WAS THE FOREX FIXING FIXED?

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ABSTRACT

"Fixing" of the exchange rate (price) is a rule among the Forex market participating institutions to set a reference/settlement price for the day. Major fixings occur at 9:55 am Tokyo time for transactions between Japanese banks and their customers, and at 4:00 pm London time for transactions between European and US banks and their customers. The two fixings have different regulations and institutions. The London fix is calculated as a median price during the one minute window around 4:00 pm. We empirically examine the movement of prices around the time of fixing. Regulators in the UK and the US have accused banks for collusive behaviors to manipulating the price around the London fixing time. It has been mentioned in the media that there was evidence of "chats" among traders of different institutions for collusion. But, is there evidence in price behavior? We found little evidence of volatile movement (or spikes) in prices around the fixing time. In fact, liquidity provision at the fixing time is larger than other times, which makes the price impact of any trade smaller. At the Tokyo fixing, however, financial institutions can fix the price by themselves based on the market price. Although the market provides deep liquidity at the Tokyo fixing as well, such financial institutions had announced prices to be more favorable for banks up until 2008. Such deviation of the fixing price from the market price might be related to the settlement needs of importers, and banks wanting to reduce the risk of being caught in the dollar shortage later in the day.

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1   Introduction

The objectives of this paper is three-fold. First, this paper will describe and compare the 9:55 am "fixing" in Tokyo and the 4:00 pm "fixing" in London. The institutional difference between Tokyo and London is expected to explain the difference in banks' behavior in bid, ask, and deal prices and volumes around the fixing time. Second, preceding papers have shown that trading volumes spike up around fixing times. This paper will extend on this through intra-day examination of price volatility, bid-ask spread, and order flows, in addition to volumes. Third, the banks' behavior around the 4:00 pm London fix has been investigated by supervisory agencies in the U.K. and U.S., for possible collusion through the sharing of customers' order information. The investigation, mostly based on the analysis of chat room records, resulted in penalties for several banks. This paper will econometrically analyze price and volume behaviors at around fixing times to see whether there is suggestive evidence of price manipulation.

"Fixing" in the foreign exchange market is a market practice that determines the bid-ask-mid-point exchange rate (price) at around a pre-announced time. The fixing price is then applied to the settlement of foreign exchange transactions between banks and retail customers including broker dealers, institutional investors, insurance companies, exporters and importers, with varying bid-ask spreads. The price is then fixed for the day. Since banks receive customer orders throughout the day, banks face two risks. If the median price of banks' interbank transactions deviates from the fixing price, banks may suffer losses from customer transactions. This is the price risk. In order to avoid this risk, banks aim to carry out interbank transactions in alignment to the net orders at the fixing price. This is a defensive motivation to carry out lots of transactions at the fixing price. The second risk is that the exact amount of net buy or sell orders may not be known at the fixing time. This is particularly true in Tokyo, when the fixing takes place at 9:55 am. This risk can be handled by keeping the bid-ask spread reasonably high, so that within the band, banks will not have to suffer from the negative spread between the customer price and fixing price.

The fixing may also pose as a profit opportunity for banks, if they can manipulate the fixing price away from the prevailing market price. If banks know that banks will be selling more dollars than buying dollars from retail customers, they may profit from setting the fixing price higher (dollar appreciation) than prices of other times of the day. Suppose that a bank can quote 100.10 yen/dollar for retail customers as the fixing price, while the bank can buy the dollar in the interbank market at 100.00 yen, then the bank can earn the extra profit of 0.1 yen per dollar. However, in order for this to transpire, the fixing price had to be "manipulated" to be higher than other times (around the fixing time), and the amount of net buy from retail customers had to be known. Whether this can be done in a deep liquid market like the foreign exchange market is a big question.

In London, WM/Reuters announces the fixing price just after 4:00 pm, based on prices that took place in the one minute window around 4:00 pm (that is, from 15:59:30 to 16:00:30). The

WM/Reuters fix is widely used as the price for customer trades in the London and New York markets. It has been established in literature that within the 24-hour cycle, transaction volumes are highest around 1:00 pm to 4:00 pm in London (8am to 11:00 am in New York). After the 4:00 pm fixing in London, transaction volumes and price volatility quickly diminish. The banks have accumulated the customer orders of the day by 4:00 pm London so that there will be no remaining uncertain exposures after the 4:00 pm fixing.

In Tokyo, the fixing price is officially called the Telegraphic Transfer Middle Rate (TTM) or *Nakane*. This price is the benchmark and mid-point price that is applied to banks' transactions with customers. Buyers and sellers pay the TTM, plus/minus the spread which becomes a profit margin of the bank. The bank sells the dollar (in exchange of the yen) from retail customers at the Telegraphic Transfer Selling (TTS), which is the TTM plus 1 yen, while the bank buys the dollar from retail customers at the TTB (Telegraphic Transfer Buying), which is the TTM minus 1 yen. Both the TTB and TTS are applicable to the customer trades that occur throughout the day. However, if the price movement is unusually volatile, and the interbank rate moves above or below the one yen, the fixing price may be revised during the day.

Each major bank announces its own fixing price (TTM) around 10:00 am, based on the actual transactions that transpire around 9:55. There is no explicit rule on how to link transactions that occur around 9:55 to the fixing price. Thus, the TTM may differ from one bank to another. This contrasts from the London WB/Reuters 4PM fix, which is to the same for all banks. By 9:55, a bank has received a substantial amount of buy and sell orders for the day. However, there are still several hours after 9:55 am where the bank may receive buy or sell orders. When the bank expects net buying of the dollar for the day, the bank has the incentive to set the fixing price (TTM) higher than the market average around 9:55 for extra profits, in addition to regular profits from the bid-ask spread.

Although the London fix and Tokyo fix are the two major fixings of the day, there is one more important pricing.

Major currency options expire at 10:00 am in New York, which is called the New York option cut. At the Chicago Mercantile Exchange (CME), European-style options expire at 10:00 am and American-style options expire at 3:00 pm. The fixing price is based on a 30 second volume weighted average price of trades in the underlying futures occurring on CME Globex immediately preceding the expiry.

The banks' behavior around the London WM/Reuters 4:00 pm fixing is a target of investigation by regulatory authorities. The investigation was first reported in the media on June 12, 2013, followed by other occasional reportings.[1] In the wake of these investigations, several traders were

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[1] On June 12, 2013, *Bloomberg* broke the story first. It was followed by *Financial Times*. Subsequent reporting were in *Bloomberg* (2013, August 27, and December 19), *Financial Times*

suspended, and resulted in penalties imposed on several large banks in London trading. In addition, a Bank of England employee was suspended.[2] There was evidence of information exchange on customer order flows of several large banks, which constituted collusion. However, no direct evidence was presented (in public) in the manner of price behavior or manipulation.

It is well known that transaction volumes tend to skyrocket around the Tokyo 9:55 am fixing, London 4:00 pm fixing, US macro announcements, and the New York option cuts.[3] The volume spikes are well documented in the existing literature on intraday, high-frequency exchange rate behaviors. However, few studies price behavior at around the time of fixing. Other than the major spikes mentioned above, there are minor spikes of transaction volumes at different times of the day. One of those times correspond to times of macro-statistical releases, such as GDP and CPI. When a macro statistical announcement contains surprises (unexpected changes), then the price will jump to a new equilibrium (Ito and Hashimoto (2006), Chaboud and Chernenko (2004)). The price jump can be regarded as a price discovery process to a new equilibrium.

The research on price behavior around the times of fixing, when transaction volumes spike, is our seminal contribution. A spike in transaction volumes may not be accompanied by unusual price behaviors. An increase in transaction volumes may be due to the price discovery process by banks that have private information on customer order flows. In this case, price volatility may increase but there would not be any predictable patterns in price levels around the time of fixing. However, volume spikes may be due to orders by banks to manipulate the price to pursue extra profits. In this case, the price may exhibit a spike or a bubble-like behavior.

The rest of the paper is organized as follows. Section 2 reviews the literature on fixing. Section 3 describes institutional details of the Tokyo fixing and London fixing. Section 4 is the theoretical inference on how the price can be manipulated around the time of fixing. The price behavior is inferred if manipulation succeeds. The pattern to look for is described. Section 5 explains the data set. Section 6 describes general patterns of intraday seasonality. Section 7 explains the econometric methodology. Sections 8 are econometric analyses of the London fixing and the Tokyo fixing, respectively. Section 9 is the conclusion.

2 Literature Review

A few papers have investigated the topic of fixings in the foreign exchange (Forex) markets. Melvin and Prins (2015) investigated the transactions around the fixing that is related to the hedging

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(2014, February 16, March 21, March 25, March 27, March 31).

[2] According to the *Economist* on March 8, 2014: "On March 5th the Bank of England announced that it too had suspended an official following an internal investigation."

[3] We refer these events as the "four events" hereafter. But our analysis primary focuses on the two fixings.

of international portfolio. Equity investors hedge the growth of equities of a foreign country by selling the currency of that country. The timing of the hedging trade is typically at the time of London fixing at the end of the month. By using high-frequency Forex transaction data and propriety data that identifies order flows from non-banking sectors, Melvin and Prins (2015) confirmed that the past positive equity return in a country is associated with the currency depreciation of that country at the end-of-month London fixing. Because of the liquidity provision by arbitrageurs, they note, price movements are predictable and statistically, significant profits exist and they are consistent with the reasonable limits to arbitrage. In line with this research, Evans (2014) investigated the Forex rate behavior around the London fixing. The paper emphasized the negative autocorrelation of the Forex rate between the pre- and post-fixing periods, particularly at the end-of-month trading day. This finding is commonly observed across all the time periods and currency pairs.

3 Institutional Background

3.1 Tokyo Fix

The fixing rates in the Tokyo market are announced at JST 10:00 (GMT 1:00) by banks. The rates are not uniform and each bank decides the fixing individually. The fixing rate of a bank is calculated based on the spot transaction prices of the bank around JST 9:55. According to market participants, although the rate may be based on rates during specific periods, banks do not share explicit rules which define the specific transactions that result in determining the fixing rate. In fact, banks are allowed to fix the rates arbitrarily within the range in which they have made their transactions around JST 9:55. This rate-setting rule is different from that of the London fixing which is provided by a third-party (i.e., WM/Reuters) and has a window period of 30 seconds before and after GMT 16:00, to fix the rate.[4] In the situation of the Tokyo fixing, banks tend to have an incentive to make deals at some extreme ranges, possibly helping determine the fixing rates with some flexibility. Such deals can appear several seconds around JST 9:55. Thus, fixing rates by each bank can deviate from the transaction prices with this institution. Then, what are the characteristics of this deviation of rates?

On the one hand, the Tokyo fixing is free from the problem of collusion towards manipulating the common fixing rate. On the other hand, the Tokyo fixing allows each bank to quote a different fixing price, which can be individually manipulated.

Market participants argued to the authors of the papers that at around the fixing period in the Tokyo market, the buy orders of foreign currency (U.S. dollar and Euro) by importers regularly exceed the sell orders by exporters. It is commonly known that the USD tends to appreciate vis-à-vis

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[4] As of February 2015, WM/Reuters had changed their rules to define the fixing rate; now they use a five minute window rather than a one minute window. Details can be found at http://www.wmcompany.com/pdfs/WMReutersMethodology.pdf

the yen at around the fixing time. This situation is more evident when large amounts of payments are due, typically on the days of the 5th, 10th, 15th, 20th, 25th, and 30th, (hereafter 5th and 10th days) as well as the end-of-month trading day. [5]

Why importers prefer to settle trades at the fixing, while exporters do not, seem to reflect the difference in sophistication of managing currency risk between importer and exporters. In the long history of continuously appreciating yen, Japanese exporters have developed various ways of currency hedge. For example, some companies concentrate on currency risk management of the group in a currency layover entity, which makes the buy-sell limit orders depend on market conditions. They do not usually ask banks for deals at the fixing rate. Japanese large importers such as electric power companies, in contrast, do not pay much attention on the intraday changes of the exchange rate, since any cost increase can be passed through to consumers. They typically ask banks to settle the trades at the fixing rates. Such difference in behaviors of Japanese industries is said to be the cause of the imbalance of orders for the Tokyo fixing time.

If this widely-held narrative is right, then the dollar rate should spike up at 9:55 am, as well as transaction volume spikes. The volume and price spikes should also be most prominent on the 5th and 10th days. This can easily be empirically tested.

Banks with private information on customer order flows can likely infer that such price spikes at 9:55 am will occur at a high probability. Then under this assumption, they can make extra profit by purchasing USD/JPY at 9:54 am and sell them at 9:55 am. This type of trading parallels front-running in the equity market, but these trades are not prohibited in the Forex market. If traders anticipate the buying at 9:54 am, they may well start trading at 9:53 am, and 9:52 am, and so on. Thus, dollars can begin to appreciate gradually towards 9:55 am and depreciate quickly after 9:55 am. Figure 1 illustrates the typical behavior of prices around the fixing. Even the occurrence of a "price spike" in Figure 1 does not necessarily mean price manipulation. If banks execute customers' orders, which had been accumulated in the inventory and anticipated for the rest of the day, such a spike can occur as a result of unbalanced demand and supply in the interbank market, reflecting the imbalance of customer orders (anticipatory behavior).

<center>Figure 1 about here</center>

We examine the following: (1) whether there are such spikes of prices around JST 9:55,(2) gradual appreciation of foreign currency to the yen before JST 9:55, and (3) whether bank with private information set higher (or more appreciated dollars and euro) fixing rates than the mean and median of interbank market rates around JST 9:55.

For case (2), front running by banks are suspected if banks trade before the fixing and have private information about the imbalance of customers' orders. But this kind of trading is not

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[5] The Japanese call these dates "Go (5) tou (10) bi."

prohibited in Forex markets. Generally, banks can make a profit by trading on the information of customers' order flows. Even before the fixing scandal emerged, this problem was discussed in academic studies (e.g., Ito, Lyons, and Melvin (2002), Evans and Lyons (1999)). Collusion among banks for implementing front-running, however, may cause more frequent spikes, which can result in the extra loss of their customers.

As mentioned in the introduction, each bank in Tokyo announces a bank-specific fixing rate. Are banks allowed to announce any price? Probably not. A bank can justify announcing the fixing rate that is within the range of the banks' actual transactions around the 9:55 am fixing. However, when the range is wide, and the setting of the rate is slightly on the appreciation (of the USD) side, banks that face more buying than selling from customers result in earning extra profits. This inference cannot be tested for individual banks, since the bid, ask, and deals in our data set do not have the banks' individual name tags. Instead we can compare individual banks' fixing prices with the volume weighted average price at 9:55 am.

