages this effect out. Note that since volume at the Fix is seven times as high as normal, this comparatively smaller increase in flows mean flows during the Fix are more balanced than usual. The average imbalance in spot order flow (defined as the absolute order flow scaled by total number of trades) is 0.44. During the 4pm Fix this drops to an average of just 0.15.

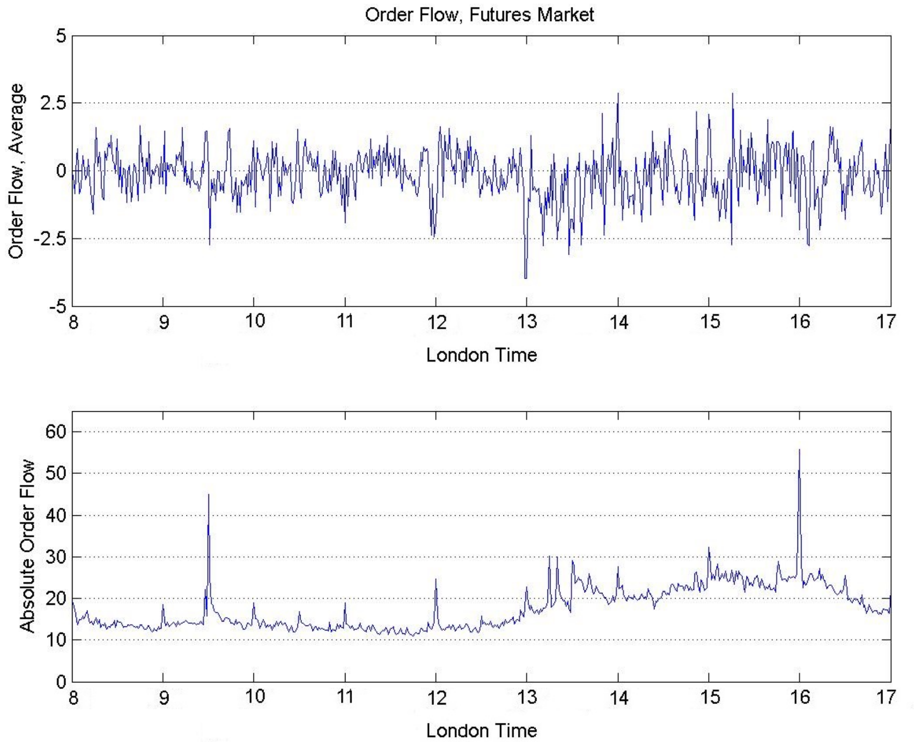
Spot and futures absolute order flows are positively correlated ($\rho = 0.38$). This raises the questions of whether spot and futures order flow contain the same information, and where price discovery takes place. We return to these questions below.

Figure 3: Spot Market Intraday Order Flow GBP/USD



Figures 5 and 6 depict average intraday spreads for the spot and futures markets respectively per minute of trading activity over the full sample period during London trading hours. For the spot market, the bid-ask spread remains relatively stable on average throughout the day with the exception of four specific points in time: 9:30pm, 1:30am, 3pm and 4pm London time. At 9:30pm, 1:30am and 3pm London time, the average spread per minute tends to spike upwards, whereas at 4pm London time tends to spike downwards. Interestingly, no other downward spike of the average spread is observed during the trading apart from the one observed at the 4pm Fix. The common feature of the first three points is the release of new information: at 9:30 UK macroeconomic indicators are published, at 1:30am there is the opening of the NY trading session where new expectations from market participants manifest and at 3pm there is the option expiration period. Note also that the publication of some U.S. macroeconomic indicators is taking place at 1:30am and 3pm London time. At these points, significant market activity is

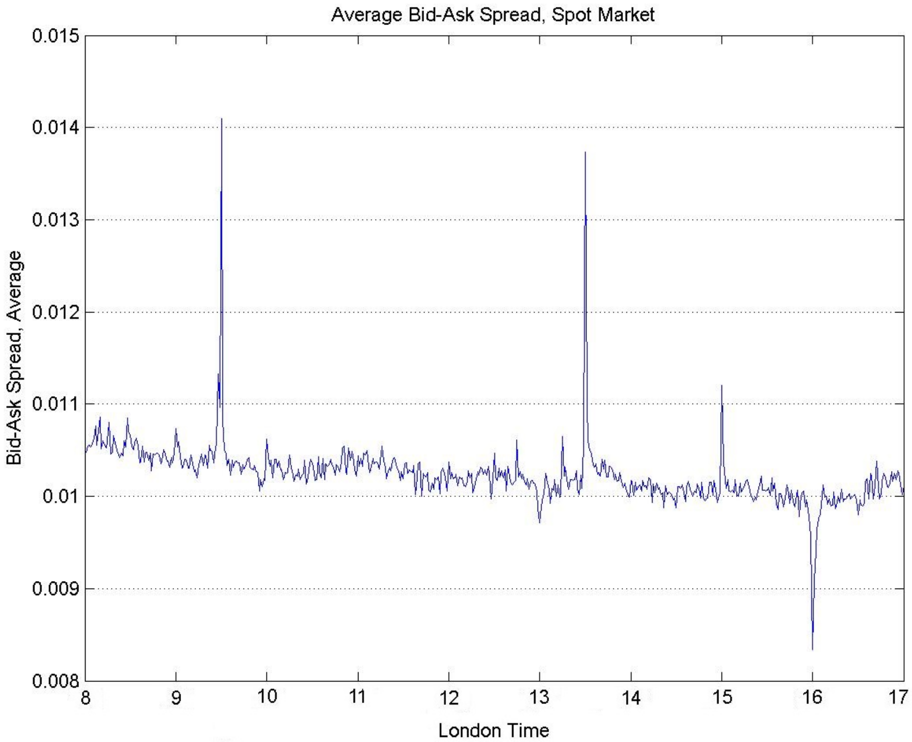
Figure 4: Futures Market Intraday Order Flow GBP/USD



concentrated and the new information is incorporated into prices and market makers attempt to protect themselves by increasing the spread.

Despite the large concentration of trades at the 4pm Fix, interbank spreads reduce significantly. This specific behaviour of the spread at the Fix could be explained by the uninformative nature of fill-at-fix orders and the competition among market makers. Fill-at-fix orders will be executed at 4pm at a price that is unknown at the time of their submission. Thus their information content should be limited. In our regression analysis section, we examine in detail the information content of order flow at the Fix. At the same time, due to the high concentration of trades there is also competition among market makers to attract trades and these predictable patterns in rate behaviour may also allow market makers to trade more profitably despite higher volatility. So, due to lower search costs, increased matching efficiency, increased participation by less-informed market participants and

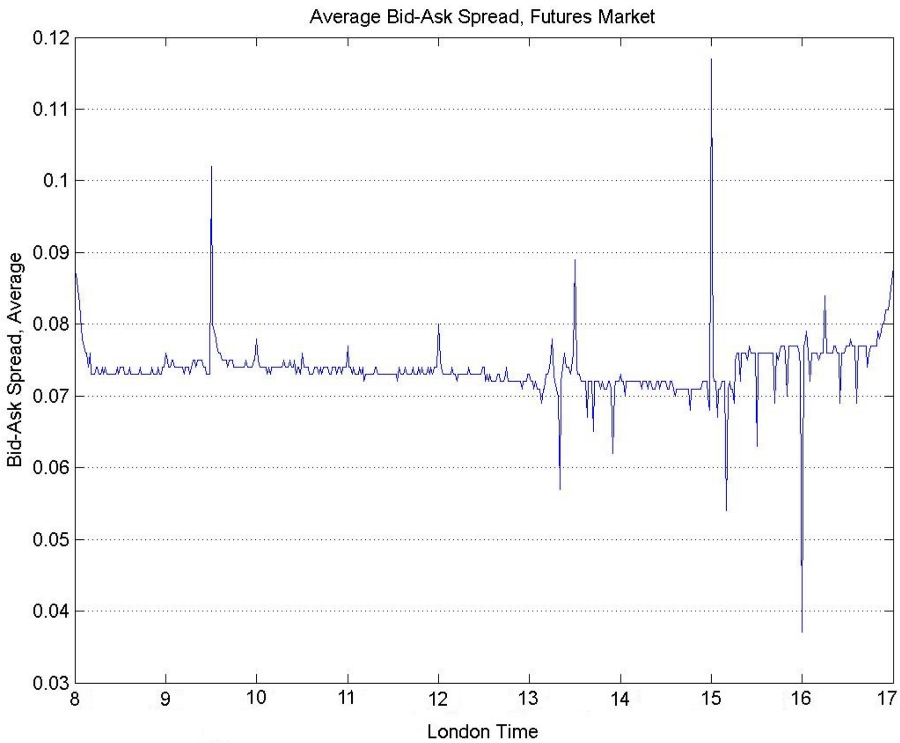
Figure 5: Spot Market Intraday Spread GBP/USD
(measured in bps)



the competition among market makers, spreads will tend to reduce. Interestingly, there is no obvious drop in spreads at the other fixes. This is our first piece of evidence that the 4pm Fix is different to other periods of high activity during the trading day.

In futures markets, we observe a slightly different pattern for the average bid-ask spread. Spreads are slightly higher during the opening and closing periods of the trading session. Usually, currency futures traders tend to square up or close any open positions at the end of each trading day to limit their overnight exposure or for margin requirement reasons. Spreads tend to spike at the same points in time as in the spot market, but the major upward spike in the futures markets is during the 3pm Fix (most probably associated with the 10am Eastern Time option expiration cut-off point and the U.S. macro news release at 3pm London time). The average spread tends

Figure 6: Futures Market Intraday Spread GBP/USD
(measured in bps)

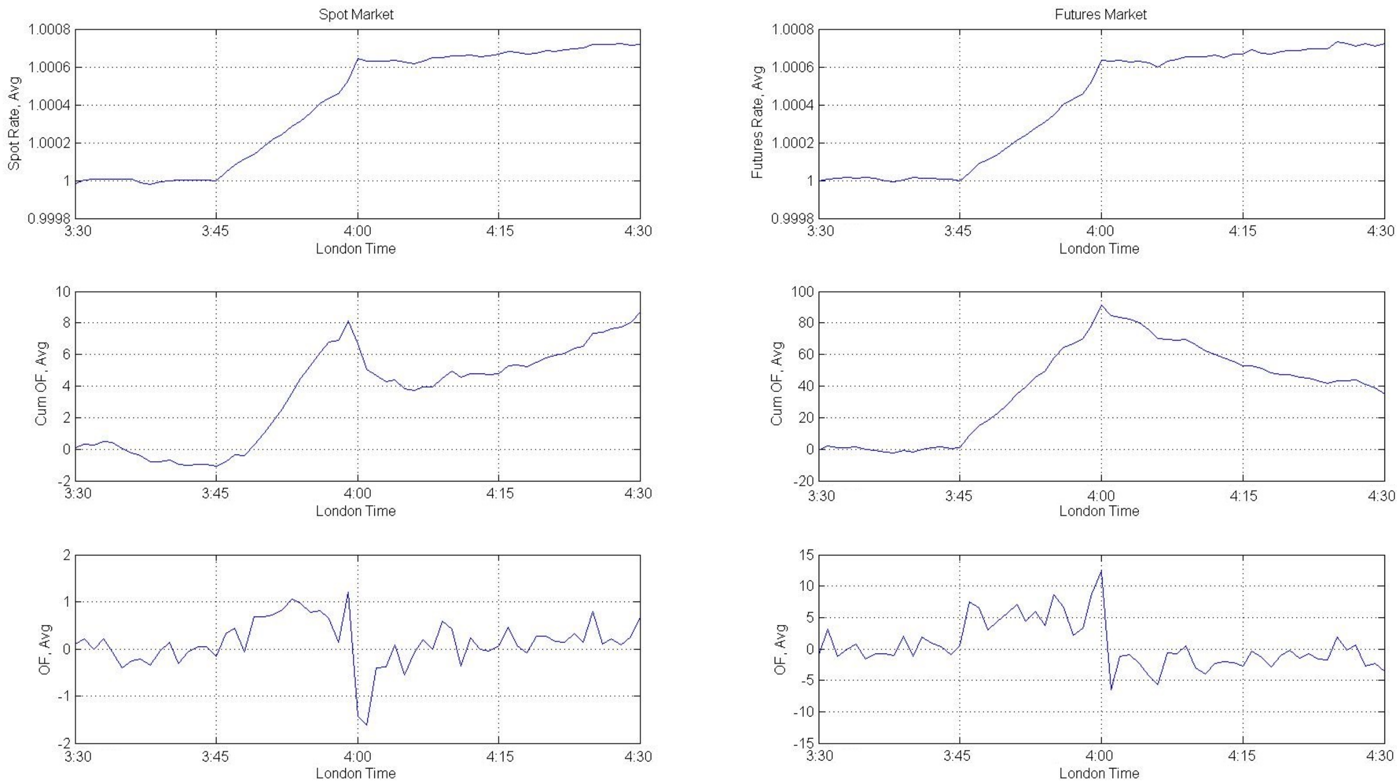


to reduce at the Fix, but unlike the spot market, this reduction in the spread is not unique and other downward spikes in the spread can be observed. Finally, we note that there is higher variability of the spread in the futures markets as compared to the variability of the average spread in the spot market.

