Foreign Exchange Fixings and Returns Around the Clock

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Abstract

This paper documents that the U.S. dollar appreciates in the run up to foreign exchange fixes, in both Asian and European time zones, and depreciates thereafter. The effect is pervasive, highly statistically significant, and implies swings exceeding a billion U.S. dollars per day. Using a series of natural experiments, we show the existence of a published reference rate determines the timing of intraday return reversals. Finally, we study potential explanations and conclude that the most likely channel driving this effect is related to the hedging activities of foreign exchange dealers who intermediate an unconditional demand for U.S. dollars at the fixes.

Keywords: foreign-exchange, fixings, high-frequency returns, inventory management, intermediation.

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The foreign exchange market trades continuously on a 24-hour decentralised basis across the globe in different time zones. Every day, benchmark rates are determined using specific procedures and published at pre-set times. These currency fixes are well established and widely followed but there exists surprisingly little insight on how they affect (intraday) price formation. In this paper, we study high-frequency currency returns around the clock and document a novel intraday return pattern: the U.S. dollar systematically appreciates against all currencies ahead of the three major currency fixes in Tokyo, Frankfurt (the ECB fix) and London, and reverts thereafter.

To establish this fact, we construct intraday returns from January 1999 to December 2019 for the G9 currency pairs which cover roughly 75% of daily spot turnover (see, e.g., BIS, 2019). Consider the dollar portfolio that invests in foreign currencies against the U.S. dollar. On average, this portfolio depreciates by around 2.5 basis points in the run up to the Tokyo and European fixes and appreciates by the same magnitude during the post-fix period. That is, during regular Asian or European trading hours, the U.S. dollar remains flat on average but displays two V-shaped return reversals with turning points marked by the fixes that take place at 9:55 Tokyo time, 14:15 Frankfurt time and 16:00 London time, respectively.[1]

While the magnitude of this effect is in line with what one might expect from a microstructure related phenomenon, the price patterns are highly pervasive and, given the size of the spot market alone, economically meaningful. Based on daily turnover numbers from the 2019 Triannual BIS survey, we estimate that the patterns we detect imply swings exceeding a billion U.S. dollars per day. In statistical terms, all the average movements in the dollar portfolio during the respective windows are highly statistically significant with t-statistics ranging between 4.5 and 11.7.

Moreover, the return patterns for the dollar portfolio are robust across individual currency

[1]Throughout the paper we use military time. Therefore, 11:00 corresponds to 11:00 a.m., and 16:00 corresponds to 4:00 p.m. Unless specifically noted, all times are Eastern Time (ET), denoting the generalised time zone in New York. Over the year, the time zones in use in New York are Eastern Daylight Time (EDT) and Eastern Standard Time (EST), respectively.

pairs with a large degree of statistical confidence. All currencies display V-shaped reversal patterns around the Tokyo and European fixes, respectively, with the Japanese yen being the sole exception to depreciate after the London fix.

Providing additional evidence pinning down turning points within the day, we exploit the fact that Japan doesn't follow daylight savings time (DST). This means that the time difference between New York and Tokyo varies between 14 hours during winter and 13 hours when DST is in use from March to November. Measured in Eastern Time (ET), the peak of the U.S. dollar around the Tokyo fix shifts by exactly one hour when DST is in use while there is no change in the timing of the reversals around the European fixes.

To study the persistence of fix reversals we calculate returns going long the U.S. dollar before the fix and reversing the position thereafter. Ignoring transaction costs, these reversal returns are persistently positive and large. Around the Tokyo fix, an initial position of one U.S. dollar in 1999 grows to 12 (yen), 9 (euro and dollar portfolio) and 5 (pound) U.S. dollars by 2019, respectively. Around the European fixes (going long the U.S. dollar before the ECB fix and short the U.S. dollar after the London fix), the initial position grows to 27 (euro), 14 (pound) and 6 (dollar portfolio) U.S. dollars, respectively.

To show that the fixes are the salient turning points within the day we calculate alternative reversal returns for both the Tokyo and European windows and show that the returns are indeed maximised exactly when the reversal points are aligned with the fixing times.

As holidays are non-synchronous across countries, we have 304 days in our sample that are holidays in Japan when reference rates are not published (Ito and Yamada, 2017). If reversals are tied to the existence of a fix, they should not emerge on Japanese holidays that are normal trading days in other countries. In line with this conjecture, we find no significant return patterns on these days around the Tokyo fix while the reversals around the European fixes remain high and statistically significant.

Conducting a second quasi-natural experiment, we extend our data set to start in 1986 to investigate price patterns before the introduction of the London (1994) and the ECB (1999) fixes, respectively. Return patterns look distinctly different before the introduction of the fixes and the turning points we document only emerge once the published reference rates become recognized as established benchmarks. This is also reflected in trading quantities over time and we can show that the fixes become gradually more important, consistent with theories of 'liquidity begets liquidity' (Duffie, Dworczak, and Zhu, 2017). Indeed, we estimate that during our main sample period, between 30% and 40% of traded volume is executed during the three hours leading up to the London fix and during the hour after.

Taken together, non-synchronous holidays and intraday patterns in the pre-fix era demonstrate the novelty of our contribution: when the fixes are not published (including when they did not exist), reversals do not occur, but when they are published, we observe reversals.

Moving beyond the empirical characteristics of fix return reversals, we consider a number of potential risk and microstructure-based explanations including calendar, information and announcement effects, stochastic volatility and price jumps, and intraday liquidity. Overall, we find little empirical support for these alternatives and rule them out.

However, using data from the Refinitiv FX Matching (RM) inter-dealer platform for the sample period between 2006 and 2019, we provide evidence that is consistent with a demand pressure and inventory management explanation where demand for U.S. dollars systematically arises at the fixes, resulting in the V-shaped return patterns. As RM is the dominant platform for Commonwealth currencies, we focus on the Australian dollar and the pound and we follow existing literature and use order imbalances in the dealer-to-dealer (D2D) market to proxy for aggregate order imbalances in the dealer-to-client (D2C) market.

First, we show that the unconditional return patterns we observe are aligned with unconditional order imbalances in the dealer market towards an excess demand for U.S. dollars before and at the fixes. For example, the median order imbalance tilted towards U.S. dollar demand before the London fix on RM for both the Australian dollar as well as the pound amounts to around 20 million U.S. dollars. Those pre-fix order imbalances are statistically significant and economically large, translating to around 6% of volume traded in advance of the London fix.

Second, we study conditional reversals whereby inventory models predict that returns for providing immediacy should be higher when absolute order imbalances are larger, and even more so during periods of heightened uncertainty, i.e., when risk-averse market makers demand a higher compensation for deviations from their desired inventory level. Using double sorts on order imbalance and intraday FX volatility we find that return reversals are (i) aligned with the direction of the conditional order imbalance, (ii) increasing in the amount of order imbalance and (iii) larger during periods of high FX volatility. In percentage terms, reversal returns increase between 32% and 68% as we move from low to high volatility days for either the Australian dollar or the pound. Moreover, when imbalances are small and volatility is low, return reversals are close to zero. Overall, all conditional results are consistent with an inventory management explanation.

Third, we explore returns to liquidity provision. To do so, we consider a hypothetical scenario with a dealer who understands there is an unconditional demand for U.S. dollars and therefore builds up U.S. dollar inventory to act as a liquidity provider in the *client* market at the fix. We also consider a trader who does not have access to the dealer market, but trades to exploit the V-shaped return pattern around the European fixes. Importantly, the trader *always* acts as a liquidity demander and can only trade in the *client* market.

We show that the unconditional return patterns cannot easily be arbitraged away by traders seeking to exploit the intraday predictability in the client market as transaction cost adjusted returns are significantly negative. At the same time, returns to liquidity provision are positive and strongly statistically significant, as is the difference between the liquidity demanding trade and the liquidity supplying trade. This is a result of the dealer acting as a liquidity provider at the fix while the trader is a liquidity demander. Thus, the trader loses out on the bid-ask spread at the fix as they sell U.S. dollars at the bid, while the dealer transacts at the ask. Overall, our findings are consistent with the idea that clients are demanding U.S. dollars at the fixes while dealers raise their prices when streaming quotes to clients; thus, supplying U.S. dollars in exchange for a liquidity premium.

In summary, we present evidence consistent with an inventory risk explanation and, in particular, show that there is an unconditional demand for U.S. dollars that manifests itself at the fixes. However, while an unconditional demand for U.S. dollars is consistent with an unconditional V-shaped reversal pattern, our analysis is silent with regards to the origins of this imbalance. We speculate that a predictable demand for U.S. dollars at the fix is related to the special role of the United States as the world's provider of safe assets and the dollar as the world's reserve currency.

Related Literature: The intraday price patterns documented in this paper are related to a well-established literature on intraday FX patterns starting with Wasserfallen (1989), and Cornett, Schwarz, and Szakmary (1995), followed, more recently, by Ranaldo (2009) and Breedon and Ranaldo (2013) who document that local currencies depreciate during local working hours. With respect to these papers, our contribution is twofold: First, our granular dissection allows the identification of price reversals around major currency fixes. Indeed, while it is true that the U.S. dollar depreciates during U.S. trading hours, the downward drift only starts after the London fix at 11:00 ET. Similarly, European currencies depreciate only until the ECB fix at 14:15 local time, i.e., a couple of hours before the end of the local trading day. Moreover, the claim that local currencies depreciate during local hours is not generally true. The yen, for example, actually appreciates during Asian trading hours against the U.S. dollar, while the opposite is true during U.S. trading hours.

Our paper is also related to a literature in market microstructure studying foreign exchange benchmarks. For the London fix, Melvin and Prins (2015) analyse hedging flows of fund managers at month-end, Evans (2018) assess price dynamics in tight windows around the fix, while Evans, O'Neill, Rime, and Saakvitne (2020) show differences in trading behavior across investor types. Furthermore, Ito and Yamada (2016) document a structural demand for U.S. dollars at the Tokyo fix. Different from these papers, we show that U.S. dollar demand manifests itself in a systematic appreciation and depreciation pattern around both the Tokyo and European fixes tracing out a W-shaped return pattern around the clock.