3.2 London Fix

WM/Reuters daily closing rate is widely used as benchmark exchange rates in the U.S. and U.K. market. This rate has been calculated and published by WM companies and Reuters since 1994. The method of calculation is to use transaction prices in the one-minute time window around 4:00 pm London time (more accurately, from 15:59:30 to 16:00:30). The WM/Reuter closing spot rates, or the "WM/Reuters 4PM London fix," are used as settlement exchange rates for numerous financial transactions involving foreign currencies, including evaluating mutual funds accounts and short-term loans, settling transactions between banks and retail customers. WM/Reuters started providing the rates for 40 currency pairs, and by now the currency pairs have widen to 160.

There are many transactions with different rates during this one-minute window. WM/Reuters explained how fixing rates are calculated from these data as follows:[6]

> Over a one-minute fix period, bid and offer order rates from the order matching systems and actual trades executed are captured every second from 30 seconds before to 30 seconds after the time of the fix. Trading occurs in milliseconds on the trading platforms and therefore not every trade or order is captured, just a sample. Trades are identified as a bid or offer and a spread is applied to calculate the opposite bid or offer.

> Using valid rates over the fix period, the median bid and offer rates are calculated independently and then the mid-rate is calculated from these median bid and offer rates,

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[6] This statement is taken from the WM/Reuters methodology guide as of 2014. Their latest statement, found on http://www.wmcompany.com/pdfs/WMReutersMethodology.pdf, explains the new methodology which employs the five minute window.

resulting in a mid-trade rate and a mid-order rate. A spread is then applied to calculate a new trade rate bid and offer and a new order rate bid and offer. Subject to a minimum number of valid trades being captured over the fix period, these new trade rates are used for the fix; if there are insufficient trade rates, the new order rates are used for the fix.

In order to calculate the fix for each currency pair, which is the mid-point of bid and ask, the WM/Reuters sampled the rates every second and calculated the median rates. It is important to point out that they are not volume weighted. If banks attempt to influence the fix rate, the chance will be higher by breaking up the large volume trades into smaller units and submitting them to the order-matching (Reuters) system. However, up until the investigation by supervisory agencies in 2013, many practitioners and academics thought it was impossible to manipulate the exchange rate, since the Forex markets accommodate a diverse mix of banks.

In contrast to the Tokyo fix, individual banks cannot arbitrarily set their own fixing price. All banks use the WM/Reuters fix. This eliminates the arbitrariness of banks when they take advantage of their positions against their own customers. Since the market houses a diverse market of participants, the fix seems to be a fair way to set the single rate for customer trades. One important recent change in the Forex market is that only a handful of large banks – Deutsche Bank, UBS, Citibank, and Barclays – have begun to dominate the Forex market.[7] The heightened concentration is due to the emergence of algorithmic trading, which requires large system investments, in 2005, and the concentration of banking business in general in the aftermath of the global financial crisis, which occurred in 2008-2009.

As trades have become concentrated in several banks, one of the assumptions which resolved why the fix could not be manipulated appeared to have been erroneous. If a handful of these banks collude, assuming that they share information on the direction of customer order flows, it is not impossible to make an impact on the fixing rate by submitting quotes very frequently for that one minute window.

In 2013, regulators had begun investigating several banks on their conducts around the time of the London fix, for possible rigging of the market rate (the WM/Reuters Scandal). The investigation revealed that the incentive to influence the fix rate was higher when customer order flows became larger on Fridays and on the end-of-month trading days. On November 12, 2014, The Financial Conduct Authority (FCA) imposed fines totaling £1,114,918,000 (USD $1.7 billion) on five banks—Citibank, HSBC Bank, JPMorgan Chase, The Royal Bank of Scotland, and UBS—for failing to control business practices in their G10 spot foreign exchange (FX) trading.[8] The FCA

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[7] These four banks were said to have a combined market share of 46.7% in interbank foreign exchange trades. (Greenwich Associate, "2014 Greenwich Leaders: Global Foreign Exchange Services" FES-2014-QSL.pdf)

[8] See the November 12, 2014 FCA announcement for details: http://www.fca.org.uk/news/fca-fines-five-banks-for-fx-failings. The amount of fines were divided among the five banks as follows:

announcement said:

> *Between 1 January 2008 and 15 October 2013, ineffective controls at the Banks allowed G10 spot FX traders to put their Banks' interests ahead of those of their clients, other market participants and the wider UK financial system. The Banks failed to manage obvious risks around confidentiality, conflicts of interest and trading conduct.*

> *These failings allowed traders at those Banks to behave unacceptably. They shared information about clients' activities which they had been trusted to keep confidential and attempted to manipulate G10 spot FX currency rates, including in collusion with traders at other firms, in a way that could disadvantage those clients and the market.*

> *Traders shared the information obtained through these groups to help them work out their trading strategies. They then attempted to manipulate fix rates and trigger client "stop loss" orders (which are designed to limit the losses a client could face if exposed to adverse currency rate movements). This involved traders attempting to manipulate the relevant currency rate in the market, for example, to ensure that the rate at which the bank had agreed to sell a particular currency to its clients was higher than the average rate it had bought that currency for in the market. If successful, the bank would profit.*

The FCA announcement also included a video explaining how this was an "example of attempted manipulation at each of the Banks." However, there was no quantitative analysis of the aggregate, market-wide price impacts from the alleged manipulation. We investigate whether the market prices behaved perversely, implying the manipulation of fixing prices.

3.3 London Fix and Tokyo Fix

Throughout this paper we emphasize the institutional differences between London and Tokyo fixings, which are expected to cause different price and volume behaviors. The major differences are as follows: First, Tokyo fixing occurs at the beginning of trading day and the fixing rate is used for the whole day after 10:00 am (JST), while the London 4:00 pm (GMT) fixing rate is a "closing rate" for trades and customers have already submitted their orders. In this sense, the Tokyo fixing may carry a larger risk for the Tokyo banks with how many exposures banks they wind up with by the end of the day. Second, Tokyo fixing rates are determined by banks individually, while the London fixing rate is a uniform price that is calculated and provided by WM/Reuters. In the Tokyo fixing institution, banks are allowed to hedge the risk by offering a fixing rate that may be biased from the median prices at around the fixing time, as they know their own customer order flows. Third, for

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Citibank N.A. £225,575,000 (USD $358 million), HSBC Bank Plc £216,363,000 (USD $343 million), JPMorgan Chase Bank N.A. £222,166,000 (USD $352 million), The Royal Bank of Scotland Plc £217,000,000 (USD $344 million) and UBS AG £233,814,000 (USD $371 million).

those orders that are settled with the Tokyo fix, the buying order amount (i.e., the demand for foreign currency) regularly exceeds that of selling order. This provides additional predictability of the behavior of price around the Tokyo fixing.

3.4 Other Fixes

The London 4:00 pm fixing and Tokyo fixing are the two main causes for the majority of the trading spikes that occur in the market. There are some other minor fixings such as the ECB fixing (ECT 3:00 pm). These fixings usually occur at the zero minute of each hour. The trading volumes cause small spikes during these times.

3.5 NY Option Cut and U.S. Macroeconomic Announcements

Other volume spikes occurs at the time of the New York currency option cut (EDT, EST 10:00 am) and during the macroeconomic statistical announcement times in the United States, Japan, and Europe. At 10:00 am, the expiring prices of many over-the-counter currency options (not just traded in New York) are determined. Participants in currency option markets who make a position for delta-hedging at the sport market need to unwind their position by this time. Also, spot rates tend to cluster around the option prices (Ni, Pearson, and Poteshman (2005)), providing another source for spot deal volumes. Some U.S. macroeconomic announcements are also released at 10:00 am (consumer confidence, factory orders, the ISM index, and new and existing home sales), but dropping the effect from such announcements lower the deal volume by only about a tenth (Chaboud and Chernenko (2004)).

Among the macroeconomic announcements of the three large economies, the U.S. macroeconomic announcements are the most influential. Exchange rates against the U.S. dollar particularly have substantial volume spikes at EST (EDT) 8:15 am (when the ADP survey comes out), 8:30 am (many macro announcements concentrate), and 2:15 pm (when the FOMC policy announcement comes out). These announcements affect the formation of price at the Forex market (Andersen et al. (2003), Evans and Lyons (2008)). Although the impacts are smaller, Japanese macroeconomic announcements are found to have impacts on the USD/JPY rate (Hashimoto and Ito (2010)).

A summary timetable disclosing a one day outlook of the Forex market is described in Table 1. In this research, we focused on the two fixings and did not report a detailed analysis regarding the

announcements and option cuts.

<div align="center">Table 1 about here</div>

4 Empirical Hypotheses

As we discussed in previous sections, each bank has its own private information on the amount of customer order flows that take place. They may take advantage of the order flows and pass on the positions to the interbank market, with or without the bank's own proprietary positions. Evans and Lyons (1999), and Ito, Lyons, and Melvin (2002) were the first to emphasize the role of order flows in the exchange rate dynamics. The previous sections of this paper emphasized how the role of order flows tend to really heighten around the fixing times.

There are two possibilities on how to take advantage of order flows using private information. First, the bank may influence the fixing price away from the market prices around the fixing time, in the benefit of the bank and at the customers' loss. When successful, the bank can earn extra profits. The process is as follows: if the order flows, which will be settled at the fixing price, is to buy foreign currency, the bank can obtain foreign exchange cheaply (close to the fixing time) and quote higher prices of the fixing to customers. This can be achieved if the fixing price is pushed up or the bank's average purchase price is lowered. Second, knowing that the fixing price may go up or down, based on the private information of order flows, a bank can front-run the orders. The bank can purchase the foreign exchange cheaply. The former can be called "manipulation" while the latter can be called "pre-hedging" or "front-running." In reality, banks can do both if informed banks have the market power, via information sharing or collusion, and manipulation of the fixing price may even be possible in London. Even in the case where there is no collusion and private information is not exposed, banks can take advantage of the predictable price change, via front-running.[9]

By example, suppose that a bank has a large block of customer orders for buying USD/JPY at the fixing price. The bank would like to buy USD/JPY cheaper in the market, while providing the customer with USD/JPY at a higher rate. For buying cheaper USD/JPY, banks try to buy USD/JPY before the fixing, if the bank is convinced that its private information is a good signal for the market-wide condition of the day. This can be considered as front-running. During the fixing time window, the bank executes the customer order, which may drive up the fix price. The bank may have an incentive to buy more than the amount of customer orders, if buying more aids in driving up the price even though the price may plummet after the fixing. This is pure manipulation. By making the fixing rate higher, the bank buys aggressively at the fixing, causing much more than offsetting sales later. This is where the manipulation occurs. This aggressive buying potentially induces a spike, or volatile

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[9] Such manipulation of market prices is not unique for currency fixing. Manipulating a market price can occur at events such as during an option cut and touching the threshold level of knock-in or knock-out options.

transitory price changes, at the time of fixing.

The bank's attempt may not always succeed, because different banks have various customer orders, some of which may be net buy while some of which may be net sell. Their demand and supply may cancel out when they are executed simultaneously at the fixing time—no price movement. Thus, manipulating the market rates can be difficult when each bank is only informed of their own idiosyncratic orders from customers. The case becomes entirely different (a) when banks collude to share information, and (b) when banks are quite sure that they have correlated customer orders. The former case is a problem discussed in the WM/R fixing rate scandal, and the latter case is relevant in the Tokyo fixing.

Based on the observation above, we summarize our empirical hypotheses as below. These hypotheses are presented as null hypotheses that fixings do not alter the formation of prices.

Hypothesis 1-a: Defensive fixing trading.

Banks take advantage of deep liquidity at the fixing and execute all of their customer order flows at the fixings. Banks aim for the average price of their customers' carry out orders in order to equal the fixing price. Because banks attempt to mitigate the price impact during the one-minute fixing window, the frequency of price spikes are not substantially different from the usual trading times.

We set this hypothesis as a null, and examine whether the price spikes are unusually frequent around the fixing. The alternative hypothesis is that price formation at the fixing is unusual and the bank's fixing rate manipulation is likely.

The emergence of frequent spikes of prices alone, however, does not indicate the intention of manipulation. Spikes also occur around macro announcements because of the lack of liquidity induced by adverse selection, disagreement to news just announced, and predatory trading aiming at stop-loss liquidation.[10] We checked this possibility by examining the dynamics of liquidity (or depth) around events and by a regression analysis that controls the changes in liquidity.

Even if banks take this defensive fixing trading scheme, large imbalance of the bank's customer orders may induce spikes. We assume that, even in such a situation, banks do not prefer making a deal at price spikes. Since extreme transaction prices are omitted for the determination of the fixing rates by WM/Reuters, banks may make a loss at the deal at unintended price spikes. Thus, we can assume that banks intend to reduce the price impact during the one-minute fixing window. Price

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[10] Banerjee and Kremer (2010) theoretically predicted that disagreement of belief can induce positive autocorrelation of trading volumes and increase volatility. Brunnermeier and Pedersen (2005) theoretically explained the presence of predatory trading in a financial market.

spikes are less likely unless the banks intend to manipulate the fixing price.

Hypothesis 1-b: Mean and median prices do not deviate.

Banks submit their orders in a way that the mean and median transaction prices do not deviate.

This is another null hypothesis in that banks behave defensively in order to not to suffer losses when executing customer orders. Put differently, banks do not attempt to manipulate the fixing prices for extra profits. Against the null, banks may behave actively to create a deviation of the fixing (median) price different from the average execution prices. In this case, banks may want to make many small orders in excess of their customer order positions, which can result in widening the gap between the median and average transaction prices. This is because the London fixing price is determined by the median rather than the average transaction prices during the fixing window. Thus, banks may be able to manipulate the fixing rates.

Hypotheses 1-a and 1-b examine the price behavior during the fixing time window. As previously described, banks may well trade before the fixing as pre-hedging or front-running, which is summarized in the following hypothesis.

Hypothesis 2: Hedging before the fixing does not affect prices.

Banks can trade before the fixing time for hedging the execution risk at the fixing, but their trades are based on temporal liquidity needs and have no permanent price impact on the price.

This hypothesis is synonymous with the statement of an efficient market. Banks can trade before the fixing for hedging the risk of not being able to fully cover the customer orders at the fixing. Although their trades look like front-running, the purpose is to reduce the total price impact in case the liquidity provision is not enough at the fixing. Such transactions related to the fixing system are motivated by temporal liquidity needs which do not depend on the fundamental values of the exchange rate; the permanent price impacts should be near zero and the past returns do not predict the future returns.

Another possibility is that banks attempt to front-run the market price before the fixing when they reliably know that the liquidity is high at the fixing. This is the type of price manipulation investigated by Kumar and Seppi (1992). Even in this situation, rational liquidity providers can prevent such transitory price fluctuations since they know the event time and the tendency for price manipulation. The rational liquidity providers submit countervailing orders against the manipulation. The return reversal would be also close to zero if there are a sufficient amount of liquidity providers.