4.1 Price-Flow Dynamics

In order to understand better the behaviour of spot prices around the Fix, we plot the average price path for GBP/USD spot and forward rates, order flows and cumulative order flows around the Fix conditioned on the pre-Fix price change. The USD/GBP spot and futures prices correspond to the price of the last trade of every minute of trading activity which, for comparability across days, are indexed to 1 at 3:45pm. Similar graphs for spot rates can also be found in Evans (2016) and Osler and Turnbull (2016). We focus on a window spanning the 30 minutes before and after the 4pm Fix. The full sample of days is split according to whether the spot price movement over the 3:45-4:00pm period is positive or negative. We plot our results for positive pre-Fix spot price movements only since negative days are a mirror image (see Appendix C). We extend the analysis of Evans (2016) and Osler and Turnbull (2016) by also considering the behaviour of inter-dealer order flows around the Fix and by simultaneously examining price and flows in the futures market.

Figure 7: Price-Flow Dynamics around the Fix GBP/USD.
(Full Sample Period, Positive Spot Price Movement before the Fix)



The upper left cell of Figure 7 shows that if we only examine days on which the dollar appreciated in the 3:45-4:00 window, the average magnitude of the appreciation is around 6.5bp. Similar results are also reported by Evans (2016) and Osler and Turnbull (2016). Recall that it is market practice that all fill-at-fix orders must be submitted to dealer banks before 3:45pm. At 3:45 the bank knows all of the orders it has to fulfil at the Fix rate. From this time (and not before) the exchange rate adjusts. The futures rate, tied to the spot rate through the arbitrage relation, follows a very similar path (top right cell). Press coverage of manipulation in the forex market has highlighted certain days where the spot rate reversed substantially immediately following the Fix, while Evans (2016) highlights a more systematic price reversal in a broad set of currencies. Our analysis - which does not seek to test for the presence of manipulation - suggests that, on average, there is a tiny reversal in spot or futures rates soon after the Fix of the order of less than one-half of a basis point. If we consider the full 30-minute post-Fix window there is some evidence of slight under-shooting at the Fix as both spot and futures rates have slight positive trends in the post-Fix interval.

The bottom left cell of Figure 7 plots the average behaviour of interbank order flows (conditional on an appreciation of the dollar in the 15-minutes leading up to the Fix), with cumulated flows in the centre left cell. Having been essentially flat before 3:45, order flows turn consistently positive in the 15-minute window before the Fix. Banks are aggressively buying the dollar in the run-up to the fix and the dollar is appreciating. This buying pressure may result from inventory adjustments and risk management operations of dealer banks in response to the fill-at-fix orders submitted by customers. However, in the final minute before the Fix interbank flows reverse and become negative, remaining so for several minutes after the Fix. This reversal, interestingly, has little or no effect on the spot rate, which as we have seen is essentially flat after the Fix.

Cells in the right column of Figure 7 relate to the futures market. Futures flows pre-Fix largely follow a similar path to that observed in the spot market. Starting at 3:45 futures flows are, on average, consistently positive and remain so until the Fix begins. Once the Fix begins, futures flows then consistently reverse and remain negative for the subsequent thirty minutes. Post-Fix flows reverse approximately 50% of the pre-Fix cumulated flow. Despite this, the futures price remains little changed - and if anything appreciates slightly -

in the post-Fix interval.

Given the arbitrage relationship between spot and forward rates it is not surprising that they move together. However, the other four graphs in Figure 7 each present interesting issues. First, there is an apparent disconnect between exchange rates and order flow in both spot and forward markets after the Fix. In the case of the futures market, the flow is consistently negative until 4:30 yet the futures rate rises. While the positive flow in the spot market from around 4:05 might account for this, the strong negative spot order flow during and immediately after the Fix - when futures order flow is also negative - does not appear to drive a fall in the spot or futures rate. We return to this in more detail below in our regression analysis where we show that the price impact of spot market flows is extremely low during and immediately after the Fix (and is lower than usual in the futures market too). Aggressive interbank selling at the Fix then has no price impact. By the time price impact coefficients return to normal levels, offsetting positive spot and negative futures flows lead to a relatively stable exchange rate.

Second, the correlation between spot and futures order flow is strongly positive pre-Fix yet negative post-Fix. In subsequent sections we show that this is a pattern common to all 'unusual' trading intervals. Pure news announcement periods such as 9:30am, pure fix intervals such as the ECB fix at 1:15pm, and hybrid periods such as 3pm are each characterised by aggressive futures buying before the event (when spot flows are also positive) being followed by futures selling after the event (when spot flow patterns are more nuanced). Futures returns flows appear predictable around these major events within the trading day.

Third, focusing more closely on flows around the Fix, it is apparent that while futures flows are on average positive in each one minute interval in the fifteen minutes up to and including the Fix, spot flows are positive until the start of the one-minute Fix window but reverse and are strongly negative on average during the Fix window. Spot flows remain negative and futures flows become negative in 4:01. The interesting inconsistent element is the spot flow behaviour during the Fix window. Our analysis below shows that this is unique to the 4pm Fix among the unusual trading intervals. Be they pure fixes, information events or combinations of the two, at no other time do we observe the rapid reversal of spot flows during and immediately after the event.

There is only a small literature within which we can attempt to place our findings. Evans (2016) demonstrates that the behaviour of exchange rates around the Fix are unlike those observed at other times. Figures 1 and 3 show that spot trading volume and spot order flow around the Fix are also very abnormal. Evans (2016) further provides evidence of return reversals around the Fix, particularly at month end.[9] Osler and Turnbull (2016) construct a model of dealer behaviour consistent with both extreme price changes and return reversals at the Fix. Even in their baseline world where dealers act independently, Fix orders are uncorrelated across dealers and dealers are risk neutral profit maximisers, they show that pre-Fix inventory accumulation occurs throughout the pre-Fix window and that dealers optimally take proprietary positions in the same direction as their customers' net Fix orders. Managing the inventory requirements of customers' Fix orders in a fifteen-minute window, together with their proprietary positions naturally leads to high trading volumes before the Fix. As Melvin and Prins (2015) and our data suggest, the high volumes leading up to the Fix are also strongly directional and so rates adjust during the pre-Fix window. This price impact caused by dealers fulfilling customer Fix orders makes their proprietary trades profitable. The price reversal at the Fix is caused by the liquidation of the dealers' proprietary positions. Evans (2016) finds only very small rate reversals on average in his much longer data set, but by focusing on end-month days when Fix orders are likely caused by portfolio rebalancing flows and so are common across dealers, he shows both larger price run-ups leading to the Fix and larger reversals afterwards. Our interbank spot data show only modest reversals.[10] However, we can see that spot flows substantially reverse. This is independent evidence in support of the model in Osler and Turnbull (2016).

[9] Evans (2016) data source is Gain Capital which aggregates data from more than 20 banks and brokerages.

[10] And our relatively short data sample limits our ability to focus solely on month-end observations.

As noted above and discussed more below, one puzzle from Figure 7 is why exchange rates do not adjust during and soon after the Fix when there is aggressive selling in both spot and futures markets. Our regression analysis below shows that the price impact of trades during the Fix collapses to almost zero. Dealers can then liquidate their proprietary positions without this being evident in the spot price. The interbank flow data, however, reveals this activity more clearly. In addition, we see that the positive build-up of inventory in the spot market is matched by a build-up in the futures market. It is unlikely that futures positions are being used to satisfy spot customer Fix orders. Rather, these too are likely to be speculative, either built up in the knowledge of Fix orders or momentum-based driven by the exchange rate movements in the pre-Fix window. Futures positions are then reversed after the Fix, but much more slowly than in the interbank market, probably because the price impact of futures flows is maintained to a much greater degree meaning positions have to be liquidated less aggressively.

In the next section, we highlight the behaviour of the relationship between order flows and exchange rates around the Fix more formally using regression analysis.

4.2 Regression Analysis

In order to examine more formally the relationship between rate changes and contemporaneous order flow, we start our analysis with the framework proposed by Evans and Lyons (2002). Our generic order flow model is represented by the following equation for the spot market (there are analogous equations for the futures markets that we discuss below):

$$\Delta S_t = \alpha_1 + \beta_1 X_t^S + \epsilon_t \tag{1}$$

where ΔS_t is the minutely log change in spot exchange rate, X_t^S is the minutely net inter-dealer order flow, and ϵ_t is a white-noise error term. We expect β_1, the coefficient on contemporaneous order flows, to be positive and significant such that the purchase of USD by dealer banks is associated with a depreciation of the GBP (increase in the exchange rate versus the US Dollar). This positive impact is usually explained via the information discovery process of the dealer, who updates his/her quotes after receiving orders from clients and other dealers.

The majority of FX order flow research papers concentrate on one market at a time. However, since currency futures rates are contractually linked to the spot rate it is of interest to investigate how order flow in one market may be used to explain the returns in the other market. The reason for considering cross-market effects between the spot and the futures market, stems from the assumption that an informed trader in one of those markets may use his/her private information to devise profitable trading strategies to use in the other market. Private information could result from proprietary information about order flow or from superior analysis of the effects of public news announcements. Thus, observed order flow by other market participants in one market may lead them to revise their expectations and so order flow in one market might drive rate changes in the other market. In this section of our analysis, we investigate the importance of the cross-market order flow in exchange rate determination, focusing on the information content of futures order flow and the role of the futures market in spot foreign exchange price discovery.

We extend equation 1 to include order flow from both markets as follows:

$$\Delta S_t = \alpha_1 + \beta_1 X_t^S + \gamma_1 X_t^F + \epsilon_t \tag{2}$$

Note that it is possible that price discovery in spot market occurs exclusively in the spot market and that futures prices quickly adjust to spot price changes through Covered Interest Parity (CIP) without adding significant information in the price determination process (Rosenberg and Traub (2009)). If this is the case, then we would not find a statistically significant coefficient on futures order flow in equation 2. If we find a positive, statistically significant effect of futures order flow on spot exchange rate returns, this confirms that there is market-relevant information in futures order flow and more importantly, different information from that it is conveyed by spot inter-dealer order flow.