I. Foreign Exchange Benchmarks

A foreign exchange fix is a pre-set time of day when bids and offers are aggregated and a reference price is published. Historically, the most popular fixes are the London, ECB, and Tokyo fixes. Figure 1 depicts these fixes visually in Eastern Time (ET, the time in New York) "around the clock." The colored blocks in Figure 1 show the regular trading hours in the futures markets of each location. The figure begins at 17:00 ET which is the end of the trading day in New York and roughly the beginning of the trading day in Australasia. The first major currency fix that occurs is Tokyo at 9:55 local time which is 20:55 ET (or 19:55 ET when daylight saving time (DST) is not in use in the United States). The red, green, and yellow blocks overlap, meaning that as Japanese trading is closing, European markets are opening. While the beginning of the trading day in New York (we assume 8:00 ET) happens close to the ECB fix at 8:15 ET (14:15 local time), the timing is clearly not exactly aligned. Moreover, and importantly, the ECB fix is also not aligned with the usual release time of macro announcements at 8:30 ET. As we argue later, this distinction in timing is important when considering intraday price movements in exchange rates. The final and most important fix of the day is the London fix at 16:00 local time (or 11:00 ET).

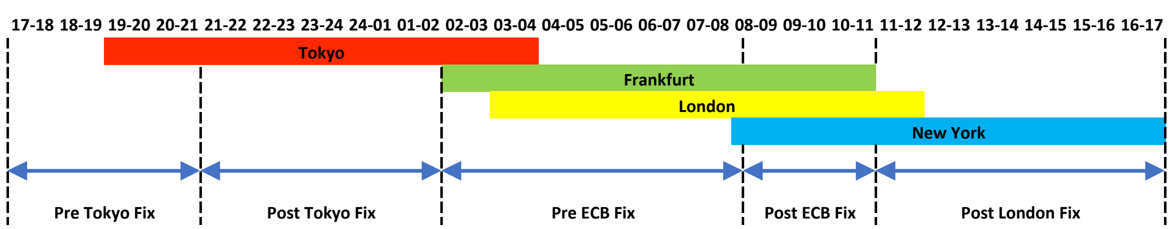


Figure 1. Currency Fixes across Time Zones

While all fixes have an impact on foreign exchange markets, they differ from each other with respect to institutional characteristics, publication time of reference rates, and the methodologies to compute fix rates. In what follows, we provide a summary of the institutional characteristics of the three major fixes in currency markets.

First, the Tokyo fix rates are published at 10:00 local time, whereby each bank determines its own individual fix rate for their customers. This is a major difference compared to the ECB and London fixes, where only one reference rate is published. The rates of the Tokyo fix are based on transacted prices, which banks sample from their own customer transactions at exactly 9:55. Further, the fixing rate applies not only to pre-fix but also to post-fix customer orders, which are submitted after 10:00. The Tokyo fixing rate, therefore, has far-reaching consequences for banks over the remainder of the trading day (see, e.g., Ito and Yamada, 2016).

Second, reference rates from the ECB fix are based on a daily teleconference between eurozone central banks at 14:15 CET. The reference rates are the average of quoted bid and offer prices against the euro, which means that the ECB reference rate is not based on actual transactions. However, the ECB reference rates are often used by non-financial corporations in the euro-area that use forward contracts for hedging purposes (see, e.g., FSB, 2014). To stress that the euro foreign exchange reference rates are for information purposes *only*, and to discourage using the ECB fix for transactions, the ECB has moved the publication of the reference rates to 16:00 CET in July 2016 while keeping the methodology unchanged (ECB, 2019). In direct response, Thomson Reuters launched the WM/Reuters 14:00 CET benchmark to target corporates who had previously valued, hedged and settled cross-border transactions using the ECB fix.

Lastly, the WM/Reuters London fix rate is set at 16:00 London time and published by Thomson Reuters. The benchmark rates are computed based on trades (and quotes for less-liquid currency pairs) in a window around 16:00. In a five-minute interval around the fix (i.e., between 15:57:30 and 16:02:30), traded rates are sourced every second from major FX platforms and a median trade based on bid and offer rates is calculated from the pooled sample of trades.[2] In contrast to the Tokyo fix, the London fix only applies to orders that

[2]Before 15 February 2015, the length of the window to calculate the fix rate was only a one-minute interval from

arrive before 16:00 local time and which are requested to execute at the benchmark rate. The London fix is prominently used by various groups of market participants to value their international portfolio positions (see, e.g., Melvin and Prins, 2015).

II. Data

We compile our data from multiple sources including Refinitiv, CME, Bloomberg, ICE and Datastream. In this section we briefly describe the main data, while we discuss additional data sources and further details regarding data pre-processing and cleaning in the Online Appendix (OA). Our full sample starts in January 1999 and ends in December 2019, covering 21 years of high-frequency tick-by-tick data for the G9 currencies, including the Australian dollar (AUD), the Canadian dollar (CAD), the euro (EUR), the Japanese yen (JPY), the New Zealand dollar (NZD), the Norwegian krone (NOK), the Swedish krona (SEK), the Swiss franc (CHF) and the British pound (GBP), all vis-à-vis the U.S. dollar. These currencies are the most liquid currencies over the sample period, and together they account for close to 75% of the total daily turnover in the foreign exchange market based on calculations using information available from the latest triannual BIS survey (see BIS, 2019).

For the sample period from January 1999 to December 2019, we have high-frequency *indicative* bid and ask quotes from Refinitiv Tick History (RTH), which essentially acts as an aggregator of quotes from individual banks that are available to market participants to trade "bank-to-client". From the RTH data, we cannot gauge the volume of transactions or the price at which transactions are executed even though most transactions in the foreign exchange market are still executed over-the-counter.

Starting in June 2006 we also have data from the Refinitiv FX Matching (RM) platform that provides real-time data on *traded* prices as well as volumes. Furthermore, the RM data includes information that allows us to calculate various measures of order flow. Together with Electronic Broking Services (EBS), RM is the leading inter-dealer platform for foreign

15:59:30 to 16:00:30.

exchange trading with a daily volume for spot transactions exceeding 100 billion U.S. dollars (compared to around 76 billion U.S. dollars traded on EBS). While not all currency pairs are equally liquid on both platforms (RM, e.g., is the leading platform for Commonwealth currencies), Breedon and Vitale (2010) show that returns for a given currency pair are very highly correlated.

III. Currency Returns Around the Clock

In this section, we provide novel evidence on the intraday behaviour of currency returns and, in particular, document the following novel stylised fact: *exchange rate returns display a predictable intraday seasonality such that the U.S. dollar appreciates in the run up to foreign exchange fixes and depreciates thereafter.*

A. Dissecting Currency Returns

Denote by s_t the log of the exchange rate, expressed in units of U.S. dollar per foreign currency and Δs_t the change in the log exchange rate between time $t-1$ and t. A negative Δs_t corresponds to an appreciation of the U.S. dollar relative to the foreign currency. Working in U.S. Eastern Time (ET) we define daily close-to-close log spot returns (Δs_t^{CTC}) as the percent change in the mid-quote from 17:00 on day $t-1$ to 17:00 on day t, i.e.,

$$\Delta s_t^{CTC} = s_t^{17:00} - s_{t-1}^{17:00}. \quad (1)$$

Next, we split the day into different periods guided by the timing of the three main currency fixes across the globe, i.e., (a) the Tokyo fix at 9:55 local time; (b) the ECB fix at 14:15 local time; and (c) the London fix at 16:00 local time. Hence, we calculate returns for the following five intraday windows (all times expressed in ET): (i) pre-Tokyo fix ("pre-T", 17:00 to 20:55), (ii) post-Tokyo fix ("post-T", 20:55 to 2:00), (iii) pre-ECB fix ("pre-E", 2:00 to 8:15), (iv) ECB fix to London fix ("E-L", 8:15 to 11:00), and (v) post-London fix ("post-L", 11:00 to 17:00).[3] To distinguish between the post-Tokyo and the pre-ECB fix periods we use 8:00 Frankfurt time (or 2:00 ET), i.e., the beginning of the FX trading day in Europe. Similarly, we define the start of the FX trading day in New York as 8:00 ET.

B. *Currency Returns Around the Clock*

We begin our analysis by plotting the annualized average cumulative 5-minute log returns from 17:00 ET until 17:00 ET on the next day for the sample period January 1999 to December 2019. Figure 2 plots the average cumulative returns (in basis points) for holding the euro, British pound, and Japanese yen while Figure 3 plots cumulative as well as the hour by hour returns of the unconditional dollar portfolio (DOL) that goes long all foreign currencies in equal weights.

All currencies show a distinct pattern of depreciation against the U.S. dollar ahead of the Tokyo fix at 20:55 ET followed by a reversal thereafter. Once European markets open at 2:00 ET, all currencies depreciate against the U.S. dollar ahead of the ECB fix. This drop is much stronger for the European currencies and more muted for the Australian, New Zealand, and Canadian dollar. The period between the ECB and London fix doesn't exhibit a clear pattern in the cross-section aside from the euro and yen who appreciate until one hour before the London fix. After the London fix, all currencies show a strong appreciation versus the U.S. dollar which continues until the end of the business day in the U.S. at 17:00 ET with the yen being the sole exception moving in the opposite direction. Overall, all currencies apart from the yen appreciate during the U.S. intraday period and depreciate overnight.

[INSERT FIGURES 2 AND 3 HERE]

Aggregating across currencies, the consistent depreciation of foreign currencies before the Tokyo fix and after European markets open combined with the depreciation of the U.S.

[3] Japan doesn't follow daylight savings time and, hence, the time difference between Tokyo and New York is either 13 or 14 hours. This means that for part of the year the windows before and after the Tokyo fix end or start at 19:55 ET, respectively. In addition, there are a couple of weeks in the year when the time difference between New York and London and the rest of Europe is an hour shorter than usual.

dollar during the intraday period leads to a distinctive W-shaped pattern of the cumulative returns measured over a full day.