We compared the pattern of price and liquidity around the London fixing and Tokyo fixing. We do not argue against the other unusual events, such as the U.S. macro announcements and NY option cut, but they are taken into account when we execute the regression analysis. Although these events commonly exhibit an abnormally large number of deals (i.e., volume spikes), they have different reasons; they tend to have different price and liquidity patterns. When the abnormal price and

liquidity pattern relates to the particular calendar date, the patterns are induced by the bank's behavior. For fixing, this occurs on the end-of-month trading days, Friday, and 5th and 10th days. In such days, customer order flows typically surge and the bank's incentive to take advantage of fixing becomes larger.

An additional concern is that banks may collude. Since an imbalance of bank's customer order flows can be a risk for trading around the fixing, sharing private information of the customer order flows make the price movements around the fixing time more predictable and reduce the risk of trades associated with fixing. Thus, banks can construct a more favorable position if they collude, and the degree of unusual price behavior around the fixing can be exaggerated. As an empirical question, however, it is difficult to come up with a direct test of whether banks collude or not.

5 Data

In this section, we describe the data and its treatment. We use the following database:[11]

- ICAP EBS Level 5 (or Level 2) data (proprietary data, purchased by the first author)
    - Level 5 data: January 2006 to December 2013. Currency pairs: 'AUD-USD', 'EUR-GBP', 'EUR-JPY', 'EUR-USD', 'GBP-USD', 'USD-CAD', 'USD-CHF', 'USD-JPY'
    - Level 2 data: January 1999 to December 2005. Currency pairs 'EUR-JPY', 'USD-JPY'
- WM/R Closing rate (Reuters)
    - January 1999 to December 2013.
- Publicly disclosed fixing rate for Japanese banks: Mizuho Bank, Bank of Tokyo Mitsubishi (BTMU)
    - January 1999 to December 2013   (BTMU in the public domain)
    - January 2002 to December 2013   (Mizuho in the public domain)

ICAP EBS Forex dataset contains the information of deals and quotes at each time-slice.[12] Each observation has the time-stamped, prices (transaction prices and limit order prices if available,) and the volume (transaction volumes, limit order volumes if available). The grid of time-slices has changed during the following periods: one second before January 22, 2008, a quarter-second from January 22, 2008 to August 31, 2009, and a 100 millisecond from August 31, 2009 to the present. The minimum tick size, or pips, also has changed. It was decimalized on March 7, 2011 and then

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[11] The samples at Christmas and New Year days are dropped. The samples on Saturday and Sunday (at GMT) are also dropped.

[12] ICAP EBS Forex data is high-frequency data which needs data cleaning. We provided a detailed data cleaning process when we introduced the methodology.

rolled back to half pips after September 24, 2012.

The dataset has different levels of recording details: EBS Level 2 and EBS Level 5. In the Level 5 dataset, each observation of the deal has buyer-initiated and seller-initiated deal volumes. The database, however, omits certain deals that show multiple transactions at the same time-stamp. The recorded prices are the most extreme ones. The observation at a time-stamp (HH:MM:SS for example) contains the deals that occur between t-1 and t, where t is by one second (HH:MM:SS).

The information of quote contains the limit order volumes and prices up to five steps of the limit order book. This observation is a snapshot of the limit order book, which are recorded when any change occurs in the book. The dataset also contain quote counts. A quote count is the number of traders who are submitting limit orders at each step of the book.

Note that EBS allows negative spreads: the best ask price can be lowered than the best bid prices. This situation happens when the two entities at the book do not have credit lines. Also, when an observation has both a deal and a quote, the dataset does not specify the order of each transaction. We need to estimate the orders of transactions.

Level 2 dataset has a coarse frequency (every one second), and provides only the first best ask and bid prices. For most of the analysis in this paper, we use the level 5 data. We use the level 2 data before 2005 only for constructing the prices to demonstrate the comparison of the fixing rates.

WM/R closing rate is provided by Reuters Datastream. The fixing rates by the BTMU and by the Mizuho bank are obtained from their websites. WM/R closing rate are calculated at normal time when two or more trading centers (U.S., U.K., Germany, Japan) are open. The Tokyo fixing rates are not available on Japanese national holidays.

We attempted to replicate the fixing rates from our EBS market prices. The WM/R closing rate is compared with the median deal prices in the London fixing window (Table 2). The Tokyo fixing rates which are published by the BTMU and the Mizuho bank are compared with the maximum deal prices in the Tokyo fixing window (Table 3). We conducted a detailed analysis for these tables in sections 8.1 and 8.2.

<center>Table 2 and Table 3 about here</center>

In the following sections, summary statistics such as trading volumes will be presented, abnormalities around the event times will be examined, the price and liquidity patterns around event

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times will be analyzed, and finally regression analysis will be conducted.

6 Intra-day Seasonality

6.1 Deal Spikes and Price impact

USD/JPY is examined for the intra-day patterns, and observe the changes in deals during a day. We only consider the days when both the U.S. and U.K. markets are under the daylight saving (summer) time. Other currency pairs have a similar intraday pattern, but we focused on USD/JPY because it is strongly affected by the Tokyo fixing.

Figure 2 shows the intraday pattern of (A) the ratio of absolute order imbalances to trading volumes, (B) order imbalances, (C) trading volumes, and (D) price impacts. Each has a sampling frequency of 15 seconds. The horizontal axis shows the intraday time in GMT. One unit of trading volume is one million currency units. The ratio of absolute order imbalances to trading volumes is a proxy for the degree of informed traders' presence (Kaul, Lei, and Stoffman (2008)). The order imbalance is defined as the difference between buyer initiated deal volumes and seller initiated deal volumes. The price impact is defined as an absolute return over a unit of deal volumes. We calculated the averages of these variables across days.

<center>Figure 2 about here</center>

The pattern of intraday deal volumes is described in Figure 2.C. The plot exhibits spikes at the Tokyo fixing (GMT 00:55), U.S. macro announcements (GMT 12:30), New York option cut (GMT 14:00), and the London fixing (GMT 15:00). In this article, we focus on the two fixings. Although they commonly have high trading volumes, the patterns of price and liquidity differ.

The ratio of absolute order imbalances to trading volumes is high during the Tokyo market (Figure 2.A). It then remains low until it suddenly climbs up after GMT 20:00, when the New York market closes. The theoretical implication of this measure is an indicator of privately informed trading (or PIN). In this sense, the measure also indicates a sort of illiquidity of the market. The intraday time-series, however, suggests that the measure is low at the U.S. macro announcement. Around fixings, the measure becomes low, potentially indicating high liquidity.

Order imbalances (OIB) typically concentrate around zero, but it jumps up to the positive around the Tokyo fixing (Figure 2.B). This is a unique feature of the Tokyo fixing (see section 3.3).

The price impact is low around fixings but high around announcements (Figure 2 D). After the New York market closes, the price impact significantly increases. Thus, as a measure of illiquidity, the price impacts are strongly correlated with the ratio of absolute order imbalances to trading

<center>17</center>

volumes.

6.2 Intraday Pattern of Limit Order Book (LOB)

A limit order book (LOB) reflects the firm quotes of banks that provide liquidity to the market. Large volumes of quotes (a thick book) mitigate the transitory price fluctuations. In order to observe the behavior of liquidity providers around each event, we examine the intraday pattern of a LOB.

In Figure 3, we plot the following: (A) A natural log of the sum of bid and ask limit order volumes (up to four steps), (B) The imbalance between the bid and ask limit order volumes divided by the sum of total limit order volumes, (C) the total number of the quote counts in each side of the book. Construction of the plot is as follows. Within every 60 seconds, we take the average of these variables. They are averaged across days for each 60 second window, providing the data for the plot.

Figure 3 about here

The sum of bid and ask limit order volumes, or the depth, is typically high during the time window when both London and New York markets are open (Figure 3.A). The quote count also has a similar pattern (Figure 3.C). The depth becomes particularly high during the fixings, but it becomes lower around the U.S. macro announcement and NY option cut.

This pattern of depth indicates that traders behave more like a market maker during the fixing time while they tend to avoid the risk associated with potential surprise contained during macro announcements. In other words, when traders anticipate the price impacts around the fixing time, it is only transitory. The price impact, as examined in the previous section, are consistent with this pattern of depth.[13] The higher the depth becomes, the more difficult it becomes for manipulators to influence the prices, implying that frequent price spikes are less likely and manipulation is more costly.

The depth does not have a particular intraday pattern except at the Tokyo fixing (Figure 3.B). The order imbalance around the Tokyo fixing is biased when buying the US dollar (Table 5). Because this temporal imbalance is commonly known, the depth is higher at the ask-side at the time of the Tokyo fixing, mitigating the price impacts from the imbalanced orders. Since the net buying pressure around the Tokyo fixing is typically observed every day, market participants provide liquidity to absorb the anticipated transitory price movement – yen depreciation. Without such traders, the market price would quickly deviate from the fundamental price. We note that this imbalance of order flows and limit orders happen only at the time of the Tokyo fixing of the USD/JPY pair. Around the London fixing, the depth increases, but there is no predictable imbalance of the depth. The imbalance of the LOB becomes volatile after the NY market closes (GMT 21:00 to 22:00), since the market

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[13] Except for during the New York option cut. This fact is somewhat puzzling.

becomes less active and the LOB becomes thin.

In this section, we examined the intraday pattern of the limit order book. In fact, more liquidity is provided around the fixing time than the other times, and this makes it difficult for a manipulator to influence the price. In this sense, markets tend to have a pressure towards the efficient market even at around the fixings.

6.3 The 90-Second Window around the Event Time

Figure 4 shows the pattern of trading volumes, the order imbalances, and the depth during a 90 second period around the four events, two of which are during fixing times. The depth is defined as the sums of the best ask and bid limit orders. Each variable is averaged across days for each three second window. The way of construction is the same as the last section. The currency pairs of the EUR/JPY, EUR/USD, and USD/JPY are chosen to be examined.

Figure 4 about here

Although each event is commonly associated with high trading volumes, its patterns are quite different. First, at the Tokyo fixing, the high trading volumes concentrates at GMT 00:55:00 (9:55AM Tokyo time) and prior to the fixing, the depth gradually increases toward the time. After GMT 00:55:00, the depth drops, perhaps because the depth is consumed by the aggressive trades. What is peculiar about the Tokyo fixing is that it tends to have positive order imbalances around GMT 00:55:00 almost every day, but only for the USD/JPY. In contrast, for the London fixing, the trading volume has its first peak at 30 seconds before GMT 15:00:00, and it has another peak at GMT 15:00:00. After GMT 15:00:00, the trading volume gradually decreases. The depth shows a hump-shaped pattern. The orders are balanced.

In the Tokyo fixing, the pattern of the USD/JPY is quite different from the other currency pairs. The trading volume for the USD/JPY strongly surges, but the other currency pairs experience only moderately increases. The EUR/USD has a negative order imbalance. Such differences across currencies are not observed around the London fixing.

Such different patterns across currency pairs may be caused by the various ways of determining the fixing rate in London and Tokyo. As explained in section 3.3, Tokyo fixing does not necessarily determine the fixing rate as a median of the deal prices in a time window. Instead, each bank can set their own rate within the range that they made a transaction during the fixing window. Thus the banks have less incentive to settle large orders. In the London fixing, the fixing rate is determined by a third party, Reuters, and takes the median of deal prices. Banks may split the orders to obtain the prices close to the fixing rate. As a result, the trading volumes are not concentrated at a few seconds.

U.S. macro announcements and NY option cut times exhibit a similar pattern. The trading volume suddenly surge at the event time. But the limit orders are not large enough to cover the orders, which

is the biggest difference from the patterns around fixing. The order flow is mostly balanced.

7 Methodology

7.1 Key variables: Major Price Shock, Spikes, and Median Prices

When manipulative trades are present in the market, the price changes tend to be more transitory. If manipulators try to influence the price during the fixing window, the price can have an acute peak. We consider this acute peaking of the price followed by a drop as a "spike".

We also define "major price shock" as a big price change. Since the large number of spikes is naturally associated with large transaction volumes, we need a way to normalize them. The number of major price shocks is used to normalize the number of spikes. The more frequent spikes indicate that the transactions do not affect the price in the long-run such as manipulative trades and the imbalance of short-term supply and the demand of the currency. Since the fixing rate is calculated as a median of the transaction prices, we calculate the gap between the median and average transaction price. This gap can be another evidence of price manipulation during the fixing time window.

The gap between the average and median prices is defined as the difference between the average price of deals in a Y-minute window and the median price of deals in the Y-minute window. The rest of this section explains how to construct the major price shocks and spikes.

In order to construct the data of spikes and major price shocks for each currency pair, we first calculate the X-second return from the EBS transaction data.[14] A return at time t can be followed by the time $t+1$ return in either direction: (1) the time $t+1$ returns in the same direction (or zero return), and (2) the opposite direction, namely a reversal. In the second case, the movement of price at t is only transitory. In order to avoid the bid-ask bounce, we focus on the case where the price change is extremely large and call them a "spike". The detailed procedure of constructing spikes and major price shocks is described as follows:

- Calculate X-second returns.
- Define a "reversal" at t for all samples as an observation where the return from $t-1$ to t is followed by a return from t to $t+1$ in an opposite direction with a magnitude of more than 80% of the return between t and $t-1$.
- Omit zero returns. Rank returns of all samples from the largest (positive) to the smallest

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[14] For calculating the return from transaction price, we use the last transaction in each interval. If we set X=10 and there is no trade during the ten seconds, we refer to the last transaction. Since the transaction is irregular, the interval of return is not exactly equal to ten seconds, but at least a minimum of ten seconds.

(negative). Extract the observations from the top 5% and the bottom 5%. The extracted observations are defined as major price shocks. If an observation has the "reversal" feature, it is defined as a spike.

- Thus, major price shocks include spikes.

We count the number of spikes and major price shocks in a Y-minute window.[15] For this construction, the number of major price shocks relative to the number of deals do not change much across currency pairs. The basis point (bp) size of the extracting point (i.e., 5% top and bottom) depends on the sampling frequency of X. For the case of X equaling to one second, low liquidity currencies such as AUD/USD, EUR/GBP, GBP/USD, USD/CAD typically have the extracting point of 4bp to 6bp, while high liquidity currencies such as EUR/JPY, EUR/USD, USD/CHF, USD/JPY have the extracting point of 1.2bp to 2.2bp.

In the following analysis, we set X as one second, and Y as one minute unless otherwise noted. Overall, results are not affected by the moderate changes in the sampling frequency.