Finally, we extend the empirical model to recognise first, that price dynamics may be important and second, that spot and futures prices are linked through an arbitrage relationship. Thus, we include lagged spot returns to control for the autocorrelation in returns together with the basis ($Basis_{t-1} = log(S_{t-1}) - log(F_{t-1})$). Our model is then described by the following equation:

$$\Delta S_t = \alpha_1 + \beta_1 X_t^S + \gamma_1 X_t^F + \eta_1 Basis_{t-1} + \lambda_1 \Delta S_{t-1} + \epsilon_t \tag{3}$$

We estimate all equations using OLS, and report Newey-West standard errors that are consistent in the presence of both serial correlation and heteroskedasticity (max 5 lags). The results are reported in the first three columns of Table 2.

Table 2: Order Flow Regression Model

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
X_t^S	0.158***	0.099***	0.099***	0.164***	0.104***	0.103***	0.094***
	(140.414)	(91.957)	(91.949)	(151.061)	(96.182)	(96.301)	(86.090)
$X_t^S * D_{4pm}$				-0.156***	-0.105***	-0.106***	-0.095***
				(-32.707)	(-28.800)	(-29.095)	(-25.541)
X_t^F		0.032***	0.032***		0.031***	0.032***	0.034***
		(109.818)	(111.082)		(108.131)	(109.404)	(107.713)
$X_t^F * D_{4pm}$					-0.001	-0.001	-0.003**
					(-0.565)	(-0.705)	(-2.201)
$Basis_{t-1}$			-0.039***			-0.039***	0.072***
			(-31.378)			(-31.451)	(17.400)
ΔS_{t-1}			-0.064***			-0.064***	-0.042***
			(-23.893)			(-24.127)	(-18.161)
Constant	0.000	0.000***	0.001***	0.000	0.000***	0.001***	-0.002***
	(1.050)	(3.004)	(28.772)	(1.034)	(2.980)	(28.823)	(-16.576)
Observations	558,360	558,360	558,359	558,360	558,360	558,359	558,359
R-squared	0.210	0.386	0.393	0.217	0.389	0.397	0.339

All equations are estimated using OLS with Newey-West standard errors (max 5 lags). We multiply the order flow coefficients with 100, t-statistics are given in parentheses below coefficient estimates. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

The first three columns report results for the benchmark specifications. Column (1) shows that the coefficient on spot order flow is positive and statistically significant, as expected. This result suggests that contemporaneous inter-dealer order flow of signed trades has explanatory power over price changes. This is now well-established in the literature. Column (2) shows that futures order flow contains information that is relevant for spot determination and that it is different information from that conveyed by spot order flow.[11] Adding order flow from the futures markets increases the fit significantly, R^2 is significantly larger for both equations, as compared to column (1). In column (3) we note that both the lagged basis and lagged spot returns are highly statistically significant but that their inclusion leaves the coefficients on spot and futures order flows unaffected. In unreported results we also find that further lagged returns and returns from the futures market are also significant but coefficients are relatively small in economic terms and they do not affect the key coefficient in the regression. These are the benchmark findings. In a regression with minutely spot returns as a dependent variable there is a large, positive and robust coefficient on contemporaneous order flows in the spot and futures markets.

We now examine what happens when we consider flows at the 4pm Fix. Specifically, we augment each of the benchmark specifications with extra terms that allow order flows in the 4pm Fix minute to have a different coefficient to the rest of the trading day. For example, the simplest specification, equation 1, now becomes:

$$\Delta S_t = \alpha_1 \,+\, \beta_1 X_t^S \,+\, \beta_2 X_t^S * D_{4pm} \,+\, \epsilon_t \tag{4}$$

where D_{4pm} is a dummy variable that takes the value 1 for the one minute of the 4pm Fix and zero otherwise. The average effect of order flow on spot prices during the day (excluding the 4pm Fix window) is then given by β_1 while the effect of flows during the 4pm Fix window is given by $\beta_1 + \beta_2$. The results reported in column (4) show that the 4pm adjustment almost exactly offsets the average coefficient, meaning that spot order flow in the one-minute of the Fix has essentially zero effect on spot returns in that minute. Column (5) augments the basic regression with futures order flow and an interaction dummy for futures flows at 4pm. Noticeably, the coefficient on futures order flow is unaffected - futures market order flow during the Fix minute has exactly the same effect on spot returns as it does on other times of day. Column

[11]The reverse is also true. Spot order flow is significant when the dependent variable is the futures return even when included alongside futures market order flow.

(6) confirms this in an expanded specification while column (7) considers futures returns as the dependent variable. Again, the effect of spot order flows on returns disappears at the Fix and while the impact of futures flows is statistically significantly lower, the economic magnitude of any adjustment is small.

As noted above, when the GBP/USD rate rises in the pre-Fix window a substantial fraction of the pre-Fix positive spot order flow is reversed during and immediately after the Fix.[12] This would be consistent with dealers, knowing they have fill at Fix orders to fulfil and knowing either through collusion or experience that other dealers likely have similar needs, buying more aggressively than needed simply to service their customers' orders in the pe-Fix window before selling the excess inventory at profit during and after the Fix. The regression results suggest that the aggressive net selling during the Fix can be done with essentially no price impact (and we will show below that price impact immediately after the Fix is lower than usual). This implies that dealers can buy aggressively pre-Fix for their own account and liquidate these positions with no price impact and with very small transactions costs since interbank bid-ask spreads narrow substantially at the Fix (Figure 5).

4.2.1 Other Currencies

Our focus so far has been on the GBP/USD exchange rate, the most active currency pair on the Reuter's dealing platform. In this section we demonstrate that our key Fix-related findings for GBP/USD carry over fully to the two other actively traded currency pairs, AUD/USD and NZD/USD.

We report results for three sets of regressions. The first is our basic return-flow regression with an interactive dummy variable allowing the order flow to bear a different coefficient during the Fix window. We run these regressions using both spot and futures returns as the dependent variable (with the spot or futures order flow as regressor as appropriate). These results are reported in the top panel of Table 3. The spot regressions show that the usual positive

[12] The situation is reversed when the GBP/USD falls pre-Fix and negative flow is partially offset by aggressive interbank buying during and immediately after the Fix.

coefficient on order flow is almost completely offset by the interactive dummy variable, meaning that the price impact of flows during the Fix goes to zero for all three currencies. The dummy is also negative in the futures market regressions but the magnitude is such that three-quarters of the "normal" price impact remain during the Fix.

The second panel adds in some flow dynamics in the form of a one-minute lagged flow terms and an associated interactive dummy term that allows the impact of lagged flows to also differ from the norm during the Fix. These dynamic terms are all statistically significant but we note that they add very little to the explanatory power of the regressions since R^2 values are unchanged from those seen in the first panel. Lagged flows are negative in each regression with a coefficient at least an order of magnitude smaller than seen for the contemporaneous flow term. Lagged flows during the Fix have an even more negative impact than usual in five of the six regressions, suggesting that aggressive buying immediately before the fix leads to a fall in the rate during the Fix. Since the price impact of flows during the Fix is close to zero, this reversal is consistent with price manipulation via so-called "banging the close" whereby aggressive buying immediately before the Fix temporarily drives up the rate.

In the final panel of Table 3 we introduce cross market flows (and drop the dynamics). Cross market flows are economically relevant, especially for spot exchange rates where we observe noticeable increases in R^2 values. These regressions highlight our key finding even more starkly. The price impacts of spot flows - normally significantly positive - all fall to essentially zero during the Fix for all three exchange rates and in both spot and futures markets. Futures order flow retains its full power during the Fix for the spot market but this drops slightly for both the GBP/USD and AUD/USD during the Fix for futures rates.

4.3 Price Impact Through the Trading Day

The regression results reveal that while the price impact of inter-bank spot order flow is, on average, highly positive, during the 4pm Fix window is

Table 3: Order Flow Model with Dummy Variables at the Fix, All Currencies

	Spot Rates			Futures Rates		
	GBP	**AUD**	**NZD**	**GBP**	**AUD**	**NZD**
$\boldsymbol{X_t^i}$	0.1637^{***}	0.1691^{***}	0.3123^{***}	0.0411^{***}	0.0529^{***}	0.1722^{***}
	(145.30)	(214.36)	(137.89)	(108.84)	(131.47)	(107.21)
$\boldsymbol{X_t^i * D_{4pm}}$	-0.1559^{***}	-0.1330^{***}	-0.3342^{***}	-0.0104^{***}	-0.0186^{***}	-0.0391^{**}
	(-32.67)	(-23.99)	(-17.56)	(-7.14)	(-12.03)	(-2.11)
$\boldsymbol{R^2}$	0.22	0.28	0.10	0.28	0.17	0.09
$\boldsymbol{X_t^i}$	0.1648^{***}	0.1707^{***}	0.3135^{***}	0.0416^{***}	0.0532^{***}	0.1722^{***}
	(145.54)	(217.14)	(137.93)	(113.82)	(135.22)	(107.39)
$\boldsymbol{X_{t-1}^i}$	-0.0149^{***}	-0.0191^{***}	-0.0189^{***}	-0.0050^{***}	-0.0049^{***}	-0.0062^{***}
	(-24.35)	(-35.19)	(-10.76)	(-31.18)	(-22.75)	(-6.09)
$\boldsymbol{X_t^i * D_{4pm}}$	-0.1568^{***}	-0.1349^{***}	-0.3350^{***}	-0.0108^{***}	-0.0186^{***}	-0.0386^{**}
	(-32.61)	(-24.21)	(-17.56)	(-7.45)	(-11.98)	(-2.10)
$\boldsymbol{X_{t-1}^i * D_{4pm}}$	-0.0369^{***}	-0.0390^{***}	-0.0068^{***}	-0.0030^{*}	-0.0155^{**}	0.1181^{***}
	(-4.36)	(-5.25)	(-2.45)	(-1.71)	(-2.10)	(4.10)
$\boldsymbol{R^2}$	0.22	0.28	0.10	0.28	0.17	0.09
$\boldsymbol{X_t^S}$	0.1036^{***}	0.1123^{***}	0.2648^{***}	0.0942^{***}	0.0987^{***}	0.2021^{***}
	(89.91)	(131.12)	(120.03)	(80.01)	(101.73)	(82.97)
$\boldsymbol{D_{4pm}^S}$	-0.1052^{***}	-0.1020^{***}	-0.2832^{***}	-0.0942^{***}	-0.0929^{***}	-0.2279^{***}
	(-28.66)	(-20.46)	(-15.52)	(-25.35)	(-18.18)	(-12.21)
$\boldsymbol{X_t^F}$	0.0314^{***}	0.0354^{***}	0.1143^{***}	0.0339^{***}	0.0394^{***}	0.1533^{***}
	(96.62)	(100.29)	(91.00)	(94.62)	(99.22)	(96.97)
$\boldsymbol{D_{4pm}^F}$	-0.0008	-0.0003	0.0011	-0.0031^{**}	-0.0058^{**}	-0.0205
	(-0.56)	(-1.38)	(0.63)	(-2.16)	(-3.55)	(-1.10)
$\boldsymbol{R^2}$	0.39	0.39	0.15	0.33	0.21	0.12

All equations are estimated using OLS with Newey-West standard errors (max 5 lags). We multiply the order flow coefficients with 100, t-statistics are given in parentheses below coefficient estimates. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

drops to essentially zero. It could be that price impact is inherently volatile intraday and that the 4pm Fix is just an example of a low impact period. We therefore estimate price impacts from equation 1 for each one-minute interval during the trading day. We then sort according to the estimated price impact coefficient and report the extreme observations in Table 4. We also report analogous futures market coefficients from a regression of futures returns on futures order flow.