On average, the intraday appreciation and depreciation of the U.S. dollar amounts to around 2 basis points twice a day. Given the size of the FX spot market, this translates into very large sums. Using daily turnover numbers from the 2019 Triannual BIS survey, the pattern we detect implies daily swings exceeding a billion U.S. dollars. Table I summarizes Figures 2 and 3 formally by reporting average FX log returns (i.e., exchange rate changes) along with t-statistics for the various intraday sub-periods as defined above. [4]

[INSERT TABLE I HERE]

As discussed above, all foreign currencies depreciate against the U.S. dollar after trading in New York ceases and in anticipation of the Tokyo fix. The Australian and New Zealand dollar (-2.7 and -3.3 bps, respectively) show the most negative average returns, while the Swiss franc and the Canadian dollar depreciate the least compared to other currency pairs. Average returns of all currency pairs are different from zero at the 1% level of significance. The reversal after the Tokyo fix is equally statistically significant for all currencies in our sample with the yen and the Norwegian krone exhibiting the highest magnitudes with 2.9 and 3.2 bps per day, respectively. Not very surprisingly, the dollar portfolio exhibits a very strong and significant reversal pattern as well, dropping around 2 bps per day before the Tokyo fix and recouping the losses thereafter.

Leading up to the ECB fix, the European currencies and the yen significantly depreciate against the U.S. dollar. The point estimates are measured with a large degree of statistical confidence. The highest drops are observed for the euro and the Swedish krona with -3.4 and -2.8 basis points per day, respectively. Between the ECB and the London fix, currencies don't move as consistently in the cross-section as during other windows although this may

[4] Note that at this stage we explicitly take Daylight Savings Time into account by calculating pre- and post-Tokyo fix returns using windows that line up around 9:55 Tokyo time. During the winter months when New York follows EST, this means the pre-Tokyo window ends at 19:55 ET and during the summer months when New York follows EDT the pre-Tokyo window runs until 20:55 ET. All figures are plotted using ET only.

be attributed to the fact that the window contains both a post-ECB fix depreciation as well as a pre-London fix appreciation of the U.S. dollar as can be seen in Figures 2 and 3.

After the London fix, the pattern is again quite striking: with the exception of the yen, all currencies appreciate strongly (i.e., between 1.5 bps for the Canadian dollar and 2.6 bps for the euro) during the period between the London fix and the close of markets in the U.S., whereas the yen depreciates by 1.14 bps. Overall, the dollar portfolio appreciates by 1.7 bps and movements for all currencies are strongly statistically significant.

The last column in Table I makes clear that the pattern we document is an intraday seasonality (i.e., a predictable component) that does not carry over to close-to-close returns. In fact, with the exception of the Swiss franc and the New Zealand dollar (average annual appreciations of 1.1 bps per day), none of the currencies in our sample move by more than one basis point per day over our sample period and none of the close-to-close returns are statistically significant.

C. Robustness

We study the robustness of the reversals around the fixes across two dimensions: (*i*) over time; and (*ii*) across datasets.

First, Table II splits intraday dollar portfolio returns for the respective windows into four subsamples. In each subsample we observe a W-shaped return pattern across the 24-hour trading day. The reversal of the dollar portfolio is strongly significant in all subsamples between 1999 and 2014, averaging around 2 bps per day on either side of the fix. In the 2014 to 2019 sample, the reversal around the Tokyo fix is notably smaller but remains statistically significant. Thus, pre- and post-fix returns are very robust over time and consistent with the notion of a reversal that nets out to zero on average, implying that intraday FX seasonalities are a robust feature of daily data. That said, on a daily basis the movements remain on the order of a few basis points, begging the question whether the pattern is merely an artefact of using RTH indicative quotes to calculate log spot changes.

[INSERT TABLES II AND III HERE]

We examine this question using three alternative data sets, computing intraday returns for the dollar portfolio from mid quotes of RTH forwards and CME futures as well as from value-weighted average prices (VWAPs) from Refinitiv's Matching (RM) trading platform. The dollar portfolio in this exercise is comprised of the euro, pound, and yen, which are the only liquid pairs for all alternative instruments over an extended sample period. In addition, we calculate intraday returns using the ICE U.S. dollar index (USDX) futures. The starting dates for each dataset are January 1999 (RTH forwards and ICE futures) as well as January and June 2006 (CME futures and RM).

Table III shows that the magnitude of the reversals around the fixes computed from forwards is very close to those computed from spot rates, suggesting there is no intraday pattern in implied interest rate differentials. The results from the CME as well as the ICE futures are also strongly statistically significant as well as consistent with the main results in Table I, confirming that the patterns also carry over to firm quotes taken from electronic FX derivatives markets. Finally, the patterns are also present in traded prices sourced from RM, and are thus not absorbed by the effective bid-ask spread.

In summary, the central contribution of this paper, the observation that the U.S. dollar appreciates in the run up to foreign exchange fixes and depreciates thereafter, is robust over time, across datasets, and across different segments of the foreign exchange market. This is important for a number of reasons that go beyond a pure academic interest. Most importantly, the presence of a robust intraday seasonality in foreign exchange spot and derivatives markets implies that the timing of portfolio adjustments should be an important consideration for asset managers, institutional investors, and corporates who receive cash flows in U.S. dollars and must convert back to their local currencies, or vice versa.

IV. Reversal Returns

In this section, we study a trading strategy that exploits the reversals by taking a long position in the U.S. dollar before the Tokyo and ECB fixes that is reversed post-Tokyo and post-London fix, respectively:

$$\Delta s_t^{\text{Tokyo}} = -\Delta s_t^{\text{pre-T}} + \Delta s_t^{post-T} \quad \text{and} \quad \Delta s_t^{\text{Europe}} = -\Delta s_t^{pre-E} + \Delta s_t^{post-L}, \tag{2}$$

where $\Delta s_t^{\text{pre-T}}$ and Δs_t^{post-T} are the returns for the pre- and post-Tokyo windows, and s_t^{pre-E} and Δs_t^{post-L} are the returns for the pre-ECB and the post-London windows, respectively. Note that the reversal returns are defined for either the Tokyo or the Europe window. The latter does not include the interval between the ECB and the London fixes as the results in Table I suggest that there is no clear directional movement during that period.

A. *Summary Statistics*

We start by reporting summary statistics for the reversal returns for all currencies as well as the dollar portfolio in Table IV. First, we show that daily reversal returns are significantly more often positive than negative. For the reversals around the Tokyo fix, the differences are always strongly statistically significant for all currencies ranging from 55% positive for the Swiss franc to almost 60% for the dollar portfolio. For the Europe window, the fractions range between 51% for the Pacific and Asian currencies and 55% or 56% for the pound, euro, and the dollar portfolio, for example. The differences for all European currencies are strongly statistically significant; and only for the Japanese yen do we obtain a p-value below 5%. These results for the reversal returns are rather striking considering that in frictionless and efficient markets, high frequency returns are unpredictable. Put differently, systematically predictable return reversals suggest a significant microstructure effect in play around the fixes. Indeed, when considering daily close-to-close currency returns, only the Australian dollar has more than 51% positive return days.

To further put the results in perspective, daily returns to the S&P 500 stock index are positive 54% of the days. Moreover, if the daily results are aggregated to a monthly frequency, we find that returns around the Tokyo fix are positive for at least 70% of months in the sample. For the Europe window, the reversal returns for the European currencies are positive for at least two-thirds of all months, again with the fraction for the monthly S&P 500 returns lagging that number (see the OA for all details).

[INSERT TABLE IV HERE]

While relatively small, the consistent positive return bias translates into significant average annualized returns over time before taking transaction costs into account. While Table IV lists the daily returns in basis points, the annualized returns for the Tokyo window range between 6.2% for the Swiss franc and 14.2% for the New Zealand dollar. For the Europe window, the annualized returns are particularly high for the euro, pound, and Swiss franc, at 15.6%, 12.4% and 12%, respectively. Annualized standard deviations are generally below 8% for all currencies and both reversal windows, or about half the standard deviation of the S&P 500 index over the same time period. Furthermore, most reversal return portfolios exhibit positive skewness and fat tails. This is in stark contrast to, for example, daily and monthly stock returns that are significantly negatively skewed for the same sample period.

The characteristics for the reversal portfolios are also very different compared to those of the carry portfolios reported in Brunnermeier, Nagel, and Pedersen (2009). While carry trades are profitable but have fat tails and are heavily exposed to crash risk, our reversal portfolios generate positive returns with fat tails but generally positive skewness. Furthermore, the skewness of the returns seems unrelated to interest rate differentials, unlike close-to-close currency returns where positive skewness is associated only with low interest rate currencies. In short, the reversal portfolios generate significant returns with favorable characteristics. Next, we explore the behavior of the reversal portfolios over time.

B. Return Indices

Using the daily reversal returns, we construct return indices that are displayed in Panels (a) and (b) of Figure 4. The reversal portfolios display large persistence over time and for both windows we consider. All portfolios (apart from the yen for the Europe window) accrue steadily over the whole period but with a stronger appreciation around the local fixes. An investment of one U.S. dollar in the yen for a trading strategy around the Tokyo fix climbs to over 12.2 U.S. dollars by the end of 2019. The same strategy for the euro, pound, and dollar portfolio results in a final portfolio value of 8.9, 5.3 and 8.6 U.S. dollars, respectively. In contrast, the portfolio values for the Europe window are 26.9, 13.5 and 6.4 U.S. dollars for the euro, pound, and dollar portfolio, respectively, while the yen portfolio actually loses about 6% of the initial value.

[INSERT FIGURE 4 HERE]

In Panels (c) and (d) of Figure 4, we display the year-by-year reversal returns for the dollar portfolio. For both fixes, the returns are particularly high during 2001 when the dot-com bubble burst as well as during the credit crisis, reaching returns of around 20% per year. On the other hand, returns are comparatively lower for the Tokyo window between 2004 and 2007 and for the Europe window in 2007.

While the reversal returns are persistently positive, we do observe a downward trend towards the end of the sample period, the reasons for which we can only speculate. First, anecdotal evidence suggests that in the later sample period, arbitrage capital is indeed allocated to exploiting the reversal patterns, leading to a decline in the intraday return predictability.

Second, in response to the WM/Reuters fixing scandal that broke in 2013, a number of regulatory changes were implemented and the lower average trading volumes around the fixes and lower reversal returns in the more recent sample period may be related to these reforms.[5] At the same time, there is no clear evidence linking changes in the level of reversal returns to the fixing scandal or the ensuing reforms and, in fact, some of the largest average European reversal returns were realised in 2015 and 2016.[6] In summary, reversals around the fixes are a robust feature of the data over an extended sample period for all G9 currencies.