We focus on the following point of times that are associated with high trading volumes: (1) 4:00 pm London fixing (GMT 15:00, summer time) and (2) 9:55 am Tokyo fixing (GMT 00:55). Although macro announcements and the NY option cuts also exhibit high trading volumes, we do not focus on these events in this paper. We apply the analysis described below to these events in each section from 8 to 8.2.

7.2 Methods of Analysis

First, we show an intraday time-series plot of the frequency of spikes. For the significance of the intraday pattern around the event times, we can apply the standard test for the differences in averages. Thus we can examine whether there is statistically a significant frequency of spikes during the time of fixings. Second, we calculate the returns before and after the fixing, and examine the correlation between them. For the time-horizon of the return, we take one, five, fifteen, and thirty minutes before and after the fixing. Third, we compare the market rate and the fixing rate that are provided by WM/Reuters (for London fixing) and each Japanese bank (for Tokyo fixing). For the latter, we conduct a regression analysis of the difference between the market rate and the fixing rate on market variables such as volatility and order imbalances. Lastly, we conduct a regression analysis of the spike to major price shock ratio and gaps in average and median prices, controlling the market

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[15] For aggregating one minute around the time of Z, we usually start sampling 30 seconds before Z and end sampling 29 seconds after Z. For robustness, in the section of regression, we show the result by sampling from 0 seconds after Z to 59 seconds after Z minutes.

conditions.

7.2.1 Intraday Seasonality of Spikes (Figure 5)

The intraday pattern of spikes are shown in Figure 5. In this analysis, we focus on the USD/JPY because they typically have high volumes in the two fixings.

Because the frequency of spikes is usually correlated with high trading volumes in a time window, we need to normalize the variable.[16] We also examine the normalization by the number of major price shocks. This normalization captures how likely large movements end up with transitory price changes (i.e., spikes). We take this normalization method as a standard for this analysis.

The frequency of spikes and major price shocks (in the common logarithm) is described in Figure 5.A. Figure 5.B and Figure 5.C show the frequency of spikes divided by the major price shocks (B) and the frequency of deals (C). Figure 5.D shows the difference between the frequency of positive spikes and the frequency of negative spikes. For the calculation, the sample is from the days that both the U.S. and U.K. are under daylight saving time. Each variable is averaged across days for every 15 seconds (here we take Y=15 seconds).

<div align="center">Figure 5 is about here</div>

7.2.2 Significance around Events (Figure 6)

Figure 6 shows the results of the test of average of variables between the event times and the other times of the day. The variables tested are: the frequency of spikes, the frequency of major price shocks, the spike to major price shock ratio, the gaps between average and median prices, the order imbalances, the bid-ask spreads, the depths, and the quote counts. The averages of these variables are calculated in before, around, and after each event. Each time interval is one minute.

<div align="center">Figure 6 about here</div>

The averages of variables in these intervals are compared with the average in the other intraday-time. The test is done through the standard Welch's t-test.[17] The vertical axis of the plot shows the t-statistics and the horizontal axis shows the time-intervals. Cases of p-value less than 1% are marked with "o".

7.2.3 Return Reversal around Events (Table 4)

The frequency of spikes can capture the transitory price changes in very short-time (or Hypothesis 1), and they cannot capture more gradual return reversal of prices (or Hypothesis 2). In order to

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[16] A natural candidate for the normalization is using the frequency of trades. For this normalization method, however, the number of spikes can be underestimated because of the many small trades.

[17] Wilcoxon's rank sum test is also performed and gives the same qualitative results. The results are omitted from this paper.

examine Hypothesis 2, we calculate the correlation between returns before and after events. If there could be a return reversal, we would observe the negative correlation of returns. Positive correlation indicates a momentum of the price after the event. Under the hypothesis of an efficient market, the correlations should be zero.

Table 4 tabulates the Spearman's correlation of coefficients of the returns for each currency pair, and the levels are significantly different from zero at less than 1%, which is marked with "o". We change the intervals to calculate the return from one minute to thirty minutes. We also tested the pattern on Friday and at the end of month when settlement needs are expected to be higher than other days.[18]

<div align="center">Table 4 about here</div>

7.2.4 Regression analysis for the fixing-market price gap in Tokyo (Table 5)

The Tokyo fixing rate announced by banks is on average 1.5 basis points higher than that is calculated by the maximum deal price during the Tokyo fixing window (Table 3). This gap is observed across banks and currency pairs. It is usually positive, varies over time and has long and short cycles (Figure 7).

<div align="center">Figure 7 about here</div>

To analyze the pattern of the gap, we conduct the following regression analysis.

$$
\begin{aligned}
\log(\text{Fix}_d) - \log(\text{P}_d) = \alpha &+ \beta_1 Before.volatility_d \\
&+ \beta_2 Before.OIB_d \\
&+ \beta_3 Before.cumRet_d \\
&+ \beta_4 (\log(P_d) - \log(VWAP_d)) \\
&+ \beta_5 (\log(\text{Fix}_{d-1}) - \log(\text{P}_{d-1})) + Dummies + \epsilon_d
\end{aligned}
$$

The frequency of the observation is daily. We used the data from the year of 1999 for the BTMU, and the data from 2002 for the Mizuho bank. The dependent variable is the difference of the log of fixing prices for the BTMU or the Mizuho bank (Fix_d) and maximum of the transaction prices during the fixing window (P_d). We take the "max" of the transaction price during the fixing, or 60 seconds from JST 9:55 am (GMT 00:55), because banks tend to use the maximum price as a fixing price, which are more favorable to the bank's interest knowing that there is an order imbalance to buy foreign currencies. Since the transaction at the Tokyo fixing is concentrated on USD/JPY, we focused on the USD/JPY. The analyses using EUR/JPY gave the same results.

The independent variables are: one minute return volatility, the sum of the order imbalance (OIB), cumulative returns, gaps between the log prices of P_d and the volume weighted average price

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[18] The sample size of the end of month is small. Evans (2014) used empirical distribution to deal with this problem and also reported the abnormality of the pattern of return around the London fixing at the end of month.

(VWAP), one lag of the independent variable, and the calendar dummies.[19] The volatility, OIB, and returns are calculated from the sample from GMT 00:00 to GMT 00:55. The calendar dummies are dated on the 5th and 10th days, Friday, and the last trading day of each month.

The standard errors are corrected by the Newey-West method. The results are shown in Table 5.

Table 5 about here

7.2.5 Regression analysis for the frequency of spikes (Table 6)

Lastly, we conduct a regression analysis for the frequency of spikes on the event dummies. This analysis is for controlling the trading activities such as deal volumes and depths.

We take the spike to major price shock ratio and the average-median gap (or the absolute value of log(averaged price) – log(median price)) as dependent variables. The sampling frequency of the variable is by one minute.[20]

Independent variables are dummies for the four events. Each event has three dummies that indicate one minute around the event time, 10 minutes before and after the event.

Our interest is the effect of the dummies on the frequency of spikes. To do this, we control the effect for the one minute trading volumes, trade size, the market price-VWAP gap, Friday, and end-of-month dummy. We also control the effect regarding the limit order book: the bid-ask spread, the depth, and the quote count. Since the sample includes the decimalized period, we define the dummies that indicate the decimalized and half-pip periods. We make interactions of such dummies and LOB variables for the controls. The results are not reported in this article for the sake of brevity.[21]

Market variables, such as the trading volume, the bid-ask spreads and the depth, may be endogenous. For this reason, we first regress such variables on their own lags and use the estimated values as dependent variables. Thus, the regression method is a two-stage least square (TSLS). We also conducted negative binomial regression for the count of the spikes and the major price shocks. The overall results are the same and we also do not report these regression results for the same reason above.[22]

Our sample ranges from January 5, 2006 to December 31, 2013. The currency pairs are EUR/JPY, EUR/USD, USD/CHF, and USD/JPY. Each variable is constructed as one-minute time aggregated variables. The trading volume is the sum of total trading volumes during each minute, and the trade

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[19] The VWAP is widely used as a reference of market price. The deviation of prices from VWAP indicates unusually high price pressures at the moment.

[20] That is, we set Y= one minute and calculate the number of spikes from 0 to 59 seconds for each minute.

[21] The results are available upon request.

[22] The results are available upon request.

size, bid-ask spreads, depth, quote count, and VWAP are the average during each minute.

Table 6 shows the estimation results. Overall, each currency has similar results for the spike to major price shock ratio, while there is little observable pattern for the results of the average-median gap. We will describe the estimation results for time-dummies in more detail in later sections. Trade controls and LOB controls have intuitive results; larger trading volumes tend to associate with many price spikes. When the liquidity is low, that is, the bid-ask spread is high, the depth is low, and the quote count is low, then the spikes become more frequent.

<div align="center">Table 6 about here</div>

Average-median gap seems to be more influenced by trade and LOB variables rather than time-dummies, but they are mostly insignificant.

From the next section, we describe the interpretation of the above results for each event separately.

8 London and Tokyo Fixings

8.1 London Fixing

WM/R closing rate and the Market rate (Table 2)

First, we examine how the WM/R closing (or fixing) rate is different from the market rate, which is calculated from the EBS market data. The median of transaction prices is calculated based on the samples of a 60-second window from GMT 14:59:30 to GMT 15:00:30, and are compared to the mid-rate of the WM/R fixing rate provided by Reuter DataStream. The gap is defined as a relative value in basis point:$[\log(\text{fixing rate}) - \log(\text{market rate})] \times 10000$.

The descriptive statistics about this gap is shown in Table 2. The EBS market rate does not exactly match the WM/R rate, but the gap is within the range of 0.5bp for 98% of the sample. We also do not observe any particular time-series pattern about this gap. [23]

WM/R is said to be from "samples" of all transactions by Reuters. Our calculation of the fixing rate slightly deviates from the one provided by Reuters. The gap, however, is usually smaller than the minimum tick size. We do not find any particular problem on the calculation of the London fixing

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[23] The time-series plot of the gap between WM/R and market rate is omitted but available upon request.

rate using the EBS data.

Intraday plots and significance

Figure 2.C shows that there is a large spike of trading volume around the London fixing time (GMT 15:00, during U.K. summer time). In addition, the depth at the LOB increases (Figure 3.A, Figure 3.C), mitigating the price impact of trades. The fact is not found around the U.S. macro announcement time and the NY option cut time. On average, the order imbalance is mostly symmetric, and so is the depth at the LOB (Figure 2.B). These patterns are common across currency pairs, which is different from the Tokyo fixing where the transaction concentrates on USD/JPY. Such an increase in trading volumes and liquidity occurs at the very starting second of the fixing window (GMT 14:59:30), and gradually decrease to the end of fixing window (GMT 15:00:30). There is a slight peak of trading volumes at GMT 15:00:00 (Figure 4).

Spikes and major price shocks are more likely to be frequent around the London fixing (Figure 5A). When the number of spikes is normalized by the number of major price shocks, the spikes are no more likely to be frequent (Figure 5.B). Another way of normalization, by using the number of trading frequency, provides the same result (Figure 5.C). We can check the significance of these results in Figure 6 (spikes, major price shocks, the spike to major price shock ratio). At the London fixing, the number of spikes, or that of transitory short-term price changes, is not particularly frequent. As Figure 5.D shows, there is no asymmetry regarding the direction of the spikes. The average-median gap tends to become slightly lower (Figure 6, Mean-Median).

We can observe the increase of liquidity around the London fixing (Figure 6, depth, bas, qc). The depth increases, the bid-ask spread decreases, and the quote count increases. These results are significant at the 1% level for every currency pair.

We can observe negative correlation between the one-minute returns before and after the fixing (Table 4), indicating the return reversal around the fixing time. The negative correlation is observed for all currency pairs, but not for the time interval exceeding one minute. Thus, the return after the fixing can be predictable and the market tends to be inefficient around the fixing time. The reversal becomes stronger on Friday and the end of month, when the demands for settlement become high.

Regression analysis

The regression analysis confirms the results above. In Table 6, the dummy for the one minute window around the London fixing (labeled as "j1500") is not significant or can even be negative, indicating the spike is less likely. Therefore we do not find there to be any direct evidence of manipulation in terms of the spikes. Although our plot indicates the average-median gap is high around the London fixing, the regression results here do not provide a particularly strong support of this finding.

These results are robust for the changes in the estimation methodology. We also attempted a

negative binomial model for the count data of spikes and major price shocks, but it shows similar results (reports are omitted in this article).

Overall, we did not find direct evidence and consequence of manipulation based on the frequent price spikes around the London fixing time. On the contrary, the liquidity tends to increase and prevent the transitory price impacts. However, there is one-minute return reversal around the fixing for every currency pair, indicating some form of market inefficiency.

8.2 Tokyo Fixing

As explained in section 3.3, the Tokyo fixing is different from the London fixing in terms of the process to determine the fixing rate and the institutional and economic background. As observed in Figure 2.A, the peak of trading volume for the USD/JPY is during the Tokyo fixing (GMT 00:55). Different from the London fixing, the orders imbalance exists in favor of buying around 10 unites (or 10 million USD) on average, and these intensive trading concentrate at just GMT 00:55:00 (Figure 4). The price impact becomes lower (Figure 2.D) and the ask-side depth increases (Figure 3.A, B). The increase of the depth, however, disappears after GMT 00:55:00 (Figure 4).

Tokyo fixing rate and the Market rate

It is important to compare the market rate to the fixing rates in Tokyo because the fixing rates are determined by individual banks independently and the banks may well have an incentive to set the rates to their favor. The fixing rates by the BTMU and Mizuho bank are obtained from their web sites. We compared them with the market rate for one-minute around the fixing time. The gap is expressed in basis points: $[\log(\text{fixing rate}) - \log(\text{market rate})] \times 10000$, that is, the fixing-max gap. The banks are said to be allowed to set the fixing rate within the ranges of their actual transaction prices during the fixing window as of 2014.[24] Considering this rule, we take a maximum of transaction prices from GMT 00:55:00 to GMT 00:55:59 rather than the median prices. We take the maximum price, not a minimum, because there are more buying orders than selling around the Tokyo fixing time and the bank profits from quoting a higher price for a foreign currency. We focus on the EUR/JPY and the USD/JPY for our analysis, which are currencies with the two largest trading volumes.

First, we examine the time-series pattern of the "fixing-max gap". For getting rid of the short-term fluctuation, we take the 30 days moving average of the fixing-max gap. The time-series plot of the gap is presented in Figure 7.

Evidently, the gaps were positive before October 2008 at the early stage of the Global Financial Crisis. That is, the banks used to set the fixing rate higher than the market rates by around 3bp during this period. The higher fixing rate is be in favor of the bank's position when they have more retail

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[24] This implicit rule was obtained by market participants in interviews.

orders buying at the fix price than selling, which is usually the case in the Tokyo market. After October 2008, this gap disappeared. There are long-term and short-term cyclical patterns for this gap.