Of the 539 one-minute windows during the active trading day, the 4pm Fix has the lowest spot price impact. The coefficient is less than one-fifth the value of the next smallest window (11:38am[13]) and an order of magnitude smaller than the 3rd ranked coefficient (10am). The 4pm Fix coefficient is the only one in the entire sample that is not statistically different from zero. The futures market price impact coefficient for this interval is also relatively small but is still of comparable magnitude to estimates from other intervals. Its remains statistically significantly positive. It is clear that 4pm is best characterised as an extreme observation in the spot market. It is also noteworthy that 4:01pm interval bears the 5th smallest coefficient.[14] Beside these two intervals, the price impact coefficient is relatively stable.

While the 4pm Fix is the most noticeable outlier event, the 10am, 11am, 1pm and ECB fixes all appear in the top half of the table. The 3pm fix is contaminated by US macro news announcements yet this too has a relatively small spot price impact coefficient. Fixes in general can be characterised as periods in which imbalances in interbank trades are associated with smaller than usual exchange rate movements.

It might appear that low price impact intervals are equivalent to periods of high activity. Fixes are undoubtedly high volume intervals but the bottom half of Table 4 reports the other extreme of the distribution - those one-minute intervals where spot price impacts are largest. A different type of high volume interval appears here, specifically the macro news announcements at

[13]We have no good explanation for why 11:38 is particularly special. In the bottom half of the table, 10:43 is highlighted as an interval with a particularly high price impact and, again, we have no explanation for this.

[14]15:59, the minute before the 4pm Fix, ranks 19th and has a spot price impact coefficient of 0.127.

Table 4: Ranked Spot Price Impact Coefficients

Spot Rank	Time	X_t^S	X_t^F	Futures Rank	Notes
1	16:00	0.0078	0.0308	32	4pm Fix
2	11:38	0.0460	0.0498	380	
3	10:00	0.0942	0.0436	257	10am Fix
4	11:40	0.1022	0.0421	235	
5	16:01	0.1043	0.0321	42	post-4pm Fix
6	13:15	0.1074	0.0317	38	ECB Fix
7	15:00	0.1104	0.0381	151	3pm Fix + US macro
8	13:00	0.1143	0.0339	67	1pm Fix
9	15:43	0.1148	0.0361	112	
10	11:00	0.1170	0.0516	415	11am Fix
⋮					
270	12:31	0.1628	0.0501	390	median
⋮					
530	12:46	0.2126	0.0528	444	
531	8:02	0.2149	0.0587	522	
532	8:05	0.2161	0.0498	377	
533	8:16	0.2274	0.0515	413	
534	8:53	0.2318	0.0569	506	
535	9:28	0.2511	0.0643	536	pre-UK macro
536	9:30	0.2726	0.0598	527	UK macro
537	10:43	0.3010	0.0685	538	
538	13:30	0.3207	0.0328	51	US macro
539	10:30	0.3275	0.0752	539	

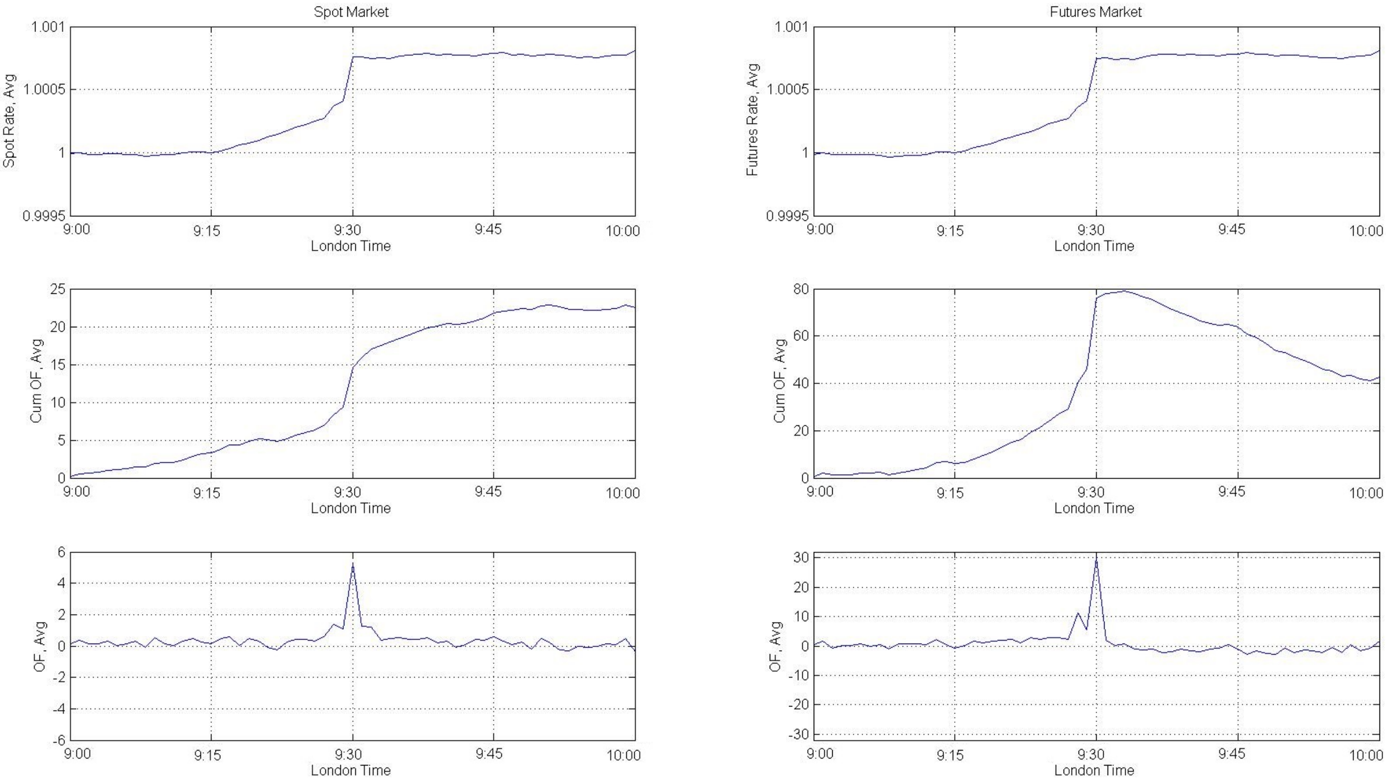
9:30, 10:30 and 13:30. With the exception of 13:30, there is also reasonable consistency between spot and futures market price impacts. Indeed, 10:30 has the highest point estimate for both spot and future markets. When new public information is released imbalances in interbank trades are associated with larger price adjustments. Our regressions make no attempt to control for endogeneity, and while it is the norm in the literature to assume causation runs from orders to prices, in a period when significant public information is revealed inferring causation is particularly troublesome. Nevertheless, the contrast between fixes in the top half of the table, and information revelation intervals in the lower half is stark, and highlights the fact that the 4pm Fix is particularly noteworthy. The full set of coefficients also makes clear that there is a trend for price impact to decline over the trading day. This explains the presence of several early morning intervals in the lower part of the table.

The figures presented in Section 4 and the results in Table 3 highlight the importance of certain points of the trading day. In particular, in addition to the 4pm Fix, the 9:30am UK macro news announcement, the 3pm Fix plus US macro news announcement and the 1:15 ECB Fix each appear to be critical points. In this section we examine returns-flows relationship around these points and we compare our findings with those for the London 4pm Fix.

4.3.1 9:30am London Time

We start by considering the flow-return relationship around 9:30am London time. This is when many major UK macroeconomic indicators are released. In other words, is a point in time where new public information is priced by the market and trading volumes are high. Market participants develop expectations about the future state of macroeconomic variables. When macroeconomic announcements contain surprises the price will change and adjust to a new level (Almeida et al. (1998); Chaboud et al. (2004)). This compares with price behaviour during fixing periods when prices respond to temporary inventory and risk management needs driven by the private information contained in customers' fix orders. Therefore, it is instructive to examine and contrast the returns-flows relation during the Fix and the time of public macroeconomic announcements.

Figure 8: Price-Flow Dynamics around 09:30am London Time, GBP/USD (Full Sample Period, Positive Spot Price Movement)



As is evident from our initial graphical analysis in Figure 8, UK macroeconomic data releases at 9:30am are clearly accompanied by large spikes in trading activity, volatility and spreads. The average spot price gradually increases by approximately 7 basis points in the build up to the news release and then sharply adjusts to the new level. The spot rates increase prior to 9:30am is similar in size to the spot rates increase prior to the 4pm Fix, however the price path prior 9:30am is more convex than the price path before the Fix with all aggressive trading concentrated within a few minutes of the news announcement.

Average order flow is marginally positive in the periods before and after the news release time and spikes during the point of the news release. This pattern might suggests that macro news triggers trading that contributes to the price discovery process. However, the spike in order flow at the time of the release could also be a result of the adjustment of dealers inventories to the new asset valuation with little incremental information value in trades. The behaviour of average order flow in the 15 minutes before the news release is significantly different to the one observed in the 15 minutes before the Fix. Average order flow does not increase in the 15 minutes build up period to the news release, as it is the case with the 4pm Fix. Futures returns and flows behave in a similar manner and futures flows matter for both markets.

One of the puzzles in Figure 7 was the pronounced difference in spot and futures order flows after the Fix. Once the immediate reversal of spot order flows is complete, spot flows are clearly positive and futures flows are negative. These appear to offset each other such that exchange rates barely change. Figure 8 also exhibits the same patterns. Indeed, we will see this repeated in each event considered below, to some extent. It appears that futures traders, having bought before and during an event with positive price movements sell after the event and reap profits. Conversely, spot flow remains positive after the event. The net effect on the exchange rate from these offsetting flows, though, is zero.

Regression results (Table 5) confirm the larger than usual coefficient on spot order flows for the GBP/USD exchange rate at 9:30. Although the 9:30 announcements relate to the UK economy, there is some evidence that the AUD and NZD markets are also similarly affected, with the coefficient on either spot and/or futures flows increasing at this time.