C. *Alternative Reversal Times*

Finally, we examine whether the fixes are really the salient turning points during the day or whether the reversals we document are a more general feature of the data arising due to the autocorrelation in returns and, thus, unrelated to the benchmarks.

To this end, we calculate alternative reversal returns for the Tokyo and the Europe windows, respectively, by moving the reversal points away from the respective fixes. Figure 5 plots the resulting returns when the reversal points are moved either up or down the timeline in five-minute increments. The red bar in each panel denotes our benchmark reversal returns for the two windows, while the other bars denote the reversal returns that are calculated for same length windows that are moved up or down the timeline.

[INSERT FIGURE 5 HERE]

Visually, the results are striking: for both the Tokyo as well as the Europe window, the maximum reversal return is obtained when the reversal points are aligned with the fixes. Moving the reversal time away from the fix leads to uniformly lower average returns that are almost monotonically decreasing with the distance to the fix. Thus, the intraday return reversals are not only a persistent feature of the data, but they are tightly aligned to the publication times of FX benchmark rates. We provide further evidence to support this conclusion in the next section.

[5]For discussions related to regulatory changes, the London fixing scandal, and the introduction of the FX Global Code of Conduct (www.globalfxc.org/docs/fx_global.pdf) see, e.g., Melvin and Prins (2015), Evans (2018) and Evans, O'Neill, Rime, and Saakvitne (2020).

[6]Bloomberg first reported on the fixing scandal in June 2013:
www.bloomberg.com/news/articles/2013-06-11/traders-said-to-rig-currency-rates-to-profit-off-clients.

V. Natural Experiments

This section further highlights the importance of the fixes in pinning down intraday reversals using three quasi-natural experiments that exploit (i) the fact that Japan does not follow daylight savings time (DST), (ii) asynchronous holidays between Japan and the U.S. and (iii) data before and after the introduction of the London and ECB fixes in 1994 and 1999, respectively.

A. A Daylight Savings Time Test

As Japan doesn't follow DST, the time difference between New York and Tokyo varies throughout the year: it is 14 hours during the winter but an hour less when DST is used between March and November. In Figure 6 we plot the intraday patterns for the euro, pound and yen during Japanese trading hours but aligned with Eastern Time (i.e., New York time). The solid line depicts return patterns during the winter while the dotted line depicts the patterns when DST is in use in the U.S. The results clearly show that the spike in the U.S. dollar at the Tokyo fix moves by one hour during roughly eight months of the year (from the perspective of a U.S. investor). At the same time, there is no clear pattern emerging that could be attributed to the start or the end of the business day. This means that while there is a clear shift in the spike of the price pattern aligned with the Tokyo fix, there is no comparable difference for the equivalent move of Asian market opening and closing times measured in Eastern Time.

[INSERT FIGURE 6 HERE]

B. Asynchronous Holidays

Japan allows for a second quasi-natural experiment by exploiting the fact that holidays are not fully aligned internationally. In our sample we have 304 Japanese holidays that are not holidays in the U.S. (or are otherwise excluded from the sample). As Tokyo fix reference rates are not published on holidays (see, e.g., Ito and Yamada, 2017), we can explore whether the fixes are indeed driving intraday reversals by testing whether the reversal returns introduced in Section IV are present on those days or not.

[INSERT TABLE V HERE]

The average daily returns expressed in basis points (but still excluding transaction costs) for the 304 Japanese holidays as well as the remaining 4,958 days in our sample are presented in Table V. During the regular business days, the reversal returns are all substantial and highly statistically significant in line with Table IV. However, these results disappear during Japanese holidays, as the average returns are generally dramatically lower and none of them are statistically significant (for many currencies the average return is close to zero, and for the yen and dollar portfolio, the drop is about 75% and 80%, respectively). Using the same split for the reversals around the European fixes, we observe that magnitudes are even higher on Japanese holidays and statistically highly significant for all European currencies and the dollar portfolio, despite the much smaller number of observations. Finally, the third and sixth columns of table V report the p-values from a one-sided test that Japanese holiday reversal returns are equal to those on business days against the alternative that they are smaller. For the Tokyo fix, we reject the null for almost all currencies at the 5% level, while for the Europe window we cannot reject the null.

That is, while the previous section highlights the importance of the timing for the reversals around the Tokyo fix, the results in this section show that the reversals are virtually non-existent on days when no benchmark rate is published. As these days are trading days in Europe and the U.S., no such difference can be observed for reversal returns during the Europe window. Overall, the evidence clearly points to the Tokyo fix as the salient turning point for return reversals during the Tokyo trading day.

C. Return Patterns and the Introduction of Currency Benchmarks

The three foreign exchange benchmarks we study are available throughout our main sample period that starts after the introduction of the euro in 1999 (although the timing of publication for the ECB fix changes in 2016). Extending our sample back to the mid-1980s allows us to consider a final quasi-natural experiment by comparing intraday currency return patterns before and after the introduction of the fixes.

First, consider the introduction of the London fix in 1994 (see, for example, Melvin and Prins, 2015) Figure 7 plots the intraday return pattern for the period February 1986 to December 1993 (dotted line) and January 1999 to October 2021 (our benchmark sample period, solid line), respectively. Before the introduction of the London fix, the plots reveal a distinct appreciation of foreign currencies during the first hour of trading starting at around 8:00 ET. Thereafter, the Deutsche mark continues to appreciate until roughly the end of the trading day in Germany. The pound on the other hand displays a more or less steady appreciation throughout the New York trading day. Finally, the yen depreciates on average after the initial appreciation.

[INSERT FIGURE 7 HERE]

Interestingly, the patterns are distinctly different for our benchmark sample period once the London fix is well established. All three currencies still exhibit an initial appreciation early in the day in New York, although the turning point is now lined up with the ECB fix at 8:15 ET. Before the London fix there is a slight drop for all currencies that reverses thereafter for the euro and the pound that appreciate steadily until the end of the trading day.

Second, we study the ECB fix that was first published in 1999. As discussed in Section I, the ECB started delaying the publication of the reference rates until 16:00 CET in July 2016 in a further attempt to discourage using the ECB fix for transactions. Table VI shows 15-minute intervals around the ECB fix for the period before the introduction of the euro

(Panel A), from January 2000 to June 2016 (Panel B), and after the change of the publication time (Panel C). In the early part of the sample and before the introduction of the ECB fix, we observe the turning point of the currency patterns between 7:15 and 8:15, i.e., all three currency pairs exhibit slightly negative (yet often insignificant) average returns before 7:15 that turn positive (and become significant) before 8:15. This is in line with the observation that foreign currencies tend to appreciate significantly in the early hours of trading in New York although the turning point does not seem to be pinned down exactly. This changes with the introduction of the ECB fix. The results in Panel B show negative (and often significant) returns during both 15-minute intervals starting at 7:45 as well as 8:00. Then, returns reverse distinctly and the 8:15 to 8:30 window exhibits positive returns that are strongly significant for both the euro and the pound. The most striking results are presented in Panel C which focus on the change in the publication time of the ECB reference rate and the introduction of the new WM/Reuters 14:00 CET benchmark moves the turning point to 8:00 ET. From July 2016, the window from 7:45 to 8:00 now exhibits negative returns while the returns measured during the new post fix window from 8:00 to 8:15 are positive and strongly statistically significant for all three currencies.

[INSERT TABLE VI HERE]

D. *Changing Trading Patterns Around the London Fix*

High-frequency volume data is not available for the sample period before the introduction of the fixes. Instead, we proxy for trading activity by the number of quote updates for CME FX futures sampled within five-minute intervals.[7] Figure 8 plots the average quote updates around the London fix as a fraction of the total number for the time period between 8:30 ET and 2:00 ET for the Japanese yen and the British pound.[8]

[7] For the sample period when information on both time series is available, we show that average quoting activity and average trading volume track each other closely over the course of the trading day. The correlation between the two series is 0.98 and 0.93 for JPY and GBP, respectively. A comparison of the intraday dynamics of both series is provided in the OA.

[8] In the OA we provide additional evidence for other currency pairs, for which data is available for this time period.

Before the introduction of fix (dotted line in Panels (a) to (b)), activity spikes both in the early and the late trading hours in New York. Otherwise, the line is fairly flat with a slight uptick at 10:00 ET around the expiration time of currency options. For our benchmark sample period from January 1999 to October 2021 (solid line in Panels (a) to (b)) the pattern looks distinctly different. Most importantly, we can observe a spike for both currencies at the London fix. At the same time, the spike at 10:00 ET is more pronounced, and we can still observe significantly more activity in the early hours, coinciding with the expiration time of currency options. However, compared to the period before the introduction of the London fix, activity during the later trading hours in New York is much smaller.

[INSERT FIGURE 8 HERE]

In Panels (c) to (d) we consider the one-hour window around 11:00 ET for various time periods. One can clearly see that before the introduction of the fix there is no increase in trading activity around 11:00 ET (red dotted line). Similarly, the spike is very distinct for the period after 2006. For the two windows after the introduction of the fix, we observe a gradual increase in quoting activity around 11.00 ET.

In summary, we show a distinct difference between trading activity before the London fix was introduced compared to a period when the fix is well established. Moreover, beyond the central finding of this paper, the findings in this section speak to theories of 'liquidity begets liquidity.' For example, Duffie, Dworczak, and Zhu (2017) show that benchmarks (or fixings) raise social surplus by increasing the volume of beneficial trade and generate self fulfilling efficient matching between dealers and customers.

VI. Order Imbalances and Price Reversals

In this section we argue that our main finding is consistent with an explanation based on demand for immediacy combined with a structural demand for U.S. dollars at the fixes. In the OA, we discuss a set of alternative potential explanations that can be ruled out.

A. Inventory Management

In benchmark models of inventory management (see, e.g., Stoll, 1978 and Grossman and Miller, 1988), dealers provide liquidity to traders that demand immediacy before offsetting their positions to new traders arriving later in the day. A feature of these models is that prices exhibit reversal patterns around 'liquidity events' due to order imbalances absorbed by intermediaries. We argue that the key times within the day for liquidity events to occur, i.e., for order imbalances to manifest, are at the major fixings.