Summary statistics are presented in Table 3. Over the sample period, the public fixing rates are on average 1.5bp higher than the market rates. Considering that the bid-ask spread is in the order of 1bp to 2bp, the gap is not very small. In addition, the fixing rates were higher than the maximum transaction prices, inferring that banks potentially do not have transactions at the fixing price during the fixing time period.

These gaps are common across banks and currencies. The two banks tend to submit similar fixing rates. The correlation of the gaps for the two banks was 80% before 2008, but it has fallen to less than 50% after 2008.

These findings are consistent with the regulation and the role of the Tokyo fixing. The banks provide the same fixing rates that are determined at the beginning of day, and they may suffer from the volatility of the rates for the rest of the day. The banks may well then impose a premium, or the gap, in setting the fixing rate. Moreover, the banks can set their own fixing rates and they have incentive to make a transaction at a more favorable price during the fixing window, which can cause spikes. Such behaviors of the banks are not necessarily for enjoying excess profits by setting higher rates, but possibly as a result of defensive hedging action as explained below.

Regression Analysis: Why do Tokyo fixing rates deviate from the market prices?

Based on what has been examined so far, it can be reasoned that the Tokyo fixing rate is not the median or average transaction rate during the time window. We can now examine determinants of the fixing rate. The methodology of regression is explained in section 7.2.4, and Table 5 presents the result. The fixing rate tends to become high (or yen depreciates) in the following situations: (1) when aggressive orders between GMT 00:00 and 00:54 depreciate the yen. (2) when the market rates become higher than the VWAP. That is, times when the market price temporarily deviates from the trader's average purchasing prices. (3) on the 5th and 10th days and Friday. (4) when the return volatility is low. Coefficients of these factors are statistically significant at a 1% level for both banks and currencies.

Each coefficient shows how they influence the incentive of banks to setting more favorable fixing rates. The positive effect of the order imbalance suggests that some market participants purchase the foreign currency even before the fixing when the fixing rate is expected to become high. Potentially banks may purchase the currency to hedge the risk of fixing determination. Since the dummies for the 5th and 10th days and Friday, or indicators of high settlement needs by clients, are positive and significant, banks may respond to the client's demand and set higher fixing rates.

One way to interpret the coefficient of VWAP is that it reflects the large needs for foreign currencies on the day of high settlement needs. In fact, order imbalances before the Tokyo fixing time tends to be high (Figure 4), which may cause the deviation of market price from the VWAP.

The order imbalance tends to be particularly high when the fixing rate is high.

It is hard to interpret the coefficient on volatility. The banks may set large gaps, or premiums, to avoid the risk of intraday price fluctuation. Thus the coefficient on volatility is expected to be positive, but the estimated value is significantly negative.

These estimation results are similar across banks and currency pairs.

One major difference between the London fixing and the Tokyo fixing is that London fixing occurs at the end of trading day in the London time zone, while in Japan, it takes place in the beginning of the day of the Tokyo market. In London, the fix rate clears the accumulated demand and supply and no more transactions are expected at the fix rate after fixing time. In Tokyo, the fixing rate is determined at 10:00 am, which may clear up the demand and supply that had accumulated by 10:00 am, but the rate is valid for retail transactions for the rest of the day. The banks are exposed to significant currency risk, by promising the fixed exchange rate to retail customers while it has to trade and square the position at the changing spot rate in the interbank market. In order to address the risk, banks may add on a risk premium to the fixing rate from the market rate, based on its expectation of orders for the rest of the day.

In summary, the fixing rate that is determined by banks is strongly influenced by the market price, order flows, and potentially their client's orders. High fixing rates (or the direction the yen depreciates) is related to the aggressive buying order before the fixing, and the VWAP tends to deviate from the market rates. These fluctuations of market and fixing rate are also related to the typical settlement schedule of firms.

Intraday plots and significance

Spikes can be more frequent during the Tokyo fixing time (Figure 5.A) than the other time. The spike to major price shock ratio is also high during the fixing, while the spike to trade ratio is not particularly high (Figure 5.B and C).[25] Figure 6 supports that there are many spikes during the Tokyo fixing (labeled as "j0055"). Average-median gaps also become higher. The order imbalance becomes positive and statistically significant for USD/JPY. In addition, the order imbalance tends to become more elevated even before the fixing. But this is not common across currencies. For example, the EUR/USD does not have such imbalanced orders. Also the depth increases only for the USD/JPY. In the Tokyo fixing, trading on the USD/JPY will dominate the other currency pairs, which is different from the London fixing.

The volume and liquidity pattern for the 90-second window around the fixing time looks different from that of the London fixing (Figure 4). The volume at the Tokyo fixing concentrate at the three

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[25] Under the mechanism of the Tokyo fixing, the banks may be satisfied with one spike of the transaction price, and our measure to capture the count of spikes may not be appropriate. This is probably one reason why the way of normalization is important for the count of spikes.

seconds around GMT 00:55:00. The depth gradually becomes higher towards this time.

While the one minute return reversal can be found at the London fixing, it is not found at the Tokyo fixing (Table 4). Days on Friday and the end of month tend to have return reversals, but they also depend on currency pairs. The EUR/JPY and USD/JPY have significant reversals at the end of month, while EUR/USD does not have such reversal for all sub-samples. There can be inefficiency to some extent, but it is less evident compared to the other findings such as frequent spikes and fixing rate gaps.

Regression analysis

Our regression analysis confirms the result of frequent spikes around the fixing. The dummy of the Tokyo fixing (labeled as "j0055") becomes positive and statistically significant, which is common across currency pairs. The average-median gap is not affected.

Thus, our analysis suggests that there can be frequent spikes at the Tokyo fixing time. As already explained, these frequent spikes do not necessarily indicate inappropriate behavior of the banks, because the banks can set their own fixing rates within the range that they have made a transaction. In that sense, they are allowed to do this for hedging their positions that may become long or short in the subsequent hours of the day.

The findings for Tokyo fixing are summarized as follows: (1) spikes are more frequent than the London fixing, (2) the customer orders are biased toward buying the foreign currencies, and this is predictable, (3) trading volumes and liquidity concentrate on the USD/JPY, (4) before 2008, the fixing price set by banks were biased upward from the market transactions rate during the fixing time, which were in favor for banks to make profits. We did not find particular return reversals like the London fixing, but occasional inefficiency of the market is evident. Calendar effects also matter for the determination of the fixing rate and the price fluctuation around fixing.

These findings do not necessarily indicate that banks tended to exploit the extra profits from fixing. Rather, the banks may hedge the particular risks arising for the rest of the day.

9   Conclusion

This paper analyzed the volume and price behaviors around the fixing times in the foreign exchange markets. In the intra-day seasonality analysis, it has been established that there are volume spikes at fixing times. We examined whether the fixing prices are properly determined by the WM/Reuters in the London 4:00 pm fix and by respective Japanese banks in the Tokyo 9:55 am fix. With empirical findings, we infer whether the market has been efficient, in the sense conditional prediction is not possible. For this intention, we compared the Tokyo 9:55 am fixing and the London 4:00 pm fixing. The patterns of liquidity and return around the events are quite different. The

comparison is summarized in Table 7.

Insert Table 7 about here

First, we did not find direct evidence that the London fixing is manipulated based on the terms of the frequent spikes of the price. Rather, the liquidity provision is plenty during the fixing window (GMT 14:59:30 to 15:00:30), mitigating the price impact of large volume of trades. This finding is robust even after controlling for the trading volume and liquidity. The return reversal, however, exists for a minute window around the London fixing. The market becomes less efficient in the sense that the price is partially predictable.

Second, the price behaviors around the Tokyo fixing time are very different from those at the London fixing. There are significantly more price spikes. The fixing prices set by individual banks had deviated from the market rate by around 3bp before 2008. But these findings may not be directly comparable to the situation in the London fixing, because banks are allowed to fix the price by themselves and the fixing occurs at the beginning of the day (London fixing occurs at the end of the trading day). Return reversal can exist only when volumes are expected to be higher, for example the 5-10 days or the end-of-month business days.

Third, even with these differences, plenty of liquidity is provided around both fixing times.

In summary, an investigation in the paper suggests no direct evidence for manipulation but there are some suggestive evidence of market participants taking advantage of the price behaviors around the fixing times. In London, there is little price spikes (up or down) during the one minute of fixing window. However, for days with higher volumes, such as the end-of-month business day, there is evidence of price reversal after the fixing time. In Tokyo, there is little or no support for an argument that banks colluded as allegedly in London, because each bank can set its own fixing rate. However, banks in Tokyo tend to fix the price higher (dollar appreciation) than median transactions prices around the fixing time. This can be explained by the fact that customers who requested fixing prices for settlements are biased towards importers and that the fixing is done early in the business hours so that banks have to hedge for unexpected customers' orders later in the day. Price changes during the fixing time shows a tendency of price spike and reversals. Some market participants expect the dollar to appreciate at the fixing time and take positions before the fixing time and make profits at the fixing time. This tendency is more prevalent in Tokyo than in London.

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Table 1: Timeline of events in the Forex market

	Winter time			Summer time				
GMT	LN	EST	JST	LN	EDT	JST	EVENT	Major Announcements
0:00	0:00	19:00	9:00	1:00	20:00	9:00	Tokyo open	
							Tokyo Fixing	
1:00	1:00	20:00	10:00	2:00	21:00	10:00	(9:55)	Australia: statistics (GMT1:30)[26]
2:00	2:00	21:00	11:00	3:00	22:00	11:00		
3:00	3:00	22:00	12:00	4:00	23:00	12:00		Japan: monetary policy announcement
4:00	4:00	23:00	13:00	5:00	0:00	13:00		RBA policy rate (GMT4:30)
5:00	5:00	0:00	14:00	6:00	1:00	14:00		
6:00	6:00	1:00	15:00	7:00	2:00	15:00	Tokyo option cut	
7:00	7:00	2:00	16:00	8:00	3:00	16:00		Switzerland: policy rate and statistics [27]
8:00	8:00	3:00	17:00	9:00	4:00	17:00	London open	
9:00	9:00	4:00	18:00	10:00	5:00	18:00		U.K.: statistics (BST10:30)[28]
10:00	10:00	5:00	19:00	11:00	6:00	19:00		
11:00	11:00	6:00	20:00	12:00	7:00	20:00		
12:00	12:00	7:00	21:00	13:00	8:00	21:00		U.K.: policy rate, ECB policy rate (GMT 12:45)
13:00	13:00	8:00	22:00	14:00	9:00	22:00	NY open	U.S. (EDT8:30)[29] and Canada (GMT12:00 and 12:30)[30] statistics
14:00	14:00	9:00	23:00	15:00	10:00	23:00	NY Option cut	Canada: policy rate (GMT 14:00)
15:00	15:00	10:00	0:00	16:00	11:00	0:00	London Fixing	
16:00	16:00	11:00	1:00	17:00	12:00	1:00		
17:00	17:00	12:00	2:00	18:00	13:00	2:00		
18:00	18:00	13:00	3:00	19:00	14:00	3:00		FOMC policy announcement and minutes (EDT 14:00 or 14:15)
19:00	19:00	14:00	4:00	20:00	15:00	4:00		
20:00	20:00	15:00	5:00	21:00	16:00	5:00	NY Close	
21:00	21:00	16:00	6:00	22:00	17:00	6:00		
22:00	22:00	17:00	7:00	23:00	18:00	7:00		
23:00	23:00	18:00	8:00	0:00	19:00	8:00		Japan: statistics (JST 8:30 and 8:50) [31]

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[26] Unemployment statistics, Retail sales, CPI, Trade balance, GDP.

[27] Retail sales (GMT 7:15), CPI (GMT 7:15). GDP (GMT 5:45), Unemployment rate (5:45), Trade balance (GMT 6:00).

[28] BOE inflation report, Unemployment statistics, Monetary policy committee, Retail sales, GDP, Trade balance)

[29] Unemployment statistics, ADP unemployment statistics (EDT8:15), Unemployment insurance claim, Retail sales, CPI, Trade balance, GDP.

[30] Unemployment statistics and CPI (GMT 12:00). Retail sales, Manufacture's sales, GDP (GMT 12:30)

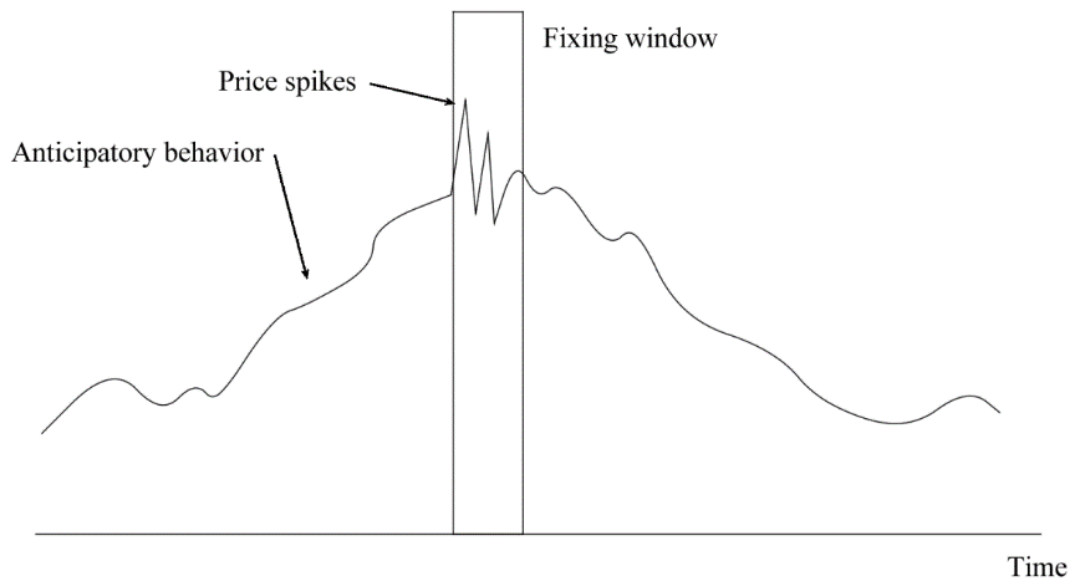[31] Unemployment statistics, CPI at JST 8:30. Machinery orders, GDP, Trade balance at JST 8:50.

Figure 1: Price behavior around the fixing

This figure illustrates the price spikes during the fixing window and the anticipatory behavior before the fixing.