4.3.2 3pm London Fix

Our second intraday comparison point is the 3pm London fix. At this point we have: the one-minute calculation window of the regular hourly fix, the option expiration cut-off (10am New York time (ET)) as well as the announcement of some U.S. macroeconomic indicators (10am ET). The option expiration cut-off is a time where almost all major FX options expire. A

Table 5: Returns-Order Flow Regressions around 9:30am London Time

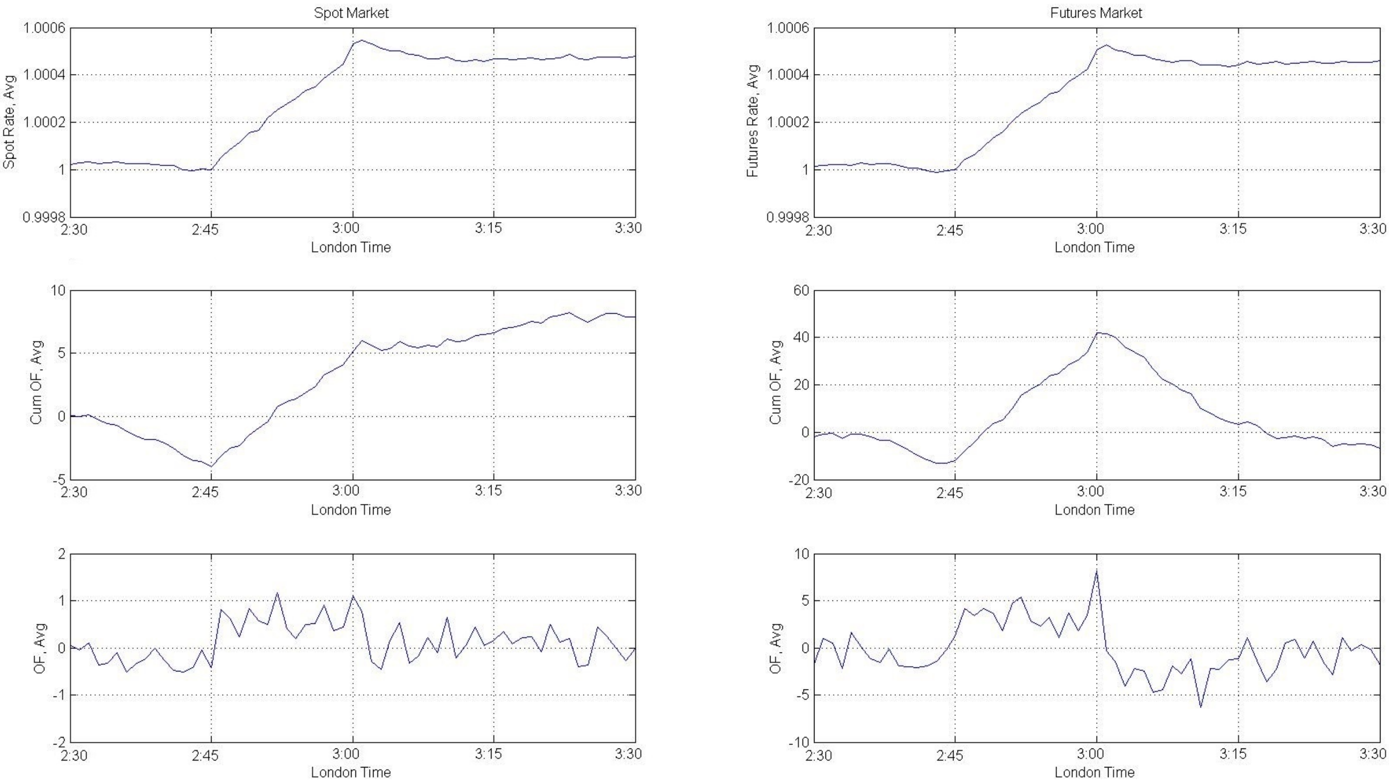
	Spot Rates			Futures Rates		
	GBP	**AUD**	**NZD**	**GBP**	**AUD**	**NZD**
$\boldsymbol{X_t}$	0.1565***	0.1660***	0.3010***	0.0406***	0.0526***	0.1715***
	(143.87)	(202.60)	(125.60)	(116.77)	(132.07)	(105.28)
$\boldsymbol{X_t * D_{9:30am}}$	0.1161***	0.0217	0.1003**	0.0191*	0.0227***	0.0921***
	(3.45)	(1.13)	(2.10)	(1.66)	(4.65)	(3.90)
$\boldsymbol{R^2}$	0.21	0.28	0.10	0.28	0.17	0.09
$\boldsymbol{X_t}$	0.1573***	0.1673***	0.3018***	0.0411***	0.0529***	0.1716***
	(144.30)	(204.95)	(125.55)	(123.38)	(135.43)	(105.47)
$\boldsymbol{X_{t-1}}$	−0.0146***	−0.0189***	−0.0187***	−0.0050***	−0.0049***	−0.0063***
	(-23.80)	(-34.49)	(-10.60)	(-31.30)	(-22.80)	(-6.12)
$\boldsymbol{X_t * D_{9:30am}}$	0.1153***	0.0212	0.1007**	0.0188*	0.0226*	0.0914***
	(3.43)	(1.12)	(2.12)	(1.70)	(1.96)	(3.91)
$\boldsymbol{X_{t-1} * D_{9:30am}}$	0.0182	0.0060	−0.0813*	0.0168***	0.0078	0.0444**
	(1.04)	(0.48)	(-1.87)	(3.88)	(1.14)	(2.13)
$\boldsymbol{R^2}$	0.21	0.28	0.10	0.28	0.17	0.09
$\boldsymbol{X_t^S}$	0.0987***	0.1096***	0.2546***	0.0897***	0.0962***	0.1942***
	(91.53)	(125.68)	(110.78)	(81.73)	(98.56)	(78.28)
$\boldsymbol{X_t^S * D_{9:30am}}$	0.0407	0.0140	0.1073**	0.0446	0.0169	0.0954**
	(1.17)	(0.75)	(2.30)	(1.31)	(0.93)	(2.36)
$\boldsymbol{X_t^F}$	0.0314***	0.0356***	0.1154***	0.0338***	0.0395***	0.1537***
	(106.19)	(101.12)	(90.49)	(103.31)	(100.18)	(96.01)
$\boldsymbol{X_t^F * D_{9:30am}}$	0.0150	0.0134***	0.0358	0.0123	0.0159***	0.0754***
	(1.23)	(2.95)	(1.56)	(1.01)	(3.41)	(3.42)
$\boldsymbol{R^2}$	0.39	0.39	0.15	0.33	0.21	0.11

All equations are estimated using OLS with Newey-West standard errors (max 5 lags). We multiply the order flow coefficients with 100, t-statistics are given in parentheses below coefficient estimates. ***$p < 0.01$, **$p < 0.05$, *$p < 0.1$.

significant portion of those over-the-counter FX options in the inter-bank market are European type options with delivery of the underlying asset. Exercise and settlement of the options is performed by London based trading centres, as the London FX trading session coincides with early morning US trading hours as well as Asian late trading hours.

Conditional on there being a price increase between 2:45 and 3:00pm, the average spot price tends to gradually increase in the pre-Fix window by approximately 5.5 basis points, slightly less than the 6.5bp moves typically observed at the 4pm Fix. There is more evidence of a price overshoot at 3pm than at the Fix, with prices drifting lower in the fifteen minutes after the 3pm fix before stabilising. This does not seem to be caused by spot interbank trading as these flows, though volatile, are still net positive. Rather, it is the

Figure 9: Price-Flow Dynamics around 3pm London Time, GBP/USD
(Full Sample Period, Positive Spot Price Movement.)



now established pattern of futures market sales following a bout of pre-Fix buying that would seem to be responsible.

Regression results provided in Table 6 confirm that the spot flow price impact coefficient drops at 3pm, but only for the GBP/USD rate. If anything, it marginally increases for the AUD/USD while the NZD/USD is unaffected. The second panel of the table suggests there is no change in dynamic relationship between returns and flows for the GBP/USD, but lagged flows at 3pm have a much larger negative impact on returns than normal for the other two exchange rates.

Table 6: Returns-Order Flow Regressions around the London 3pm Fix

	Spot Rates			Futures Rates		
	GBP	**AUD**	**NZD**	**GBP**	**AUD**	**NZD**
$\boldsymbol{X_t}$	0.1586***	0.1659***	0.3012***	0.0410***	0.0526***	0.1715***
	(136.00)	(202.71)	(125.91)	(109.56)	(131.84)	(105.10)
$\boldsymbol{X_t * D_{3pm}}$	−0.0482**	0.0268*	-0.0075	−0.0029*	0.00084*	0.0256
	(-2.38)	(1.88)	(-0.18)	(-1.90)	(1.73)	(1.17)
$\boldsymbol{R^2}$	0.21	0.27	0.10	0.28	0.17	0.09
$\boldsymbol{X_t}$	0.15945***	0.1673***	0.3021***	0.0415***	0.0530***	0.01716***
	(136.38)	(204.92)	(125.79)	(114.89)	(138.89)	(105.18)
$\boldsymbol{X_{t-1}}$	−0.01468***	−0.0189***	−0.0187***	−0.0050***	−0.0049***	−0.0063***
	(-23.94)	(-34.50)	(-10.59)	(-31.15)	(-23.09)	(-6.11)
$\boldsymbol{X_t * D_{3pm}}$	−0.04972**	0.0265*	-0.0082	-0.0032	0.0082	0.0256
	(-2.37)	(1.86)	(-0.19)	(-1.15)	(1.58)	(1.17)
$\boldsymbol{X_{t-1} * D_{3pm}}$	-0.02042	−0.0266***	−0.0766**	-0.0009	−0.0265***	-0.0097
	(-1.19)	(-2.58)	(-2.40)	(-0.45)	(-3.33)	(-0.50)
$\boldsymbol{R^2}$	0.21	0.28	0.10	0.28	0.17	0.09
$\boldsymbol{X_t^S}$	0.0996***	0.1096***	0.2548***	0.0907***	0.0961***	0.1943***
	(86.20)	(125.67)	(110.94)	(77.29)	(98.28)	(78.67)
$\boldsymbol{X_t^S * D_{3pm}}$	−0.0298**	0.0228*	0.0174	-0.0226	0.0319**	0.0236
	(-2.02)	(1.80)	(0.46)	(-1.58)	(2.51)	(0.45)
$\boldsymbol{X_t^F}$	0.0317***	0.0355***	0.1151***	0.0341***	0.0394***	0.1535***
	(97.66)	(100.75)	(90.25)	(95.67)	(99.90)	(95.80)
$\boldsymbol{X_t^F * D_{3pm}}$	0.0023	0.0136***	0.0533***	0.0001	0.0088*	0.0372*
	(0.94)	(3.56)	(2.87)	(0.05)	(1.87)	(1.99)
$\boldsymbol{R^2}$	0.39	0.39	0.15	0.33	0.21	0.11

All equations are estimated using OLS with Newey-West standard errors (max 5 lags). We multiply the order flow coefficients with 100, t-statistics are given in parentheses below coefficient estimates. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

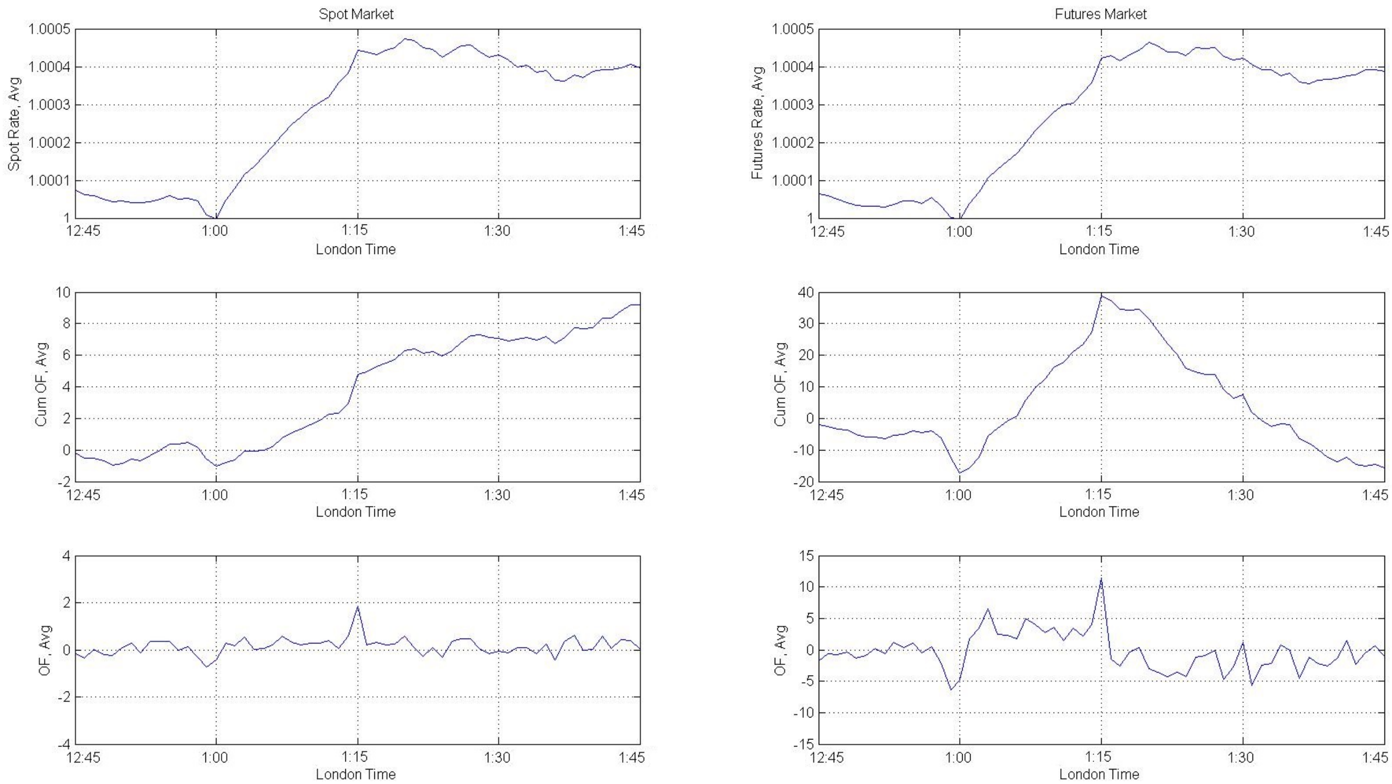
4.3.3 ECB Fix

Finally, we consider the 1:15pm ECB fix. The ECB has been setting, administering and publishing euro foreign exchange benchmark rates for approximately 32 different currencies on a daily basis since January 1999. The Euro foreign exchange rates set by the ECB at 2:15pm CET (1:15 London local time)[15] are also used by a wide range of participants, especially European