To support this claim, we study dealer-to-dealer (D2D) trading volumes on RM, the leading inter-dealer platform for Commonwealth currencies. Figure 9 provides a visual representation of trading volumes throughout the day for the G9 currencies.[9] For every hour over a 24-hour period, we calculate the average fraction of daily volume traded. For all currencies, the two hours around the London fix are the busiest with a total fraction of between 17.5% and 27% traded, while the second busiest hours are those around the ECB fix. Even though trading on RM is concentrated during European and U.S. trading hours in general, the heatmap also reveals a spike in trading activity around the Tokyo fix for the yen, the Australian dollar, and the New Zealand dollar.

[INSERT FIGURES 9 HERE]

In inventory risk models, dealers are compensated for providing liquidity through bid-ask spreads *and* positive expected returns for holding risky assets. Assuming a structural demand for U.S. dollars at the fix as implied by the return patterns presented earlier, the mechanism through which this might occur is an accumulation of U.S. dollars ahead of the fix, that are subsequently sold at higher prices to clients at the fix.[10] This is a well-known practice in the foreign exchange market commonly referred to as 'pre-fix hedging.' Indeed, banks with advanced knowledge of order imbalances are explicit in their intentions to hedge

[9] Section VI of the OA discusses further intraday volume characteristics on the RM platform.

[10] In contemporaneous work Osler and Turnbull (2020) propose a model with this mechanism embedded that predicts gradual price drifts together with reversals around the fix.

their positions and make clear that this practice may have negative consequences for the rates at which client orders are executed.[11]

In the following, we use the volume and order flow data available from RM to test standard predictions arising in inventory management models.[12] Different from the rest of the paper, we focus here on results for the pound and the Australian dollar around the European fixes for mainly two reasons. First, RM is the preferred platform for Commonwealth currencies only, meaning that volumes for the euro and the yen are not necessarily representative on RM. Second, liquidity on RM is much higher during European and U.S. trading hours.[13] The results for the Tokyo fix are in line with those discussed here but are presented in the OA.

B. Unconditional Order Imbalance

We start by examining the relationship between the unconditional reversal patterns and unconditional order imbalances. Indeed, Grossman and Miller (1988) write that *"in the absence of an asynchronization of order flows [reversal returns should equal zero]. It is the asynchronization of these flows and the finite risk-bearing capacity of market makers that leads [reversal returns] to deviate from zero."*[14] Thus, the stylised fact that the U.S. dollar exhibits a local peak at fixing times implies an unconditional net demand for U.S. dollars (or, equivalently, a net supply of foreign currency) at each fix.

Panel A in Table VII contains pre- and post-fix summary statistics for order flow on RM, defined as buyer minus seller-initiated trading volume, i.e., a negative order flow implies U.S.

[11]The practice is usually described in the "FX Disclosure Notice" that forms part of the client agreement to trade currencies. See, e.g., the notice by Citi Group (www.citigroup.com/citi/spotfxdisclosurenotice.html). Pre-fix hedging has also attracted attention from policymakers as evidenced in the global foreign exchange committee press release on the relevance of pre-hedging activities for the principles of good practices in the foreign exchange market (https://www.globalfxc.org/press/p210511.htm).

[12]Section VII in the OA reviews the Grossman and Miller (1988) framework recast in the context of foreign exchange fixings and derives predictions linking order imbalances and FX volatility to the reversal returns defined in Section IV.

[13]In the OA we provide a more detailed analysis of trading volumes on RM.

[14]For ease of interpretation we change the notation in the quote and replace $E_1\tilde{r}$ by "reversal returns" to match our terminology.

dollar buying pressure. We report both median and mean values, but our focus lies on the former as the distribution is skewed and contains significant outliers. For both currencies, the means as well as the medians are negative before the London fix and positive thereafter. Moreover, the medians are strongly statistically significant for the pre- and post-fix windows. For the pre-fix window, the median order imbalance is around 20 million U.S. dollars for either currency which translates to 6% and 10% of the volume traded at the London fix for the pound and Australian dollar, respectively. Table VII also shows that the fraction of days with negative (positive) order flow is significantly larger than 50% before (after) the London fix for both currencies. Pre-fix results are qualitatively similar when considering the ECB fix that takes place roughly three hours before the London fix, i.e., the unconditional order imbalance is not simply driven by trading activity that occurs tightly around the London fix.

[INSERT TABLE VII and FIGURE VII HERE]

Figure 10 displays the median order flow (in million U.S. dollars) throughout the day for one-hour intervals. The positive (blue) bars represent U.S. dollar selling pressure while the negative (red) bars display U.S. dollar buying pressure. The figure visualises how the price patterns documented in Section III carry over to patterns in quantities in the inter-dealer market displaying an unconditional U.S. dollar buying pressure ahead of the London fix that reverses thereafter.

The explanation proposed in this section relies on a structural demand for U.S. dollars arising in the dealer-to-client (D2C) market. However, our order flow data is only available for a dealer-to-dealer (D2D) platform. When inferring a structural demand for U.S. dollars from our data, we are making the assumption that D2C order flow can be proxied by D2D order flow. This is in line with a large literature (see, e.g., Evans and Lyons, 2002, Ito and Yamada, 2017, or Bjønnes, Osler, and Rime, 2021) that tests inventory and asymmetric information models where D2D order flow is predicted to have explanatory power for contemporaneous and leading price changes. Indeed, the two-tier structure of the FX market is such that a vast majority of volume is intermediated by a small number of liquidity providers. Put differently, a small number of dealers absorbs order flow from a vast number of customers.[15] Managing inventory risk, these dealers try to offset dollar supply or demand as much as possible internally through dealing with customers directly. Remaining imbalances that cannot be hedged internally are routed to inter-dealer platforms and offloaded to other liquidity traders. Thus, any demand imbalance observable in the D2D market can be reasonably assumed to be positively correlated with unobservable aggregate imbalances arising in the D2C market. Moreover, with risk averse market makers it is these imbalances which drive inventory effects.

C. Conditional Order Imbalance and FX Volatility

In this section we study predictions from inventory models which state that returns for providing immediacy are higher when order imbalances are larger, and even more so in states of heightened uncertainty when risk-averse market makers demand a higher premium for holding larger price risk.

To this end, we double sort daily reversal returns defined in Section IV for the Europe windows into six portfolios based on the pre-fix net dollar demand (low, medium, high) and FX volatility (low and high). We use the same definition for order flow as above, implying that low net dollar demand (DD) is characterised by positive order flow and high dollar demand by negative order flow. FX volatility (FXV) is computed as the intraday sum of squared returns during the previous day computed at the 1-minute sampling frequency. Table VIII reports the average imbalances, volatilities and reversal returns for each of the pound and Australian dollar portfolios, respectively.

[INSERT TABLE VIII HERE]

First, the distribution of net dollar demand appears quite symmetric conditional on the level of volatility. That is, there is no tendency of pre-fix dollar demand to arise in states

[15] In fact, data from Euromoney FX Surveys shows that within any given year from 1999 to 2019, between 30% and 60% of total spot volume is concentrated amongst five banks. In 2019 the top five liquidity providers account for 40% of total volume.

of larger FX volatility or vice versa. Furthermore, consistent with an unconditional pre-fix dollar demand, the order imbalances in the DD^M buckets are negative for both the Australian dollar as well as the pound. In fact, summing up the order imbalances across the sorted portfolios, we recover the mean values in Table VII.

Second, conditional on the level of DD, moving from low to high FXV always increases the magnitude of reversal returns, and these differences are highly statistically significant. Third, moving from states of pre-fix dollar supply (DD^L) to pre-fix dollar demand (DD^H), reversal returns go from being negative to strongly positive, and these differences are also strongly statistically significant. Of course, conditional on any imbalance (either excess demand or supply of U.S. dollars), inventory models predict positive average returns for liquidity provision. The reason that reversal returns are negative in the DD^L buckets is that throughout the paper we define the return reversals as a strategy that goes long the U.S. dollar before the fix and reverses the position thereafter. Thus, the returns always reflect a strategy based on the unconditional imbalance discussed in the previous section.

Third, in terms of economic magnitudes, return reversals can be quite large depending on whether volatility is high or low. For DD^L the reversal returns go from -16bps to -23bps for the Australian dollar and from -13bps to -22bps for the pound, and for DD^H, they increase from 18bps to 28bps (Australian dollar) and from 21bps to 30bps (pound), respectively. In percentage terms, the increases in the reversal returns as we move from low to high volatility days range from 32% to 68%. Finally, we note that when imbalances are small and volatility is low, return reversals are close to zero, again consistent with an inventory management hypothesis.

In sum, and as predicted by Grossman and Miller (1988)-style models, return reversals are larger in magnitude when order imbalances are larger in absolute terms, and even more so in periods of heightened uncertainty as proxied by FX volatility.

D. Asymmetric Information vs. Inventory Effects

We now study a regression specification closely related to Campbell, Grossman, and Wang (1993) and Andrade, Chang, and Seasholes (2008) who derive price pressure predictions in equilibrium models. In their models, returns are positively related to contemporaneous order imbalances through an information effect, and negatively related to lagged order imbalances through an inventory effect. Considering the effects of asymmetric information and inventory risk together, we estimate

$$\Delta s_t^{post} = \alpha + \beta_1 OF_t^{pre} + \beta_2 OF_t^{post} + \varepsilon_t \tag{3}$$

where Δs_t^{post} denotes the return measured over the post-fix window on day t, while OF_t^{pre} and OF_t^{post} are the order flow before and after the fix, respectively.

[INSERT TABLE IX HERE]

The results are summarised as follows. First, all coefficients on contemporaneous order flow in Table IX are strongly positive and highly significant, consistent with the idea that dealer order flow is informative about price discovery. Second, the coefficient on the lagged pre-fix order flow is always estimated to be negative and significant, consistent with conditional reversals arising around the fix due to inventory effects. Interestingly, the relationship between pre-fix order flow and post-fix returns remains statistically and economically strong if we exclude the last three hours leading up to the London fix and measure the order flow only up to the ECB fix. Thus, inventory effects are not simply driven by trading activity in the last few minutes leading up to the London fix as studied in the previous literature (see, e.g., Evans, 2018).

For the pound, the point estimate of -4.2 for the lagged order flow before the London fix implies that an order imbalance of one standard deviation (amounting to approximately 5.5% of the trading volume during that window) leads to a reversal of around 2.5 basis points, which is larger than the average unconditional effect we document in Section III. For the Australian dollar the results are even stronger and a one standard deviation shock to lagged order flow (surprisingly also 5.5% of trading volume during the window) implies a reversal of over 3.3 basis points.