Table 2: WM/R fixing rate and EBS market rate

WM/R fix - EBS median market rate

	mean	median	std	skew	kurt	q1	q99	Lowest day	2nd lowest	2nd highest	Highest day
AUD/USD	0.379	0.506	1.83	-0.154	11.6	-5.42	5.34	20090109	20081024	20081124	20081231
EUR/GBP	0.227	0.24	1.7	0.183	6.74	-4.73	5.55	20090123	20081216	20090713	20081006
EUR/JPY	0.489	0.399	1.52	0.413	7.27	-3.53	5.22	20000731	20111130	20081231	20101231
EUR/USD	0.29	0.319	2.62	1.89	58.4	-7.84	9.59	20050720	20050629	20050722	20050603
GBP/USD	0.159	0.207	1.48	0.342	10	-4.22	4.28	20080930	20090309	20091030	20090130
USD/CAD	0.399	0.468	1.92	0.488	6.87	-4.62	6.17	20071129	20090120	20100531	20081029
USD/CHF	0.131	0	0.976	-0.0401	5.83	-2.4	2.64	20110801	20110712	20081127	20130211
USD/JPY	0.143	0.406	2.31	-2.18	51	-8.17	6.15	20050603	20030418	20050831	20050429

This table is the summary statistics of the gaps between WM/R rate and the median market prices that we calculated from the EBS data in the fixing window. The gap (in basis point) is defined as $[\log(\text{fixing rate}) - \log(\text{market rate})] \times 10000$. The market rate is calculated as a median transaction price for the sample starting from GMT 14:59:30 (for summer time) to GMT 15:00:30.

Table 3: Tokyo fixing rate and EBS market rate (USD/JPY)

Tokyo fix public rate - EBS max market rate

	mean	median	std	skew	kurt	q1	q99	Lowest day	2nd lowest	2nd highest	Highest day
BTMU, Event max price	1.34	1.21	2.83	-0.0289	3.74	-5.52	8.28	20081127	20110928	20001228	20000502
BTMU, Event median price	3.14	2.88	2.82	0.286	3.55	-3.21	10.4	20130610	20030129	20000502	20071228
Mizuho, Event max price	1.15	1.16	2.38	-0.4	5.2	-5.42	6.93	20130329	20081127	20061228	20060502
Mizuho, Event median price	3.06	2.99	2.51	0.235	4.5	-3.1	9.74	20110928	20090128	20080917	20081230

This table is the summary statistics of the gaps between the Tokyo fixing rates and the maximum market price at the EBS market during the Tokyo fixing window. The gap (in basis point) is defined as $[\log(\text{fixing rate}) - \log(\text{market rate})] \times 10000$. The market rate is calculated as a "maximum" transaction price for the sample starting from GMT 00:55:00 (for summer time) to GMT 00:55:59. For the fixing rates, we use the rates that each bank (the BTMU and Mizuho bank) publishes on their web sites.
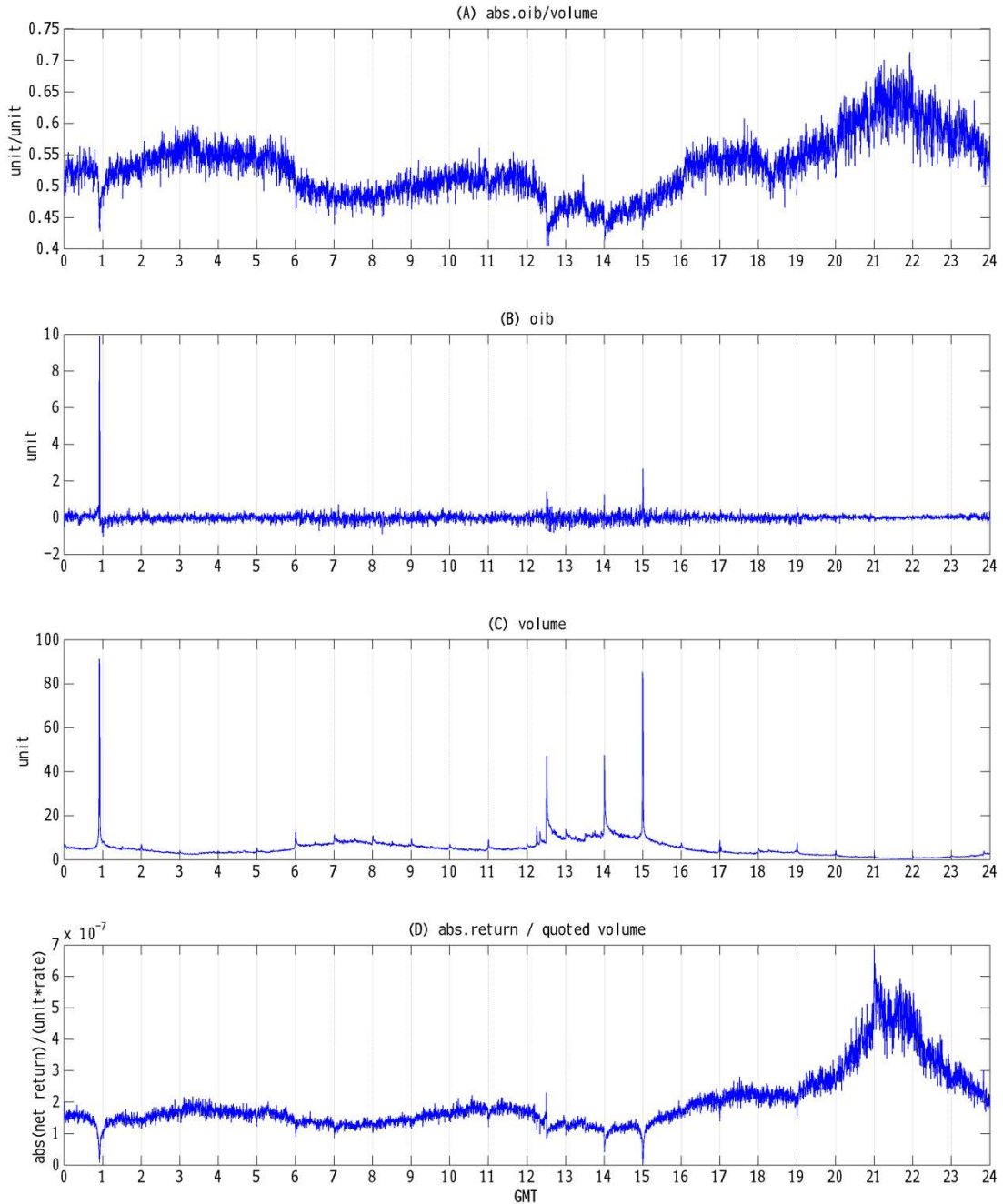
Figure 2: Intraday patterns of four variables

Intraday pattern of USD/JPY (from January 4, 2006 to December 31, 2013) for: (A) The ratio of absolute order imbalances to trading volumes, (B) the order imbalances (unit is one million currency), (C) the trading volumes (unit is one million currency pair unit), (D) the price impact (unit is log price changes for each one million yen trades). The sample is from the days that both U.S. and U.K. are under daylight saving time. Each variable is averaged across days for every 15 seconds. The horizontal axis is the time of GMT. The four major peeks of trading volumes correspond to: (1) The Tokyo fixing (GMT 00:55), (2) U.S. macro announcement (GMT 12:30), (3) New York currency option cut (GMT 14:00), (4) the London Fixing (GMT 15:00).
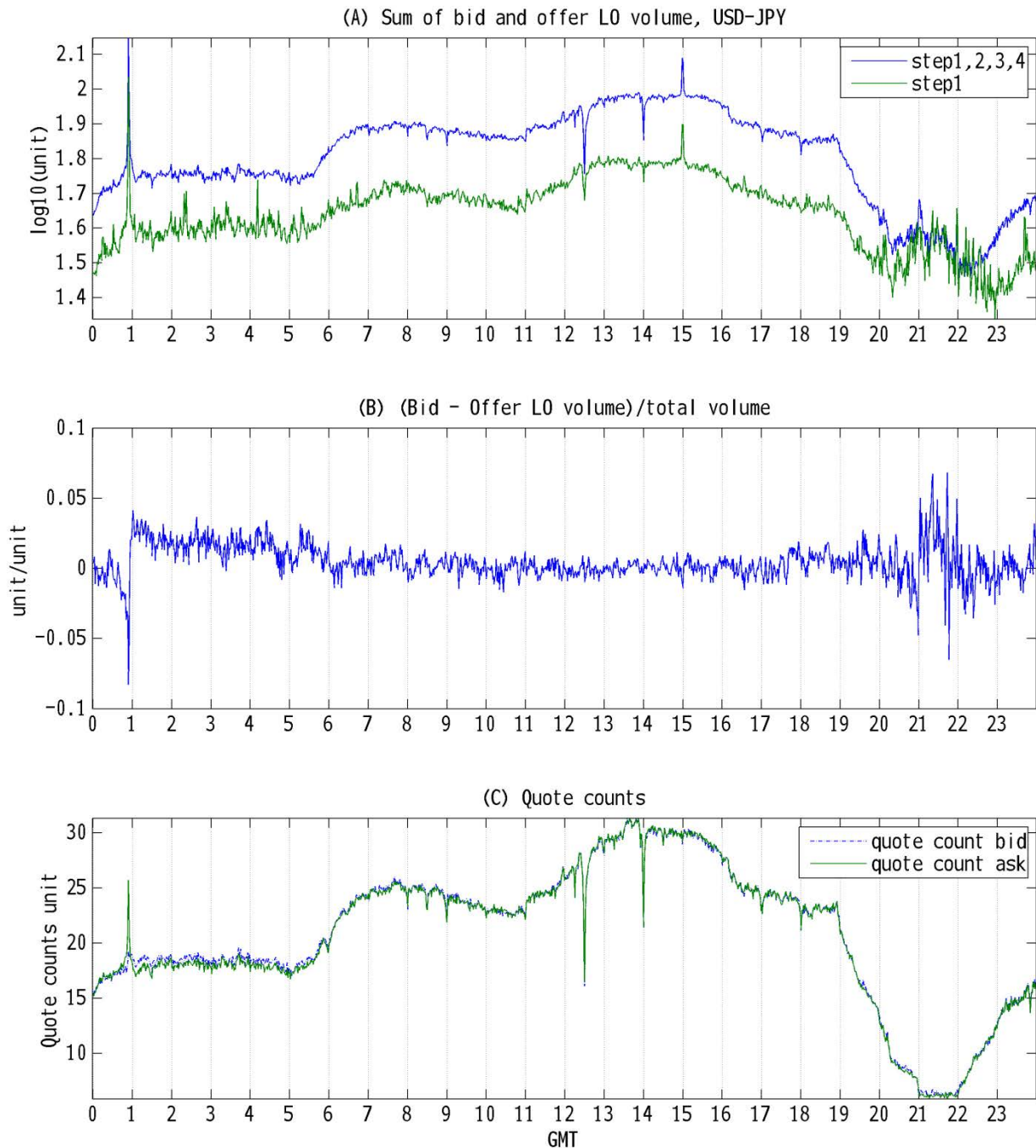
Figure 3: Intraday pattern of limit order books

These panels show intraday pattern of the limit order book: (A) The natural log of the sum of bid and ask side limit order volumes up to four steps (blue) and the best quote (green). (B) The difference between the bid limit order volumes and the offer limit order volumes. The values are divided by the total limit order volume. (C) The quote counts of bid and ask side books. The sample is from the days that both U.S. and U.K. are under daylight saving time. Each variable is averaged across days for every 60 seconds. The horizontal axis is the time of GMT.
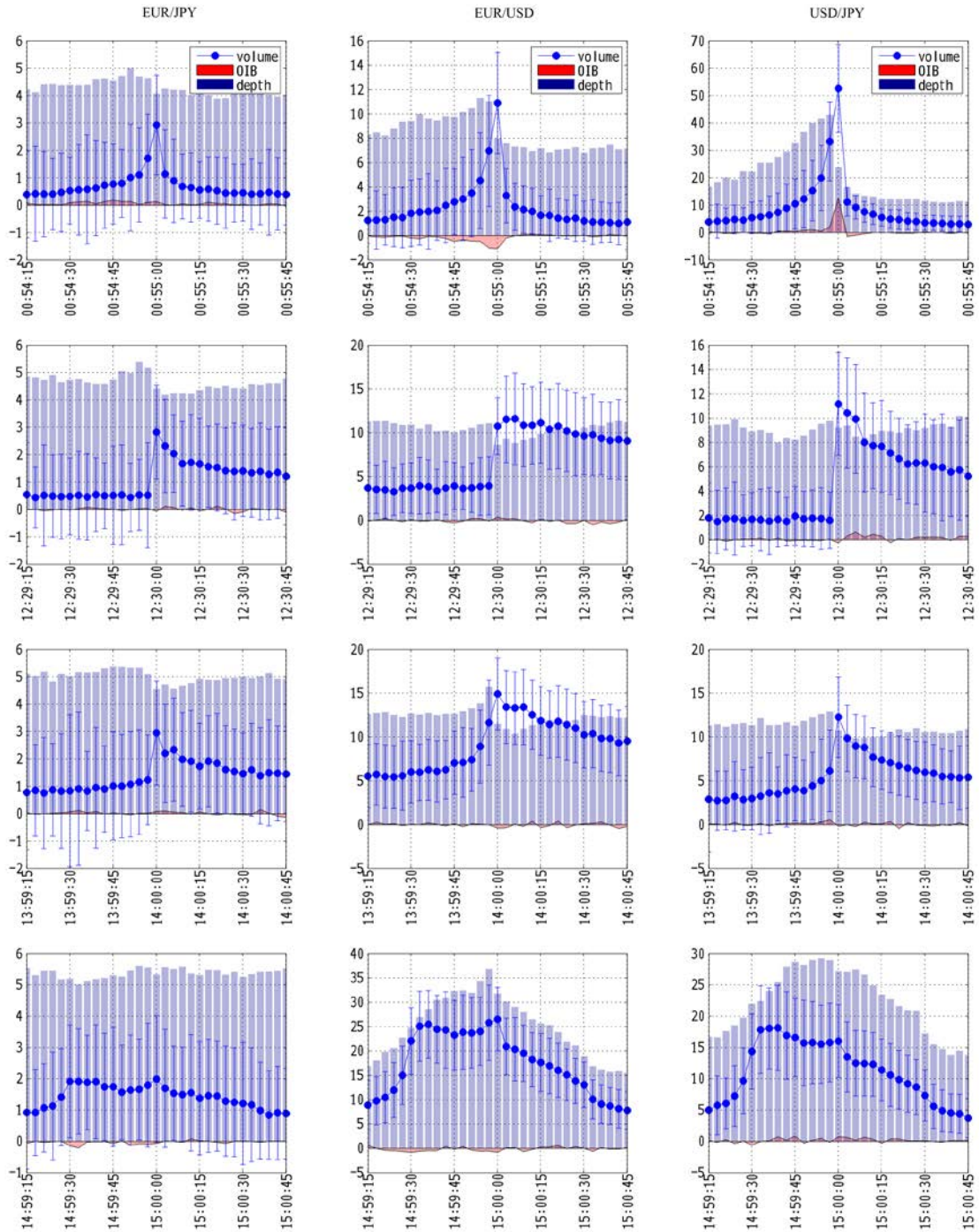
Figure 4: The 90-second window around four events