[15] Based on the recommendations of the Financial Stability Board on FX benchmarks, as well as the principles for benchmark-setting practices dictated by the European Securities and Markets Authority (ESMA) and the European Banking Authority (EBA), the ECB changed the publication time of the fix from 2:30 CET to 4:00 CET as of July 01, 2016.

non-financial companies both for transaction and information purposes (as e.g. in contractual obligations, internal transactions as well as for financial reporting and inter-company valuation purposes). The benchmark rate is calculated using transactional data between buyers and sellers given that those data are available and reflect sufficient liquidity. In a market where there is lower liquidity, the benchmark rates may be calculated using an average of quoted bid and ask prices for the various currencies against the Euro or prior transactions.

Figure 10: Price-Flow Dynamics around ECB Fix, GBP/USD.
(Full Sample Period, Positive Spot Price Movement)



The ECB fixing rates will continue to be determined using the current methodology, which is based on a point-in-time snapshot at 2:15 CET. These changes underlie ECB's policy to emphasize the "for information only" character of the benchmark rates and discourage their use for transaction purposes.

Conditional on the spot rate rising between 1:00 and 1:15 we observe positive net flows in the spot and forward markets. On average, spot and futures flows at the ECB fix are around two-thirds of those seen at the 4pm Fix. Both spot and futures markets exhibit a positive spike very close to the fixing point (unlike at the Fix where spot flows spike negative during and immediately after the Fix window). Again we observe the reversal of futures flows after the fix, while spot flows continue to be positive.

Table 7: Returns-Order Flow Regressions around the 1:15pm ECB Fix

	Spot Rates			**Futures Rates**		
	GBP	**AUD**	**NZD**	**GBP**	**AUD**	**NZD**
$\boldsymbol{X_t}$	0.1585***	0.1661***	0.3014***	0.0410***	0.0526***	0.1716***
	(134.64)	(202.59)	(125.69)	(109.91)	(131.94)	(105.09)
$\boldsymbol{X_t * D_{ECB}}$	−0.0511***	−0.0374***	−0.0860**	−0.0029**	-0.0030	-0.0057
	(-4.69)	(-2.67)	(-1.99)	(-2.36)	(-0.71)	(-0.30)
$\boldsymbol{R^2}$	0.21	0.27	0.10	0.28	0.17	0.09
$\boldsymbol{X_t}$	0.1594***	0.1675***	0.3021***	0.0415***	0.0529***	0.1717***
	(135.05)	(204.90)	(125.65)	(115.37)	(135.20)	(105.22)
$\boldsymbol{X_{t-1}}$	−0.0146***	−0.0189***	−0.0187***	−0.0050***	−0.0049***	−0.0063***
	(-23.86)	(-34.47)	(-10.60)	(-31.14)	(-22.80)	(-6.11)
$\boldsymbol{X_t * D_{ECB}}$	−0.0505***	−0.0367***	−0.0861**	−0.0095**	-0.0027	-0.0052
	(-4.69)	(-2.73)	(-2.00)	(-2.33)	(-0.66)	(-0.28)
$\boldsymbol{X_{t-1} * D_{ECB}}$	0.0124	-0.0089	0.0245	0.0003	−0.0090**	-0.0040
	(0.11)	(-0.75)	(0.51)	(0.12)	(-2.02)	(0.18)
$\boldsymbol{R^2}$	0.21	0.29	0.10	0.28	0.17	0.09
$\boldsymbol{X_t^S}$	0.0996***	0.1098***	0.2551***	0.0907***	0.0964***	0.1944***
	(85.86)	(125.82)	(110.90)	(77.12)	(98.65)	(78.35)
$\boldsymbol{X_t^S * D_{ECB}}$	−0.0428***	−0.0434***	−0.1015***	−0.0306***	−0.0346**	-0.0208
	(-5.41)	(-2.95)	(-2.77)	(-3.10)	(-2.42)	(-0.50)
$\boldsymbol{X_t^F}$	0.0317***	0.03561***	0.1153***	0.0341***	0.0395***	0.1538***
	(98.01)	(101.02)	(90.30)	(96.02)	(100.07)	(95.83)
$\boldsymbol{X_t^F * D_{ECB}}$	-0.0045	0.0044	0.0025	−0.0067*	0.0024	0.0007
	(-1.18)	(0.93)	(1.49)	(-1.74)	(0.53)	(0.40)
$\boldsymbol{R^2}$	0.39	0.39	0.15	0.33	0.21	0.12

All equations are estimated using OLS with Newey-West standard errors (max 5 lags). We multiply the order flow coefficients with 100, t-statistics are given in parentheses below coefficient estimates. $^{***}p < 0.01$, $^{**}p < 0.05$, $^{*}p < 0.1$.

Regression results in Table 7 show a much reduced, though still significantly positive coefficient on spot flows for all three currencies, and some weak evidence that the power of futures flows for the GBP/USD is also diminished. Dynamics are not obviously affected by the ECB fix.

5 Summary

This study empirically examines the intraday foreign exchange rates and inter-dealer order flow relationship around the WMR 4pm London Fix for both spot and futures markets for three G10 currencies. We also compare and contrast intraday liquidity and price behaviour with other fixing points, such as the 3pm London fix and the ECB fix, as well as with other key intraday points such as the 9:30am London time when UK macroeconomic indicators are published. Our analysis indicates that the behaviour of prices and flows around this time is quite unlike that observed at other points in time.

Our main findings are summarized as follows: (1) During the 60 second calculation window of the Fix, there is an extreme concentration of interbank trading activity not present during any other point in time of the day generating order flow spikes for both the spot and the futures markets. (2) There is a small price reversal in the one minute after the 4pm Fix for both markets that is not observed at other fixing points. (3) More obviously, in the spot market there is a clear reversal during the Fix of positions accumulated in the pre-Fix window. This suggests that during the pre-Fix window dealers accumulate larger positions than necessary to fulfil their customers' Fix orders and liquidate these excess proprietary positions for profit during the Fix. (4) The price impact of interbank order flow during the one-minute Fix is essentially zero, and bid-ask spreads are much narrower than usual, due to the extremely high levels of liquidity seen at the Fix. The liquidation of proprietary positions during the Fix is therefore extremely cheap. (5) Price discovery temporarily migrates from the spot to futures markets at the Fix since futures order flow maintains price impact. (6) Positions accumulated in the futures market during the pre-Fix are also reversed, though over a significantly longer time interval than in the spot market probably due to the more consistent price impact seen in the futures market. This reversal of futures positions is common across all 'extreme' intervals in the trading day.

The behaviour of liquidity, prices and flows around fixes has not been extensively studied up until recently and not accounted for in existing microstructure FX trading models. Our study contributes towards this end. Further research could be related to the study of returns-order flow relationship after the widening of the calculation window of the Fix and examine whether price and order flow behaviour has qualitatively changed.

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Appendix A: WMR FX Benchmarks

A currency fix is the setting of a daily reference rate. This rate is set at a specific time of day and is intended to express a representative rate of the market at the time at which the rate is calculated. The most important and widely used benchmark rate in spot foreign exchange markets is the London WMR 4pm Fix. It is produced and administered jointly by The World Markets Company and Thomson Reuters[16]. In 2016, Thomson Reuters acquired The World Market's Company WMR FX benchmark calculation business from State Street Corporation. The service was introduced in 1994 to provide a standard set of currency benchmark rates so that portfolio valuations could be compared with each other and their performance measured against benchmarks without having any differences caused by exchange rates. The rates are intended to cover the currencies for those countries that are included in a global or regional stock market index or where there is sufficient liquidity in the currency market to provide accurate fixings. These rates were adopted by index compilers, the Financial Times and other users and became the de facto standard for spot rates on a global basis. WMR provides rates for approximately 155 currencies on an hourly frequency, with half-hourly rates provided for the 22 most traded currencies, and forward rates for 80 currencies.

The calculation differs between forward and spot rates. We focus on spot rates only here. Over a one-minute fix period, actual trades executed and bid and offer order rates from the order matching systems are captured every second from 30 seconds before to 30 seconds after the time of the fix. Note that from 15 February 2015 and onwards, the data sourcing window is widened to a five-minutes fix period. Trading occurs in milliseconds on the trading platforms and therefore not every trade or order is captured, just a sample. From each data source, a single traded rate will be captured – this will be identified as a bid or offer depending on whether the trade is a buy or sell. A spread will be applied to the trade rate to calculate the opposite bid or offer. The spread applied will be determined by the order rate captured at the same time. This may result in some captured data being excluded

[16]WMR FX Benchmarks. Spot & Forward Rates Methodology Guide.

from the fix calculation. Valid trades from all sources captured during the fix period will be "pooled" together. Subject to a minimum number of valid trades being present within this pool of data – the trade rates will be used for the fix. A median trade bid and trade offer are calculated independently, using data from the single pool of trades across data sources. The mid-rate is calculated from the median trade bid and trade offer. A minimum standard spread is applied to the mid-rate to calculate a new bid and offer. These bid, offer and mid rates will be validated prior to publication, against currency specific tolerance thresholds, and this may result in expert judgement being applied. If there are insufficient valid trade rates from the pooled data sources, to be used in the fix then order rates will be used. From each data source, the best bid and best offer rates will be captured simultaneously to the Trade data from each data source. All captured order rates will be subjected to validation checks. This may result in some captured data being excluded from the fix calculation.