E. Liquidity Provision

In this section we explore returns to liquidity provision and gauge whether dealers are indeed providing liquidity at the fixes. [16]

We start our analysis by considering a trader that seeks to exploit the intraday predictability around the European fixes. Expecting an appreciation of the U.S. dollar they enter a position in the D2C market at $t = 1$ and subsequently sell U.S. dollars at the fix ($t = 2$). To also benefit from the post-fix depreciation, they then reverse the trade and short the U.S. dollar, closing out the position at $t = 3$. Throughout, the trader always transacts in the D2C market and is always the liquidity demander, implying that they sell the foreign currency at the bid at $t = 1$ and $t = 3$. Most importantly though, at the fix they *buy* the foreign currency at the *ask*, $s^a_{2,D2C}$ (or, equivalently, sell U.S. dollars at the bid). The resulting returns are the two legs of the reversal returns defined in equation (6) with transaction costs taken into account:

$$\Delta s^{pre}_{t,LD} = s^b_{1,D2C} - s^a_{2,D2C} \quad \text{and} \quad \Delta s^{post}_{t,LD} = -s^a_{2,D2C} + s^b_{3,D2C}, \tag{4}$$

where the total return is calculated as the sum of the two legs.

In addition to the trader we consider a dealer that acts as a liquidity provider in the D2C market and, on average, will purchase foreign currencies for U.S. dollars at the fix to satisfy the unconditional demand for U.S. dollars. In contrast to a liquidity demander, however, liquidity providers purchase the foreign currency at the (lower) *bid* price. Further, we assume that the dealer sources U.S. dollars in the D2D market in the morning ($t = 1$).

[16] This question is related to a literature on the supply and demand of liquidity such as, the return to liquidity-providing trading strategies (Nagel, 2012), liquidity demand by mutual funds (Coval and Stafford, 2007; Da, Gao, and Jagannathan, 2011; Rinne and Suominen, 2016) or by hedge funds (Jylhä, Rinne, and Suominen, 2014; Choi, Shachar, and Shin, 2019).

To match the speculative positions of the trader, we also assume that the dealer reverses their position at the fix as well by shorting the U.S. dollar and closing out the position in the D2D market in a post fix trading period ($t = 3$). Note that when sourcing the U.S. dollars in the D2D market, the liquidity provider acts as the 'aggressor' and sells foreign currency at the bid price $s^b_{t,D2D}$. Only when providing liquidity at the fix, the dealer buys the foreign currency at the bid (or, equivalently, sells U.S. dollars at the ask). The resulting returns for the liquidity provider and the two legs can be calculated as follows:

$$\Delta s^{pre}_{t,LP} = s^b_{1,D2D} - s^b_{2,D2C} \quad \text{and} \quad \Delta s^{post}_{t,LP} = -s^b_{2,D2C} + s^b_{3,D2D}, \tag{5}$$

where the total return is again calculated as the sum of the two legs.

[INSERT TABLE X HERE]

Table X reports unconditional returns for a liquidity demander and a liquidity provider as per equations (4) and (5). The results are summarised as follows. First, for the trader (or liquidity demander), reversal returns turn negative once transaction costs are taken into account. Thus, the unconditional return patterns cannot easily be arbitraged away by traders that seek to exploit the intraday reversals. Second, and most importantly, returns to liquidity provision are *positive*, in line with the notiion that dealers *supply* dollars in exchange for a liquidity premium. The observation that both the pre-fix returns for liquidity provision are significantly positive is further consistent with a situation where clients are demanding U.S. dollars ahead of the fixings and dealers raise their prices when streaming quotes. Indeed, if it were dealers demanding U.S. dollar liquidity, one would expect the opposite finding, i.e., negative returns for an unconditional trade in this direction.[17]

F. Discussion

To summarise, we exploit data from both D2C and D2D platforms to present evidence consistent with an inventory risk explanation: we show that (i) there is a unconditional

[17]We thank an anonymous editor and referee for highlighting this question.

demand for U.S. dollars that manifests itself at the fix; (ii) return reversals are larger when order imbalances are bigger and in states of higher uncertainty; (iii) expected returns to liquidity provision are substantial, providing indirect evidence that dealers indeed act as liquidity providers to customers demanding U.S. dollars, as opposed to demanding U.S. dollars which are sourced from their clients.

While the unconditional imbalance lines up with an unconditional V-shaped reversal pattern, our analysis is *silent* with respect to where this unconditional demand originates. However, we speculate that a predictable demand for U.S. dollars at the fix could be related to the special role of the United States as the world's provider of safe assets and the dollar as the world's reserve currency (see, e.g., Jiang, Krishnamurthy, and Lustig, 2021). We also note that a predictable demand for immediacy at certain points within the day is consistent with existing evidence on intraday equity reversals (see, for example, Heston, Korajczyk, and Sadka, 2010 and Lou, Polk, and Skouras, 2017). We leave a full investigation of the underlying origins for dollar demand at the fixes to future research.

VII. Conclusion

This paper studies demand shocks for U.S. dollars in high frequency around currency fixings and documents a new empirical fact: the U.S. dollar systematically appreciates ahead of the three major currency fixings and depreciates thereafter. That is, the U.S. dollar reaches an intraday peak at the Tokyo, ECB, and London fixes, respectively.

Using a set of quasi natural experiments, we pin down the importance of the fixes for the intraday reversal patterns. Furthermore, we show that the reversals around the fixes are a pervasive feature of the data, robust over the 21 years of our data span, and are present for all of the G9 currencies, which cover close to 75% of global transaction volumes. The return patterns spill over into over-the-counter forward as well as the exchange-traded futures markets. This is important for institutional investors and corporate hedgers alike because it implies that the intraday timing of their speculative and hedging activities, as well as the timing of currency conversions and portfolio adjustments, affects their balance sheets.

We rule out a set of candidate explanations and provide evidence that is consistent with an explanation based on demand for immediacy combined with a structural demand for U.S. dollars at the fixes. Using volume data from a dealer-to-dealer market we show an unconditional order imbalance towards U.S. dollars at the fix. Conditionally, reversal returns are larger with higher order imbalance and higher uncertainty as proxied by FX volatility. Finally, returns to liquidity provision can be substantial for dealers that source U.S. dollars in the dealer-to-dealer market and act as liquidity providers at the fix.

VIII. Tables

NOTE 1: Intraday Returns. Different intraday periods around the Tokyo, ECB and London fix are defined as follows: The pre-Tokyo fix window starts at 17:00 ET until the Tokyo fix at 9:55 local time ("pre-T"), followed by the post-Tokyo window ("post-T") that runs until 2:00 ET (when European markets open). The pre-ECB fix window ("pre-E") spans the period between European opening hours until the ECB fix at 8:15 ET. The "interfix" window ("E-L") covers the period between the ECB and the London fix at 11:00 ET. The final window spans the period after the London fix ("post-L") starting at 11:00 ET and ending at 17:00 ET. Thus, the intraday period is the sum of the "E-L" and the "post-L" windows whereas the overnight period covers the "pre-T", "post-T" and "pre-E" windows. All times are measured in Eastern Time, taking into account daylight savings time. Data is daily and covers the sample period from January 1999 to December 2019 (5,264 daily observations). Returns are measured as the log changes in the mid quote for the respective currency (Δs). Thus, positive values imply the foreign currency appreciates versus the U.S. dollar. The dollar portfolio "DOL" is an equal weighted average of all nine currencies in our sample.

NOTE 2: Reversal Portfolios. We compute reversal portfolios around the 'Tokyo' and a 'Europe' fixes for each day t by taking a long position in the U.S. dollar before the Tokyo and ECB fixes that is reversed post-Tokyo and post-London fix, respectively:

$$\Delta s_t^{\text{Tokyo}} = -\Delta s_t^{\text{pre-T}} + \Delta s_t^{post-T} \quad \text{and} \quad \Delta s_t^{\text{Europe}} = -\Delta s_t^{pre-E} + \Delta s_t^{post-L}, \tag{6}$$

where $\Delta s_t^{\text{pre-T}}$ and Δs_t^{post-T} are the returns for the pre- and post-Tokyo windows, and s_t^{pre-E} and Δs_t^{post-L} are the returns for the pre-ECB and the post-London windows, respectively.

For the Tokyo window the long position in the U.S. dollar is held from 17:00 ET to the Tokyo fix at 9:55 local time (taking DST into account), and the short position is held from the Tokyo fix until 2:00 ET. For the "Europe" window, the long position is held from 2:00 ET until the ECB fix at 14:15 local time, and the short position is held starting with the London fix at 16:00 local time until 17:00 ET. The three-hour period between the two fixes is dropped.

	pre-T	post-T	pre-E	E-L	post-L	CTC
AUD	-2.84	1.85	-0.41	-0.05	1.93	0.48
	(-8.24)	(3.94)	(-0.77)	(-0.10)	(3.75)	(0.44)
CAD	-1.52	1.50	-0.76	-0.41	1.54	0.36
	(-8.74)	(7.15)	(-1.92)	(-0.89)	(3.81)	(0.47)
CHF	-1.24	1.25	-2.55	1.26	2.24	0.96
	(-5.56)	(4.94)	(-4.19)	(2.54)	(5.19)	(1.00)
EUR	-1.80	2.34	-3.52	0.63	2.73	0.37
	(-8.83)	(9.29)	(-7.24)	(1.35)	(6.78)	(0.43)
GBP	-1.89	1.27	-2.29	0.42	2.65	0.15
	(-9.12)	(5.04)	(-4.62)	(1.04)	(7.44)	(0.20)
JPY	-1.61	3.15	-1.03	0.62	-1.16	-0.03
	(-5.87)	(8.22)	(-2.37)	(1.42)	(-3.03)	(-0.04)
NOK	-1.94	2.95	-1.39	-2.02	2.14	-0.25
	(-7.51)	(9.66)	(-2.19)	(-3.77)	(4.49)	(-0.24)
NZD	-3.39	2.29	-0.34	0.56	1.81	0.93
	(-8.41)	(4.99)	(-0.60)	(1.10)	(3.30)	(0.84)
SEK	-1.80	2.16	-3.07	-0.06	2.60	-0.16
	(-6.52)	(7.05)	(-4.93)	(-0.11)	(5.38)	(-0.16)
DOL	-1.99	2.10	-1.67	0.14	1.84	0.41
	(-11.69)	(9.19)	(-4.50)	(0.37)	(5.48)	(0.59)