This is a plot of the trading volumes (and their one standard deviation bars across days), the order imbalances, and the depth (the sum of best bid and ask limit order volumes). Each variable is the average across days for every three seconds. We focus on 90 seconds at around the Tokyo fixing (GMT 00:55), U.S. macro announcement (GMT 12:30), NY option cut (GMT 14:00), the London fixing (GMT 15:00).
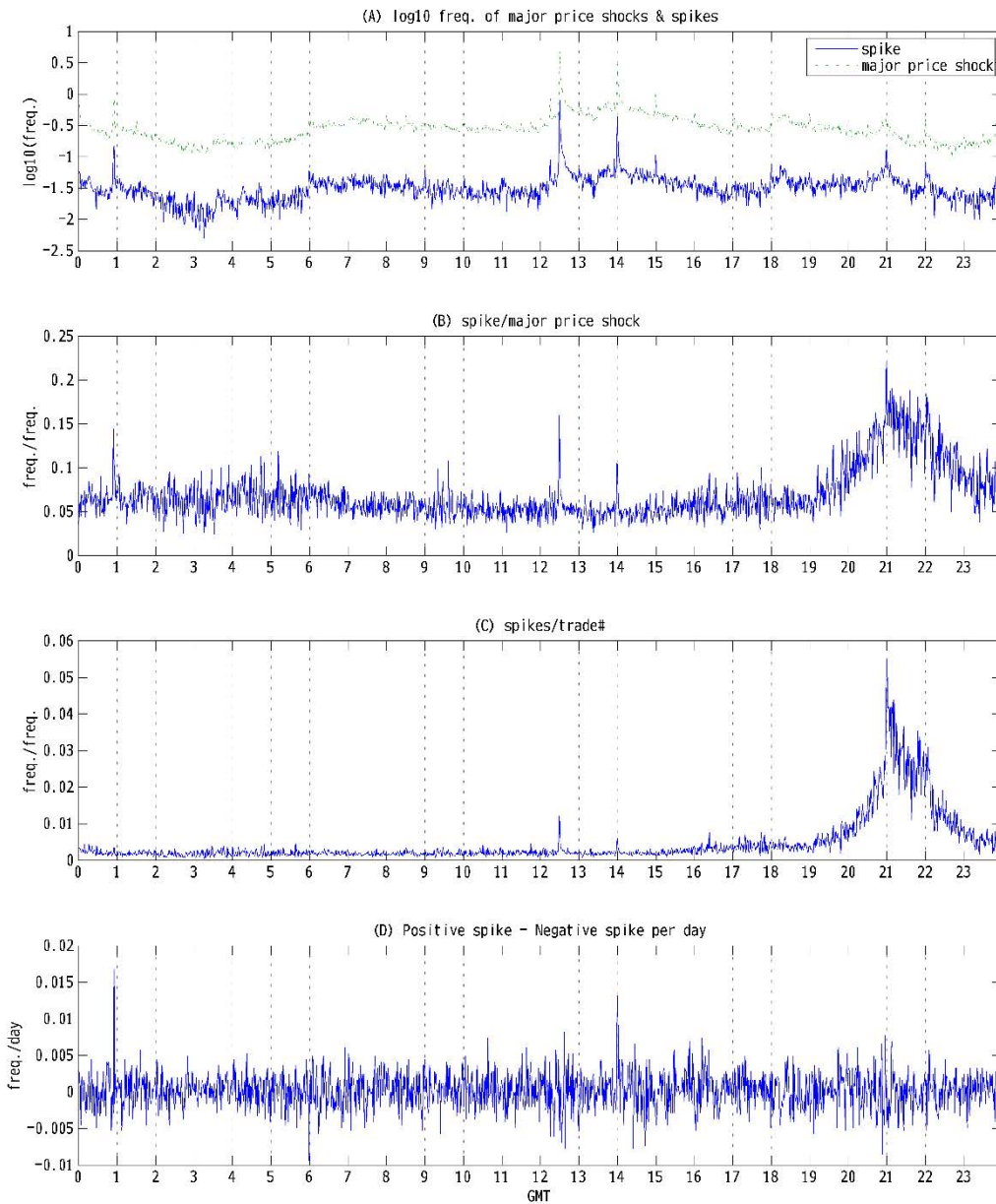
Figure 5: Intraday pattern of spikes

These panels show the frequency of spikes with various normalizations. (A) The frequency of spikes and major price shocks. (B) The frequency of spikes divided by the frequency of major price changes. (C) The frequency of spikes divided by the frequency of deals. (D) The difference between the frequency of positive spikes and the frequency of negative spikes. The sample is from the days that both U.S. and U.K. are under daylight saving time. Each variable is averaged across days for every 15 seconds. The horizontal axis is the time of GMT.
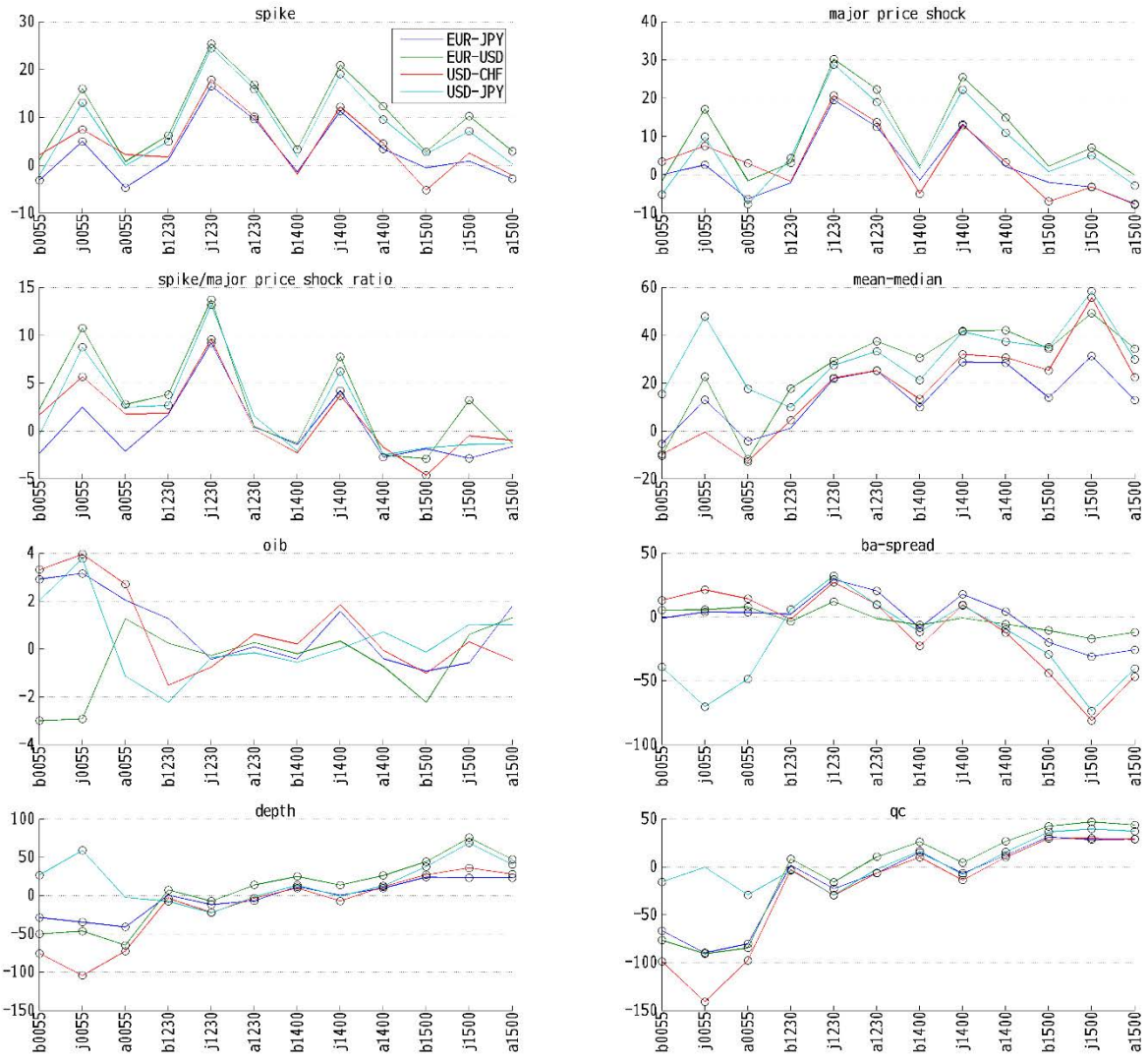
Figure 6:   Significance of abnormality around events

This panel shows the Welch's t-statistics for the average of following variables: the frequency of spike, the frequency of major price shocks, the ratio of spikes to major price shocks, the absolute value of average-median price gaps, the order imbalances, the bid and ask spreads, the depths, the quote counts. The null is the average of each variable in each event window is equal to the average of the other time of a day. The horizontal axis shows event times with prefixes. Prefix of b, j, a represents -90 seconds to -30 seconds, -30 seconds to +30 seconds, and +30 seconds to +90 seconds. The level of significantly different from zero at 1% is marked as "o".

Table 4: Negative correlation around events

Sample	Interval (min)	EUR/JPY		EUR/USD		USD/JPY	
		Tokyo Fix	London Fix	Tokyo Fix	London Fix	Tokyo Fix	London Fix
All	1	-0.00411	-0.103 ***	-0.0393 *	-0.0887 ***	0.0154 *	-0.124 ***
		(0.852)	(2.39e-06)	(0.0738)	(5.3e-05)	(0.0738)	(5.3e-05)
	5	-0.00594	-0.0776 ***	0.0198	-0.013	-0.00728	-0.0945
		(0.787)	(0.000408)	(0.367)	(0.554)	(0.367)	(0.554)
	10	0.00503	-0.0343	0.000179	0.00641	-0.00421	-0.0677
		(0.819)	(0.119)	(0.994)	(0.771)	(0.994)	(0.771)
	15	-0.0162	-0.00365	-0.013	0.0219	0.0133	-0.0444
		(0.463)	(0.868)	(0.554)	(0.32)	(0.554)	(0.32)
	30	0.0306	-0.0368 *	-0.00334	0.00151	0.0512	-0.0649
		(0.164)	(0.0941)	(0.879)	(0.945)	(0.879)	(0.945)
Friday	1	-0.0376	-0.0804	-0.107 **	-0.197 ***	0.0525 **	-0.0675 ***
		(0.446)	(0.102)	(0.0296)	(5.34e-05)	(0.0296)	(5.34e-05)
	5	-0.0251	-0.148 ***	-0.000843	-0.07	0.0515	-0.0629
		(0.611)	(0.00255)	(0.986)	(0.155)	(0.986)	(0.155)
	10	0.052	-0.0378	-0.0424	-0.00335	0.0473	-0.0305
		(0.291)	(0.443)	(0.389)	(0.946)	(0.389)	(0.946)
	15	0.0257	-0.00715	-0.0935 *	0.0471	0.0814 *	-0.0872
		(0.602)	(0.885)	(0.0574)	(0.339)	(0.0574)	(0.339)
	30	0.0751	-0.085 *	-0.0864 *	-0.0151	0.122 *	-0.0686
		(0.127)	(0.0843)	(0.0791)	(0.759)	(0.0791)	(0.759)
End-of Month	1	-0.0801	-0.408 ***	-0.0859	-0.299 ***	-0.0829	-0.309 ***
		(0.438)	(3.76e-05)	(0.405)	(0.00308)	(0.405)	(0.00308)
	5	0.0438	-0.436 ***	0.257 **	-0.206 **	0.0196 **	-0.329 **
		(0.672)	(8.86e-06)	(0.0114)	(0.0443)	(0.0114)	(0.0443)
	10	0.027	-0.262 ***	0.0342	-0.0593	0.0538	-0.145
		(0.794)	(0.00993)	(0.741)	(0.566)	(0.741)	(0.566)
	15	-0.0188	-0.203 **	0.0958	-0.089	0.0278	-0.0468
		(0.856)	(0.0472)	(0.353)	(0.389)	(0.353)	(0.389)
	30	0.0764	-0.156	0.0475	-0.0785	0.137	0.0466
		(0.459)	(0.129)	(0.646)	(0.447)	(0.646)	(0.447)