Appendix B: Time line of the Forex Scandal

In the summer of 2013, news reports began to circulate stating that Financial Conduct Authority (FCA) began preliminary investigation into potential manipulation of FX benchmarks, amid allegations that traders at banks were colluding in rigging spot benchmark rates. According to the articles, the behavior occurred daily in the spot foreign-exchange market and went on for at least a decade. The investigation quickly went global with at least six regulatory authorities across the globe – the European Commission, Switzerland's financial markets regulator Finma and the country's competition authority Weko, the UK's Financial Services Authority, the Department of Justice in the US and the Hong Kong Monetary Authority - launching formal investigations. In November 2014, the United Kingdom's Financial Conduct Authority (FCA) imposed fines totaling \$1.7bn on five of the world's largest banks (Citibank, HSBC, JP Morgan, RBS and UBS) for failing to control business practices in their G10 spot foreign exchange trading businesses. The FCA determined that the five banks had failed to manage risks around client confidentiality, conflict of interest, and trading conduct. The banks used confidential customer order information to collude with other banks to manipulate fixing rates for G10 currency rates and profit illegally at the expense of their customers and the market. The FCA also published transcripts detailing examples of misconduct by traders attempting to manipulate the Fix. On the same day the United States Commodity Futures Trading Commission (CFTC) in coordination with the FCA imposed collective fines of \$1.4bn against the same five banks for attempted manipulation of, and for aiding and abetting other bank's attempts to manipulate global FX benchmark rates to benefit the positions of certain traders. The regulators found that currency traders at the five banks coordinated their trading with traders at other banks in order to manipulate the foreign exchange benchmarks rates. Currency traders at the banks used private chatrooms to communicate and plan their attempts to manipulate the foreign exchange benchmark rates. In these chatrooms, traders at the banks disclosed confidential customer order information and trading positions, changed trading positions to accommodate the interests of the collective group, and agreed on trading strategies as part of an effort by the group to manipulate different foreign exchange benchmark rates. These chatrooms were often exclusive and invitation only, and were named for example *The Club*, *The Bandits' Club*, *The Mafia*, *The Dream Team*, *One Team One Dream*, *The Three Musketeers* and *The Cartel*. On 20 May 2015, the five banks pleaded guilty to felony charges by the United States Department of Justice and agreed to pay fines totaling more than $5.7bn. Four of the banks pleaded guilty to manipulation of the foreign banks. UBS also pleaded guilty to committing wire fraud and agreed to a $203m fine. A sixth bank, Bank of America, while not found guilty, agreed to a fine of $204m for unsafe practices in foreign markets. Civil litigation from investors against the perpetrating banks and regulatory investigations into forex trading misconduct are still ongoing.

Appendix C

Figure 11: GBP/USD Price-Flow Dynamics around the Fix
(Full Sample Period, Negative Spot Price Movement before the Fix.)

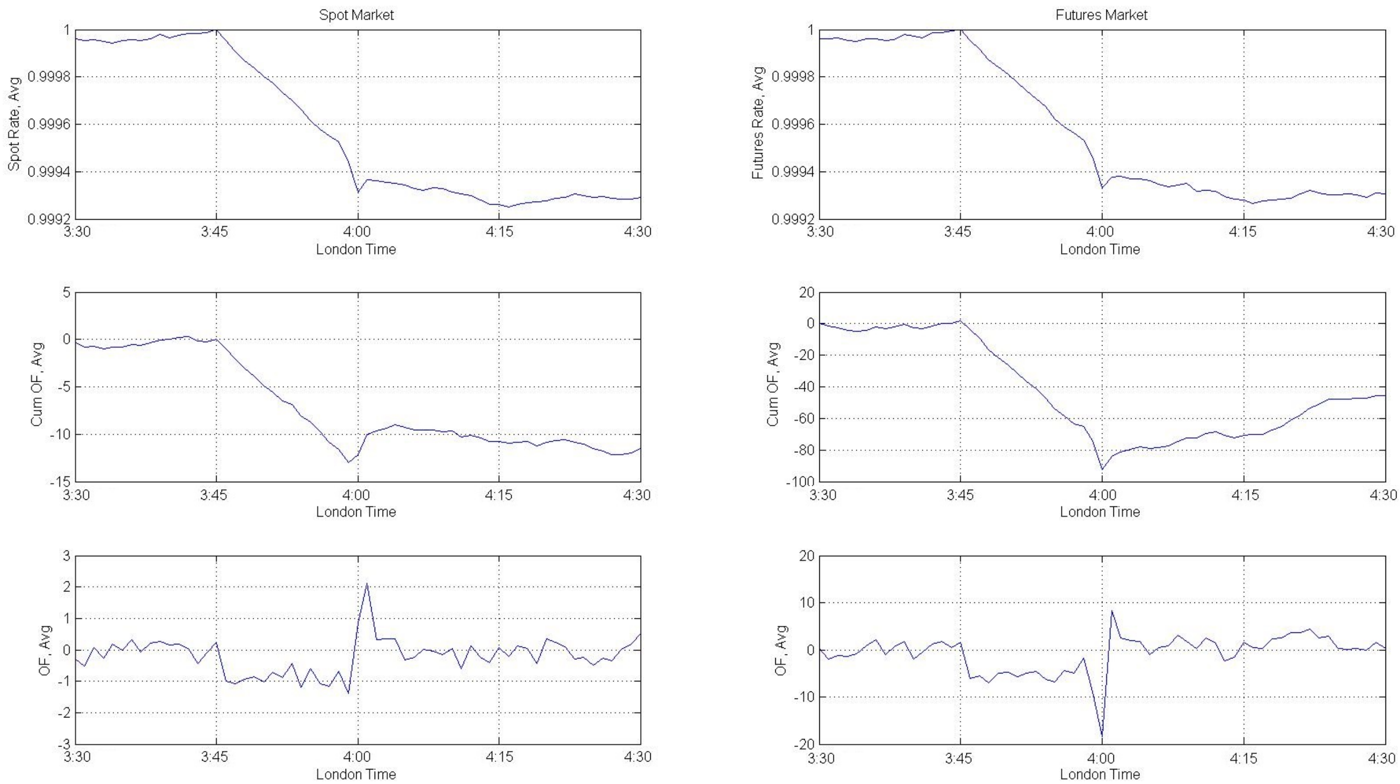


Figure 12: GBP/USD Price-Flow Dynamics around 09:30am London Time.
(Full Sample Period, Negative Spot Price Movement.)

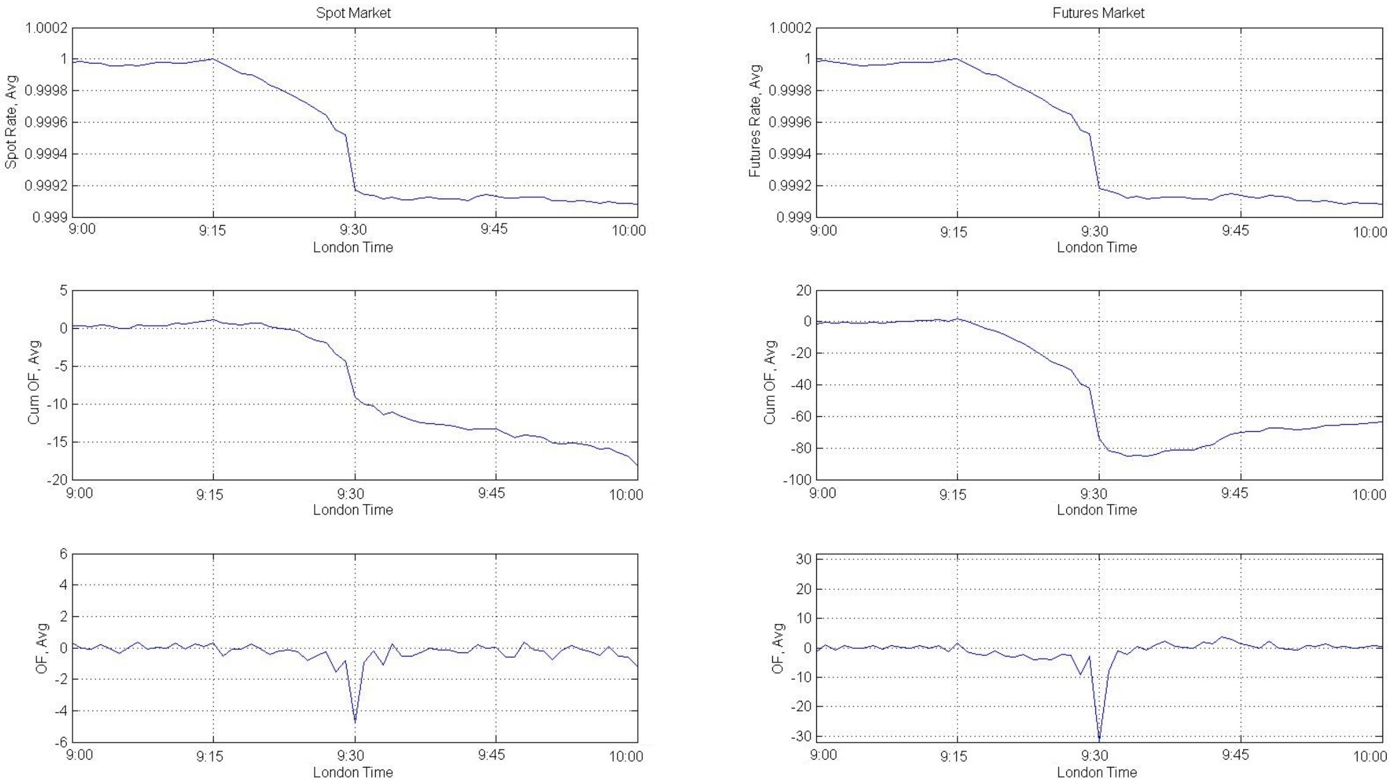


Figure 13: GBP/USD Price-Flow Dynamics around 3pm London Time.
(Full Sample Period, Negative Spot Price Movement.)

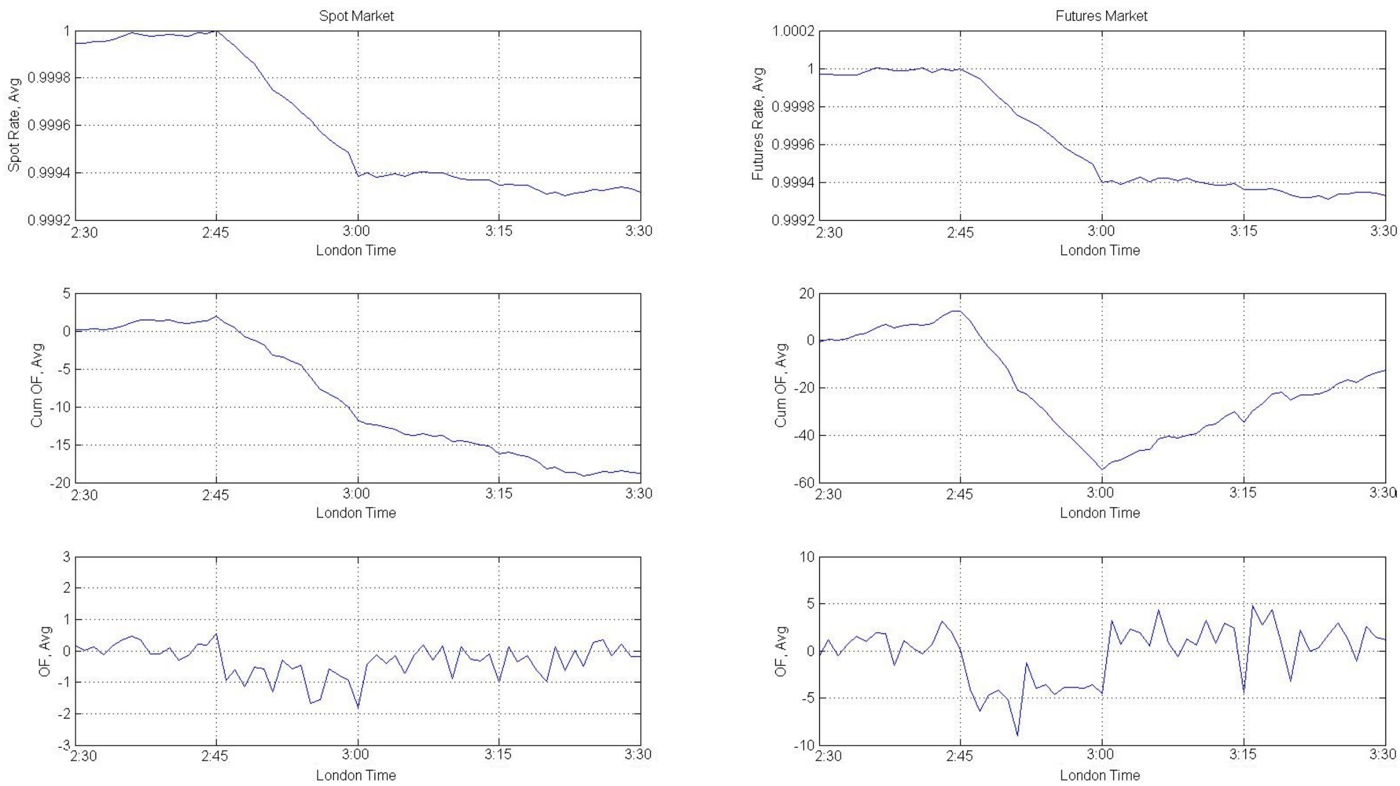


Figure 14: GBP/USD Price-Flow Dynamics around ECB Fix.
(Full Sample Period, Negative Spot Price Movement.)