Table I. Intraday Returns and the Tokyo, ECB, and London Fix

This table reports average returns in basis points for the intraday periods around the Tokyo, ECB, and London fixes. t-statistics are reported in parentheses. See note 1 for the definitions of the intraday periods. The sample period is January 1999 to December 2019. The data is sourced from Refinitiv's Tick History (RTH) database.

	pre-T	post-T	pre-E	E-L	post-L	CTC
99-03	-1.64	2.48	-3.43	1.32	2.80	1.53
	(-5.15)	(6.63)	(-4.84)	(1.98)	(4.57)	(1.19)
04-09	-2.67	2.91	-1.50	-0.11	2.29	0.92
	(-6.92)	(5.88)	(-1.80)	(-0.13)	(3.09)	(0.60)
10-13	-3.49	2.31	-0.35	0.11	1.43	0.01
	(-8.38)	(3.87)	(-0.40)	(0.14)	(1.80)	(0.01)
14-19	-0.63	0.82	-1.25	-0.60	0.86	-0.80
	(-2.64)	(2.25)	(-2.28)	(-1.02)	(1.62)	(-0.76)

Table II. Intraday Dollar Portfolio Returns Year-by-Year

This table reports average returns in basis points for the intraday periods around the Tokyo, ECB, and London fixes for the dollar portfolio for a set of equally spaced sample periods. See note 1 for the definitions of the intraday periods. *t*-statistics are reported in parentheses. The sample period is January 1999 to December 2019. The data is sourced from Refinitiv's Tick History (RTH) database.

	pre-T	post-T	pre-E	E-L	post-L	CTC
TRTH Spot	-1.58	1.88	-1.65	-0.04	1.20	-0.20
	(-8.16)	(7.32)	(-3.73)	(-0.10)	(3.08)	(-0.25)
TRTH Forwards	-1.57	1.85	-1.61	-0.05	1.20	-0.19
	(-8.12)	(7.18)	(-3.65)	(-0.12)	(3.08)	(-0.24)
CME Futures	-1.46	1.80	-1.64	0.11	0.64	-0.56
	(-8.94)	(9.37)	(-4.76)	(0.30)	(2.20)	(-0.90)
ICE Futures	-1.27	1.37	-1.70	0.10	1.12	-0.38
	(-3.55)	(4.40)	(-4.27)	(0.26)	(3.56)	(-0.52)
RM VWAPS	-0.87	1.18	-1.10	-0.45	1.14	-0.09
	(-6.12)	(5.63)	(-2.70)	(-1.16)	(3.35)	(-0.12)

Table III. Intraday Returns for Across Different Data Sets

This table reports average returns in basis points for different intraday periods around the Tokyo, ECB and London fixes for the dollar portfolio using different data sets. t-statistics are reported in parentheses. Intraday returns are computed from RTH forwards, CME futures, intercontinental-ICE dollar index (DX) futures and VWAPs from Refinitiv Matching (RM). See note 1 for the definitions of the intraday periods. Dollar portfolio returns from CME futures and RM are computed from the EUR, GBP and JPY which are the most liquid pairs over an extended sample period. The sample periods are January 1999 to December 2019 for RTH forwards, January 2006 to December 2019 for CME futures, January 1999 to December 2019 for ICE, and June 2006 to December 2019 for RM.

Panel A: Tokyo										
	AUD	CAD	CHF	EUR	GBP	JPY	NOK	NZD	SEK	DOL
Fraction positive	0.56	0.57	0.55	0.57	0.56	0.57	0.58	0.56	0.56	0.59
Probability	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mean	4.69	3.02	2.49	4.14	3.15	4.76	4.89	5.68	3.96	4.09
t-stat	(8.03)	(10.68)	(7.19)	(12.60)	(9.87)	(10.12)	(11.93)	(9.29)	(9.56)	(14.46)
Median	5.30	2.65	1.67	3.26	2.59	4.17	3.94	5.06	2.91	3.59
z-stat	(8.47)	(10.47)	(6.93)	(9.85)	(9.21)	(10.49)	(11.27)	(8.63)	(8.96)	(13.32)
Std. Dev.	42.36	20.52	25.10	23.85	23.17	34.14	29.75	44.37	30.05	20.50
Skewness	-0.33	0.77	0.80	0.25	-0.24	-0.05	0.47	0.02	2.30	0.02
Kurtosis	10.48	16.67	34.22	8.67	38.30	15.35	17.70	7.40	55.60	8.46
Panel B: Europe										
	AUD	CAD	CHF	EUR	GBP	JPY	NOK	NZD	SEK	DOL
Fraction positive	0.51	0.52	0.54	0.56	0.55	0.51	0.52	0.51	0.55	0.55
Probability	0.04	0.00	0.00	0.00	0.00	0.35	0.00	0.04	0.00	0.00
Mean	2.34	2.31	4.79	6.26	4.95	-0.12	3.54	2.16	5.68	3.51
t-stat	(3.20)	(4.01)	(6.81)	(9.95)	(7.96)	(-0.21)	(4.51)	(2.70)	(7.25)	(7.03)
Median	1.60	1.72	4.26	5.41	4.53	0.44	2.46	1.79	5.61	3.63
z-stat	(2.04)	(3.45)	(6.23)	(8.55)	(7.01)	(0.94)	(2.92)	(2.07)	(6.77)	(7.01)
Std. Dev.	53.11	41.76	51.09	45.61	45.15	42.66	56.96	57.95	56.81	36.23
Skewness	0.14	0.36	-0.63	0.01	0.30	-0.18	0.03	0.08	-0.08	0.01
Kurtosis	10.41	7.39	36.26	6.87	6.94	6.79	6.01	8.23	6.25	6.61

Table IV. Statistical Properties of Return Reversals

At the daily frequency, each panel reports the fraction of return observations that are positive, the p-value from a two-sided test of observing returns in one direction under the null hypothesis of a random walk, as well as mean, median, z-score, standard deviation, skewness, and kurtosis. Returns are expressed in basis points. The z-score refers to a non-parametric test assessing if the median is different from zero. Panels A and B report summary statistics for the Tokyo and Europe fix reversal portfolios, respectively. See note 2 for the definitions of the reversal portfolios. The sample period is January 1999 to December 2019. The data is sourced from Refinitiv's Tick History (RTH) database.

	Tokyo			Europe		
	JP H-Days	JP B-Days	p-val	JP H-Days	JP B-Days	p-val
AUD	-1.16	5.05	0.00	4.90	2.19	0.82
	(-0.53)	(8.35)		(1.69)	(2.89)	
CAD	1.67	3.10	0.13	4.00	2.21	0.78
	(1.37)	(10.67)		(1.82)	(3.70)	
CHF	0.16	2.63	0.06	5.96	4.72	0.66
	(0.11)	(7.41)		(2.08)	(6.50)	
EUR	2.26	4.26	0.08	8.94	6.09	0.83
	(1.67)	(12.57)		(3.10)	(9.47)	
GBP	1.60	3.25	0.12	8.98	4.71	0.94
	(1.18)	(9.88)		(3.42)	(7.34)	
JPY	1.31	4.97	0.01	1.56	-0.22	0.77
	(0.92)	(10.12)		(0.67)	(-0.37)	
NOK	1.58	5.09	0.03	4.20	3.50	0.58
	(0.84)	(12.14)		(1.32)	(4.32)	
NZD	0.51	5.00	0.02	5.99	1.92	0.90
	(0.19)	(9.54)		(2.01)	(2.32)	
SEK	0.06	4.20	0.01	8.23	5.52	0.79
	(0.04)	(9.84)		(2.53)	(6.84)	
DOL	0.89	4.28	0.00	5.82	3.37	0.88
	(0.76)	(14.71)		(2.87)	(6.54)	

Table V. Reversal Returns: Japanese Holidays and Business Days

The table reports average reversal returns in basis points, i.e. taking a short position in foreign currencies in the pre-fix period, and a long position in foreign currencies in the post-fix period, on Japanese holidays ("JP H-Days", 304 days) and business days ("JP B-Days", 4,958 days). The columns "p-val" report the p-value from a one-sided t-test against the alternative hypothesis that returns on JP H-Days are smaller than reversal returns on JP B-Days (i.e. H_A : JP H-Days $<$ JP B-Days) around the Tokyo or Europe fix. The sample period is January 1999 to December 2019. The data is from Olsen and Refinitiv Tick History (RTH).

Panel A: February 1986 - December 1998			
	07:45-08:00	08:00-08:15	08:15-08:30
EUR	-0.05	0.50	0.22
	(-0.47)	(3.89)	(1.47)
GBP	0.12	0.21	0.05
	(1.12)	(1.74)	(0.34)
JPY	0.25	0.42	0.33
	(1.93)	(2.45)	(2.24)
Panel B: January 2000 - June 2016			
	07:45-08:00	08:00-08:15	08:15-08:30
EUR	-0.61	-0.89	0.96
	(-4.76)	(-7.31)	(7.53)
GBP	-0.38	-0.19	0.50
	(-3.61)	(-1.74)	(4.19)
JPY	-0.14	-0.32	0.20
	(-1.39)	(-2.84)	(1.53)
Panel C: July 2016 - December 2019			
	07:45-08:00	08:00-08:15	08:15-08:30
EUR	-1.33	1.04	-0.07
	(-6.08)	(5.93)	(-0.44)
GBP	-0.33	0.97	-0.50
	(-1.48)	(3.69)	(-2.21)
JPY	-0.36	0.51	-0.38
	(-2.34)	(3.27)	(-1.87)

Table VI. Introduction and Changes to ECB Fix

The table reports 15-minute returns in basis points before and after the ECB fix at 8:15 a.m. Panel A refers to the period February 1986 to December 1998, comprising the years before the introduction of the ECB Fix. Panel B refers to the period January 2000 to June 2016, when the ECB fix reference rates were published at 8:15 a.m., and July 2016 to December 2019, when the publication of reference rates were postponed to align with the London fix. Numbers in parentheses show t-statistics. The data is from Olsen and Refinitiv Tick History (RTH).