This panel shows the Spearman's correlation of returns before and after each fixing event time window (GMT 00:55:00, GMT 15:00:00). Each parenthesis indicates the p-value. The intervals for calculating the return are one, five, ten, fifteen, and thirty minutes before and after the events. The samples starting from 30 seconds before the event and 30 seconds after the event are omitted. The null hypothesis is zero correlation. The negative correlation indicates a return reversal. ***, **, and * denote levels significantly different from zero at the 1 percent, 5 percent, and 10 percent, respectively.
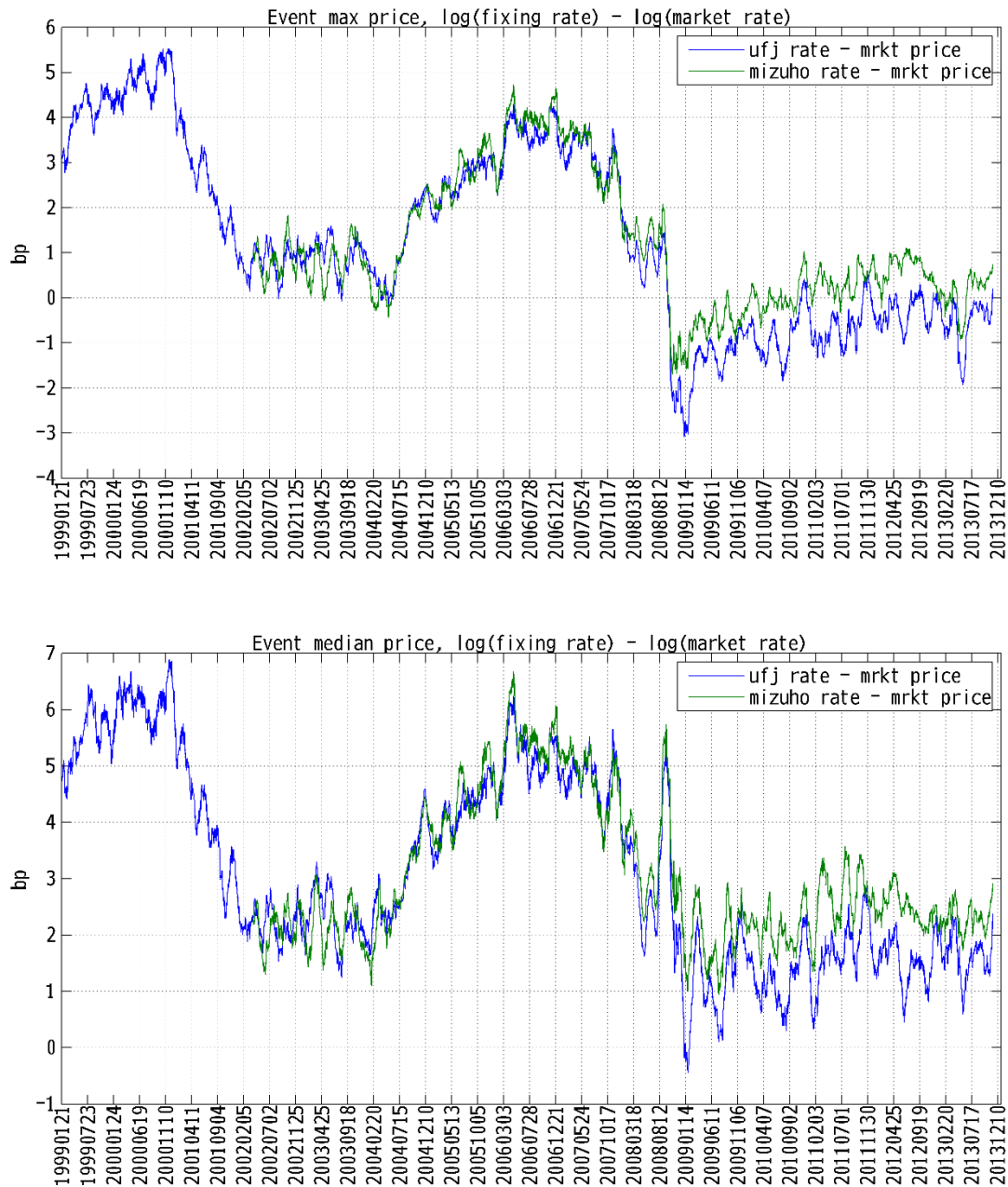
Figure 7: **Time series pattern of the difference between the Tokyo fixing rate and the market rates (USD/JPY)**

This panel shows 30 days moving averages for the gaps between the Tokyo fixing rates and the maximum market rate that we calculated from EBS data in the Tokyo fixing window. The gap (in basis point) is defined as $[\log(\text{fixing rate}) - \log(\text{market rate})] \times 10000$. The market rate is calculated as a "maximum" transaction price for the sample starting from GMT 00:55:00 (for summer time) to GMT 00:55:59. For the fixing rates, we use the rates that each bank (the BTMU and Mizuho bank) publishes on their web sites. The currency pair is USD/JPY maximum price (top panel) and median price (bottom panel) during the fixing window.

Table 5: Regression analysis for the Tokyo fixing – market rate gaps

$y_{day} = \log(\text{Fix}_{day}) - \log(\text{P}_{day})$, independent variables are from the observation 9:00 to 9:54 (before fixing)

	Use maximum event price		Use median event price	
	Mizuho, USD/JPY	BTMU, USD/JPY	Mizuho, USD/JPY	BTMU, USD/JPY
Volatility	-0.674 ***	-0.763 ***	-0.0846	-0.225 **
	(-7.42)	(-8.56)	(-0.776)	(-2.01)
OIB (before)	1.03e-07 ***	1.35e-07 ***	1.45e-07 ***	1.81e-07 ***
	(2.56)	(3.78)	(3.06)	(4.13)
Return (before)	0.00269	-0.00017	0.00501	0.00172
	(0.645)	(-0.0497)	(0.871)	(0.342)
Price - VWAP	0.0537 ***	0.0731 ***	0.0568 ***	0.0774 ***
	(4.33)	(6.53)	(3.9)	(5.76)
Lag(1) of y	0.312 ***	0.395 ***	0.25 ***	0.307 ***
	(12.6)	(19.9)	(10.3)	(14.3)
5th and 0th days	1.47e-05 *	5.74e-05 ***	4.39e-05 ***	8.48e-05 ***
	(1.52)	(5.77)	(4.02)	(7.68)
Friday	4.37e-05 ***	6.7e-05 ***	7.34e-05 ***	9.71e-05 ***
	(4.31)	(6.87)	(6.32)	(9.16)
End of Month	-1.16e-06	5.42e-05 ***	4.89e-05 **	0.000108 ***
	(-0.0523)	(2.66)	(1.79)	(4.04)
Constant	0.000151 ***	0.000111 ***	0.000207 ***	0.000162 ***
	(11.4)	(8.43)	(12.8)	(9.88)
# of observation	2846	2846	2846	2846
R squared	0.209	0.31	0.141	0.223

This regression analysis describes the gaps between the Tokyo fixing rates and the maximum market rates. The regression equation is as follows.

$$\log(\text{Fix}_d) - \log(\text{P}_d) = \alpha + \beta_1 Before.volatility_d + \beta_2 Before.OIB_d + \beta_3 Before.cumRet_d + \beta_4(\log(P_d) - \log(VWAP_d)) + \beta_5 lag\ of\ indep + Dummies + \epsilon_d$$

[Dependent variable] The dependent variables are the log differences between the fixing rate and the maximum market price. As a reference of the market price, we take "max" of the transaction price during fixing, or 60 seconds from JST 9:55 (GMT 00:55). The currency pairs is USD/JPY. We use the sample from the Mizuho bank and the BTMU.

[Independent variables] The independent variables are: one minute return volatility, sum of the order imbalances (OIB), cumulative returns, differences of log prices of P_d and volume weighted average prices (VWAP), one lag of the independent variable, and calendar dummies. The volatility, OIB, and returns are calculated from the sample from GMT 00:00 to GMT 00:55. Calendar dummies are the date of 5th and 0th days, Friday, and the last trading day of each month. ***, **, and * denote levels significantly different from zero at the 1 percent, 5 percent, and 10 percent, respectively.

[Methodology] The regression is done though OLS. The standard errors are corrected by the Newey-West method.

[Notes on samples] The sample of the fixing rate from Mizuho bank is from May 16, 2002 to Dec 30, 2013. The sample of the fixing rate from BTMU is from January 5, 1999 to Dec 30, 2013.

Table 6: Regression analysis for the frequency of spikes

	y = spike/major price shock				y = |log(mean.price) - log(median.price)|			
	EUR/JPY	EUR/USD	USD/CHF	USD/JPY	EUR/JPY	EUR/USD	USD/CHF	USD/JPY
volume	-2.63e-07	0.000156 ***	0.000101 ***	2.78e-06 ***	1.39e-10 ***	1.23e-09 **	-4.2e-09	1.69e-11
	(-0.712)	(2.41)	(3.02)	(3.21)	(3.02)	(1.86)	(-0.739)	(0.839)
trade size	-0.000334 ***	-0.0119 ***	-0.0179 ***	-0.00016 ***	6.69e-10	2e-07 ***	-7.71e-09	8.44e-10 *
	(-8.98)	(-9.45)	(-5.75)	(-8.69)	(0.516)	(2.84)	(-0.0357)	(1.64)
end of month	-0.00111	0.00224 **	0.00149	0.00245 *	1.19e-08	2.61e-07 ***	1.56e-07	1.28e-08
	(-0.585)	(1.78)	(0.775)	(1.56)	(0.0946)	(3.41)	(1.24)	(0.137)
Friday	0.00323 ***	0.00221 ***	0.0017 **	0.00195 ***	8.92e-08	4.68e-08	-1.13e-07 *	2.12e-09
	(3.27)	(3.45)	(1.69)	(2.48)	(1.26)	(1.11)	(-1.29)	(0.0398)
gaps from VWAP	0.154	1.61	1.11 ***	1.73	-1.59e-05	9.13e-06	-7.12e-05 **	-1.88e-05
	(1.06)	(0.963)	(5.64)	(1.26)	(-0.617)	(0.67)	(-1.76)	(-0.864)
Tokyo fix								
b0055	-0.00716 *	0.00052	0.00212	-0.00151	3.06e-08	4.58e-09	-4.25e-07 *	-5.73e-07 ***
	(-1.61)	(0.173)	(0.331)	(-0.459)	(0.117)	(0.0296)	(-1.46)	(-2.68)
j0055	0.0199 **	0.0506 ***	0.0597 ***	0.0491 ***	1.23e-06	4.37e-07	-2.48e-06 **	-1.19e-06 *
	(2.15)	(9.56)	(4.17)	(7.39)	(1.17)	(0.633)	(-2.32)	(-1.32)
a0055	-0.0116 ***	0.00432 *	0.00159	0.0103 ***	1.76e-07	6.02e-08	-4.08e-07 *	3.8e-07 **
	(-3.16)	(1.56)	(0.272)	(3.13)	(0.67)	(0.375)	(-1.47)	(1.66)
London fix								
b1500	-0.00249	-5.52e-05	-0.00717 ***	-0.00318 *	-1.62e-07	-8.62e-08	-5.46e-08	-1.27e-07
	(-0.798)	(-0.034)	(-2.9)	(-1.52)	(-0.529)	(-0.417)	(-0.208)	(-0.496)
j1500	-0.0131 **	0.0131 ***	0.0149 **	0.00528	-1.34e-07	2.48e-07	-4.1e-07	9.93e-07
	(-2.23)	(2.39)	(2)	(0.952)	(-0.13)	(0.345)	(-0.417)	(0.997)
a1500	-0.00468 *	-0.000504	-0.00736 ***	-0.00207	1.09e-07	2.05e-07	1.57e-07	1.63e-07
	(-1.51)	(-0.312)	(-2.81)	(-0.931)	(0.353)	(0.967)	(0.552)	(0.666)
BA spread	0.922 ***	359	148 ***	2.57	2.01e-06	-0.000158	0.00252	-7.31e-06
	(13)	(1.23)	(19.1)	(1.13)	(0.14)	(-0.215)	(1.13)	(-0.66)
depth	0.000762 ***	0.000153 ***	0.000186 **	3.31e-05 ***	-8.89e-09 **	-2.68e-09 **	1.34e-09	4.51e-10
	(3.47)	(3.11)	(2.04)	(3.23)	(-1.76)	(-2.15)	(0.338)	(0.874)
quote count	-0.00145 ***	-0.00104 ***	-0.00136 ***	-0.00102 ***	1.45e-09	-5.04e-10	5.72e-09	-3.64e-09 ***
	(-5.83)	(-13.5)	(-13)	(-8.84)	(0.199)	(-0.331)	(0.833)	(-2.9)
constant	0.103 ***	0.0789 *	0.0788 ***	0.0963 ***	3.21e-08	-1.91e-07	-4.99e-07	2.02e-07 *
	(15.4)	(1.6)	(14.9)	(2.38)	(0.0556)	(-1.11)	(-0.659)	(1.34)
# of obs	400523	750949	350085	503360	1819197	2616098	1797017	2542457
R squared	0.0071398	0.029225	0.030032	0.032302	0.0003524	2.9182e-05	9.7536e-06	3.4059e-05

The estimation results for the ratio of spikes to major price shocks and average-median price gaps. The sampling frequency of the variables is a minute.

[Dependent variables] We take the ratio of spikes to major price shocks (left panel) and average-median price gap (or absolute value of log (averaged price) – log(median price), right panel) as dependent variables.

[Independent variables] Independent variables include the dummies for the events: Tokyo fixing, U.S. macro announcement, NY option cut, and London fixing. Each event has three dummies that indicate one minute around the event time, 10 minutes before and after the event. For the sake of brevity, we only present the estimates for the fixing dummies. We also add control variables: the one minute trading volumes, trade sizes, the difference between the market price and the VWAP, Friday and end of month dummies. We also control the effect from the limit order book: the bid-ask spreads, the depths, and the quote counts. Since the sample includes the decimalized period, we define the dummies that indicate the decimalized and half-pip periods. We make interactions of such dummies and LOB variables for the control. We omit the results for presentation. ***, **, and * denote levels significantly

different from zero at the 1 percent, 5 percent, and 10 percent, respectively.

[Methodology] Market variables such as trading volume, bid-ask spreads, and depth may have endogeneity. For this reason, we first regress such variables on their own lags and use the estimated values as dependent variables. Thus the regression method is two-stage least square (TSLS). We also conducted Negative binomial regression for the count of spikes and major price shocks. The overall results are the same and we do not report the regression results.

[Notes on samples] Our sample ranges from January 5, 2006 to December 31, 2013. The currency pairs are EUR/JPY, EUR/USD, USD/CHF, and USD/JPY.   Each variable is constructed as one-minute by one-minute variables. The trading volume is the sum during each minute, and the trade size, bid-ask spread, depth, quote count, and VWAP are the average during each minute.

Table 7: Summary of empirical findings

	Tokyo fixing (GMT0055)	London fixing GMT1500(1600), UK summer (winter) time
Major institutional differences	1. Each bank can decide the fixing price within the range of their trading history during the fixing period. 2. The fixing occurs at the beginning of the trading day, and the fixing price is available for the rest of the day unless a large price change occurs.	1. Every bank use the same uniform price determined by WM/Reuter. 2. The fixing occurs at the end of the trading day.
Trading volume Figure 2.C, Figure 4, and Figure 6.	Large spikes of volume for USD/JPY at GMT00:55:00.	Large spikes of volume from GMT14:59:30.
Order imbalance Figure 2.B, Figure 4, and Figure 6.	1. More buying order than selling for USD/JPY. 2. This imbalance occurs before the fixing window.	Nearly Zero order imbalances on average.
Liquidity (LOB) Figure 3 and Figure 6 (depth, bas, qc)	1. Depth becomes high and spread decreases (especially for USD/JPY) 2. Offer side depth becomes higher.	Depth becomes high and spread decreases.
Return reversal Table 4	Return reversal is present at the end of month, but not as evident as at around the London fixing.	1. Return reversal for one minute around the fixing. 2. This reversal is strengthened at the end of month.
Frequency of spikes Figure 5, Table 6 (spike, spike/major price shock)	Frequent spikes, relatively high spike to major price shock ratio.	Spikes become more frequent a bit, but the spike to major price shock ratio does not change.
Deviation of fixing prices from market prices Table 2, Table 3, Figure 7	1. Foreign currency (USD and JPY) tend to appreciate at the fixing rate (before 2008). 2. No particular gaps after 2008.	No particular gaps.