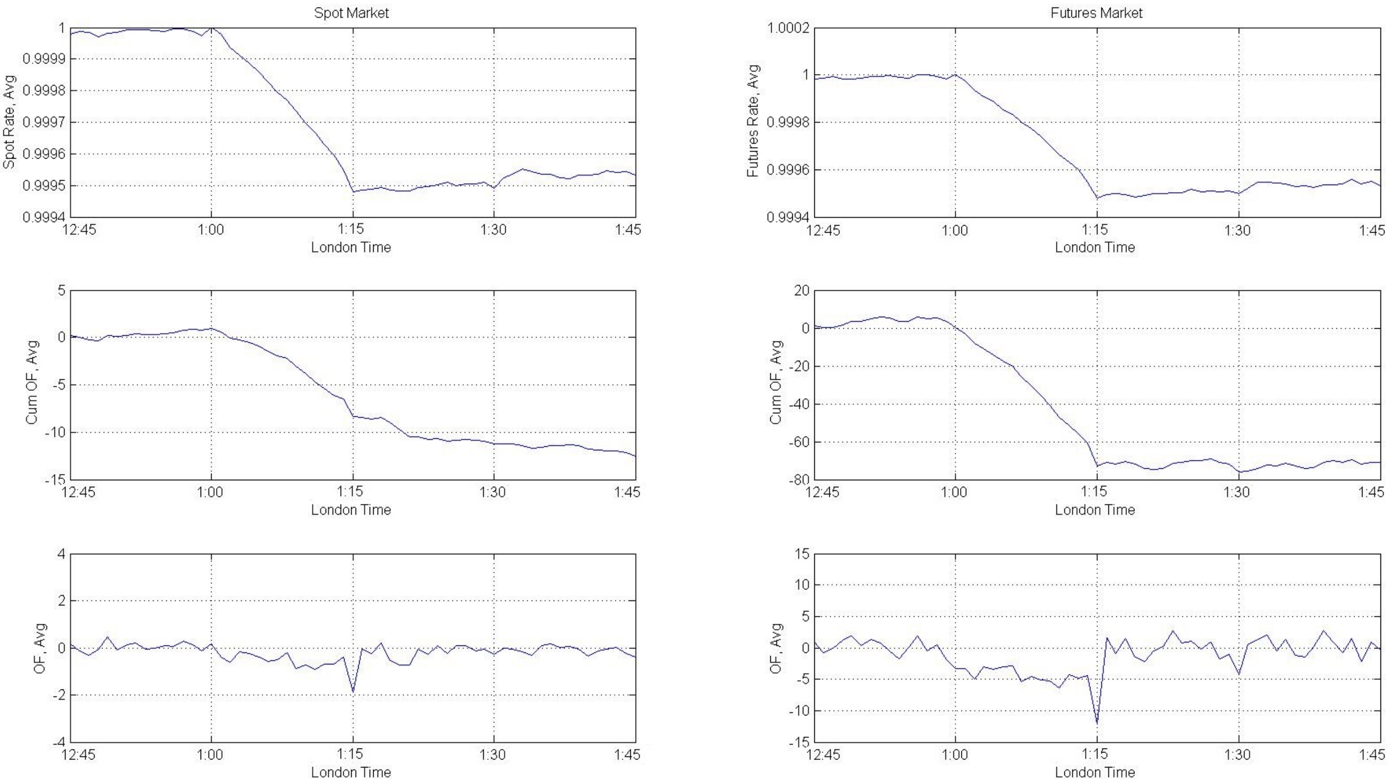
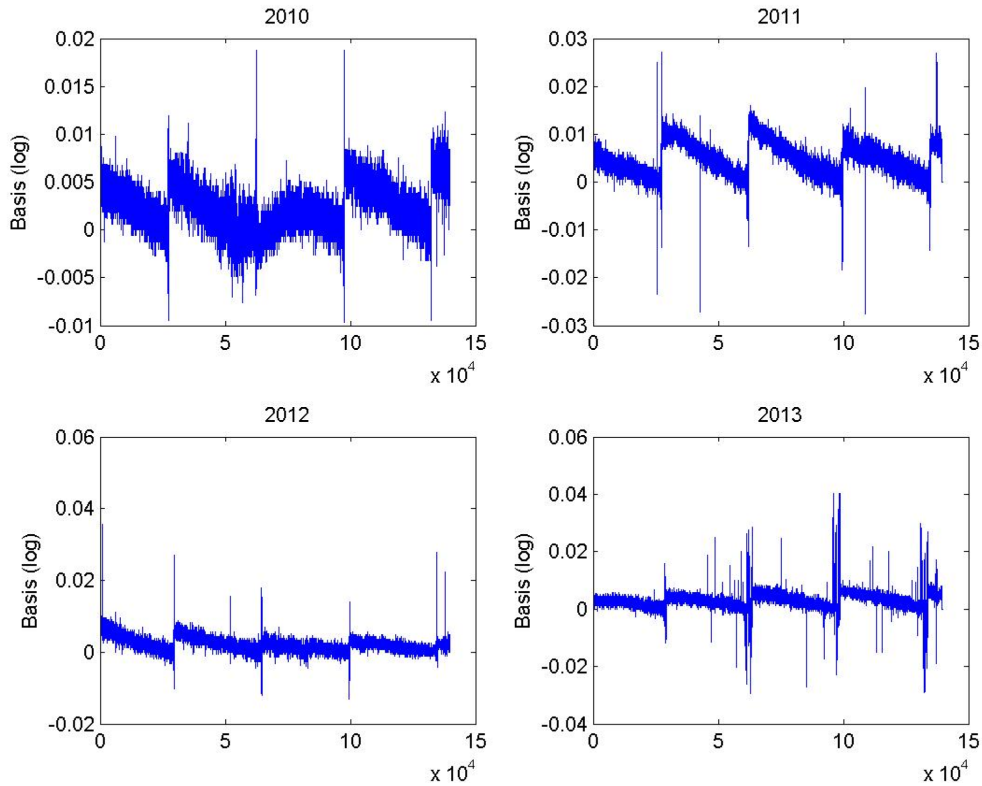


Figure 15: GBP/USD Basis (log)



Appendix D

Table 8: Summary Statistics for Spot and Futures AUD/USD.

	Spot Data			Futures Data		
	Trades	**Flows**	**Returns**	**Trades**	**Flows**	**Returns**
Panel A: Minute (obs: 558,360)						
Mean	16.878	-0.086	2.33×10^{-5}	73.628	-0.033	1.83×10^{-5}
Median	11.000	0.000	0.000	45.000	0.000	0.000
Maximum	785.000	162.000	1.071	3,428.000	936.000	1.618
Minimum	0.000	-168.000	-0.777	0.000	-1,017.000	-1.629
Std.Dev.	20.827	7.826	0.025	93.534	26.665	0.034
Q(5)	5,295.298	3,669.310	858.275	6,814.959	3,286.206	2,846.516
ADF	-289.484	-696.927	-772.265	-280.306	-702.502	-939.251
AR(1)	0.568	0.069	-0.033	0.600	0.062	-0.224
Panel B: Daily (obs: 1,034)						
Mean	9,114	-46.554	0.013	39,759	-17.785	0.010
Median	8,794	-34.500	0.000	39,121	-5.000	0.000
Maximum	28,879	944.000	2.801	122,591	3,595.000	2.798
Minimum	541	-1,124.0	-2.608	53.00	-4,139.000	-2.604
Std.Dev.	3,704	283.964	0.511	16,638	815.951	0.516
Q(5)	1,270.2	13.343	1.183	733.070	67.858	1.655
ADF	-5.614	-28.305	-31.186	-6.057	-26.971	-31.192
AR(1)	0.585	0.102	0.032	0.537	0.172	0.033

This table presents summary statistics for trades, order flow and returns for both the spot and futures market for the AUD/USD currency pair. Full period statistics are calculated over the period January 2010 to December 2013. Number of observations correspond to each market separately. Q(5) denotes the Ljung-Box Q-test statistic for the first five serial correlations of returns. Under the null hypothesis of no serial correlation, the LBQ statistic is asymptotically distributed as $\chi^2(5)$. ADF denotes an Augmented Dickey-Fuller test for non-stationarity in each series.

Table 9: Summary Statistics for Spot and Futures NZD/USD.

	Spot Data			**Futures Data**		
	Trades	**Flows**	**Returns**	**Trades**	**Flows**	**Returns**
Panel A: Minute (obs: 558,360)						
Mean	3.836	0.002	3.06×10^{-5}	8.360	-0.012	3.82×10^{-5}
Median	2.000	0.000	0.000	3.000	0.000	0.000
Maximum	223.000	77.000	1.131	605.000	208.000	2.228
Minimum	0.000	-57.000	-1.397	0.000	-194.000	-1.762
Std.Dev.	6.139	2.920	0.029	15.102	6.105	0.035
Q(5)	2,413.133	766.769	796.447	2,694.342	276.527	1,124.609
ADF	-387.086	-720.941	-765.787	-405.067	-737.070	-854.652
AR(1)	0.412	0.036	-0.025	0.407	0.014	-0.133
Panel B: Daily (obs: 1,034)						
Mean	2,071	0.991	0.017	4,514	-6.750	0.021
Median	1,982	1.500	0.024	4,293	-3.500	0.000
Maximum	6,782	440.000	2.293	13,764	1,034.000	2.297
Minimum	168.000	-338.000	-2.891	3.00	-1,108.000	-2.949
Std.Dev.	801.606	86.714	0.580	2,175	206.069	0.617
Q(5)	526.638	4.837	2.822	1,104.070	45.651	3.362
ADF	-6.242	-30.936	-32.016	-6.277	-27.602	-30.519
AR(1)	0.446	0.038	0.005	0.608	0.150	0.052

This table presents summary statistics for trades, order flow and returns for both the spot and futures market for the NZD/USD currency pair. Full period statistics are calculated over the period January 2010 to December 2013. Number of observations correspond to each market separately. Q(5) denotes the Ljung-Box Q-test statistic for the first five serial correlations of returns. Under the null hypothesis of no serial correlation, the LBQ statistic is asymptotically distributed as $\chi^2(5)$. ADF denotes an Augmented Dickey-Fuller test for non-stationarity in each series.