	AUD			GBP		
	pre-E	pre-L	post-L	pre-E	pre-L	post-L
Fraction positive	0.48	0.47	0.52	0.48	0.48	0.54
Probability	0.01	0.00	0.01	0.02	0.04	0.00
Mean	-7.97	-26.47	2.52	2.35	-3.39	22.55
t-stat	(-1.87)	(-4.26)	(0.71)	(0.30)	(-0.33)	(5.04)
Median	-10.26	-19.49	6.37	-13.12	-20.57	18.64
z-stat	(-2.77)	(-3.42)	(2.50)	(-2.26)	(-2.02)	(4.82)
Std. Dev.	248.65	363.55	208.63	450.71	592.74	261.51
Skewness	-0.21	-0.23	-0.46	0.61	0.36	0.18
Kurtosis	6.34	5.34	9.40	10.52	7.54	8.02

Table VII. Summary Statistics: Order Flow Around European Fixes

At the daily frequency, each Panel reports the fraction of order flow observations that are positive, the p-value from a two-sided test of observing order flow in one direction under the null hypothesis of a random walk, as well as mean, median, z-score, standard deviation, skewness, and kurtosis. The z-score refers to a non-parametric test assessing if the median is different from zero. Order flow is defined as buyer minus seller-initiated volume measured in million U.S. dollars. See note 1 for the definitions of the intraday periods. The sample period is June 2006 to December 2019. Data is sourced from Refinitiv's Matching (RM) trading platform.

Panel A: AUD								
	Avg. DD		Avg. FXV		Avg. Returns			
	FXV^L	FXV^H	FXV^L	FXV^H	FXV^L	FXV^H	H-L	p-val
DD^L	214.05	256.44	6.84	24.50	-16.19	-23.31	-7.11	0.04
DD^M	-12.76	-7.17	5.71	18.48	-0.69	3.88	4.57	0.11
DD^H	-235.96	-277.08	6.32	23.66	17.52	28.42	10.90	0.00
H-L					33.71	51.73		
p-val					0.00	0.00		

Panel B: GBP								
	Avg. DD		Avg. FXV		Avg. Returns			
DD^L	449.02	409.56	3.42	11.37	-13.00	-21.84	-7.84	0.00
DD^M	-16.62	-12.05	3.50	10.72	1.72	7.66	5.95	0.01
DD^H	-422.30	-419.37	3.44	12.64	21.30	30.22	8.91	0.00
H-L					35.30	52.05		
p-val					0.00	0.00		

Table VIII. Double Sorts: Dollar Demand and FX Volatility

This table reports returns for reversal strategies around the European fixes for AUD and GBP, when sorted by dollar demand during the European pre-fix (DD) hours and FX volatility (FXV) over the previous trading day. Daily reversal returns are first sorted into tertiary portfolios (Low, Medium, High) according to dollar demand during the European pre-fix trading hours, and then within each set, sorted into high and low portfolios according to the level of FX volatility. Average dollar demand and average annualized FX volatility in each state are reported in the first four columns. Average reversal returns are expressed in basis points. Dollar demand refers to total order flow during the pre-fix window and is expressed in millions U.S. dollar. FXV refers to the sum of squared 1-minute returns over the previous day and is expressed in annualized percentage. The row (column) "H-L" refers to the difference between portfolio returns in the high and low states. The sample period is 2006 to 2019. The data is from Refinitiv's Tick History (RTH) and Reuter's Matching (RM) databases. See note 2 for the definition of reversal strategies.

	AUD		GBP	
α	1.21	1.02	0.91	0.87
	(2.36)	(1.98)	(2.15)	(2.06)
OF^{preECB}	-7.23		-3.54	
	(-2.80)		(-3.77)	
OF^{preLON}		-9.29		-4.17
		(-5.89)		(-5.67)
OF^{post}	106.25	108.75	46.85	47.65
	(24.39)	(24.95)	(18.09)	(18.43)
adj-R2	0.30	0.30	0.21	0.22
Obs	3,407	3,407	3,407	3,407

Table IX. Return Reversal Regressions Around European Fixes

This table reports results referring to the regression model

$$\Delta s_t^{post} = \alpha + \beta_1 OF_t^{pre} + \beta_2 OF_t^{post} + \varepsilon_t$$

where Δs_t^{post} refers to log spot returns, based on volume-weighted average prices (VWAP), during the post-fix hours for the Australian dollar (AUD) or the British pound (GBP) on day t, and OF_t^{preECB}, and OF_t^{preLON} measure the order flow in the pre-fix hours of the European fixes, respectively. OF_t^{post} is order flow during the post-fix hours. Returns are measured in basis points. Order flow is defined as buyer minus seller-initiated volume and is measured in billion U.S. dollar. See note 1 for the definitions of the intraday periods. The sample period is June 2006 to December 2019. Parentheses report t-statistics based on Newey-West adjusted standard errors. All data is sourced from Refinitiv's Matching (RM) trading platform.

	AUD			GBP		
	LP	LD	p-val	LP	LD	p-val
Δs^{pre-E}	0.60	-4.51	0.00	1.89	-0.54	0.01
	(0.87)	(-6.59)		(2.86)	(-0.81)	
Δs^{pre-L}	1.23	-3.70	0.00	2.15	-0.28	0.04
	(1.35)	(-4.10)		(2.55)	(-0.34)	
Δs^{post-L}	1.85	-2.83	0.00	2.06	-0.44	0.00
	(2.68)	(-4.14)		(4.61)	(-0.98)	
$\Delta s^{pre-E} + \Delta s^{post-L}$	2.45	-7.34	0.00	3.95	-0.98	0.00
	(2.55)	(-7.72)		(4.83)	(-1.19)	
$\Delta s^{pre-L} + \Delta s^{post-L}$	3.08	-6.53	0.00	4.21	-0.73	0.00
	(2.74)	(-5.86)		(4.32)	(-0.74)	

Table X. Trading Venues, Reversal Portfolios and Transaction Costs

This table reports returns accounting for transaction costs for a liquidity provider (LP) who sources foreign currency at the prevalent bid at the beginning of the pre-fix period in the dealer-to-dealer market and provides foreign currency at the bid in the dealer-to-client market at the fix (D2D & D2C). D2C considers a liquidity demander (LD) who buys foreign currency at the beginning of the pre-fix period in the customer-to-dealer market and sells at the fix in the same market segment. In the post-fix period these trades are reversed. The column "p-val" shows a p-value from a two-sided t-tests comparing the average returns between liquidity demander and provider. The post-L trade is closed at 16:00 due to low liquidity on Reuter's platforms. Returns are measured in basis points. Numbers in parentheses show t-statistics. The sample period is 2006 to 2019. The data is from Refinitiv's Tick History (RTH) and Reuter's Matching (RM) databases. See note 2 for the definition of reversal strategies.

IX. Figures

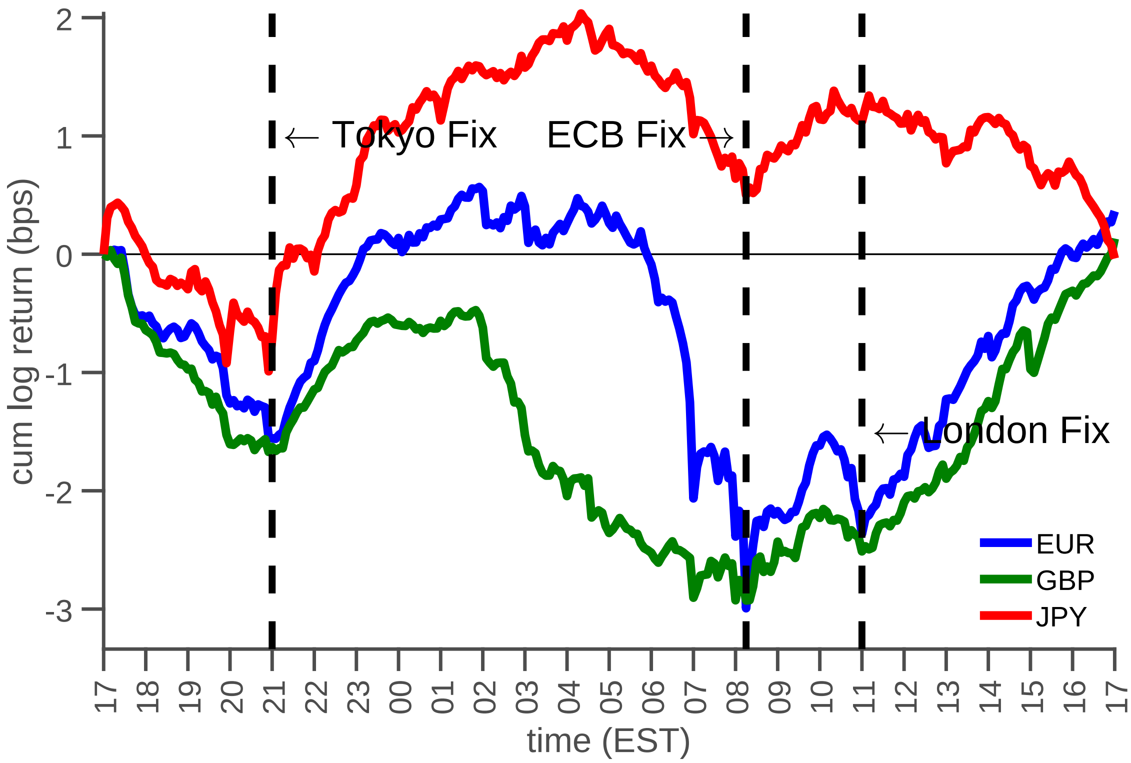


Figure 2. Cumulative 5-min Returns for EUR, GBP, and JPY
This figure displays cumulative average 5-min returns (Δs) in basis points over the course of a trading day for the EUR (blue), GBP (green), and JPY (red), respectively. An increase means the foreign currency appreciates against the U.S. dollar. The three black dashed lines at 20:55, 8:15, and 11:00 refer to the Tokyo fix, the ECB fix and the London fix, respectively. Returns are expressed in basis points. The time is measured in Eastern Time (ET). The sample period is January 1999 to December 2019.

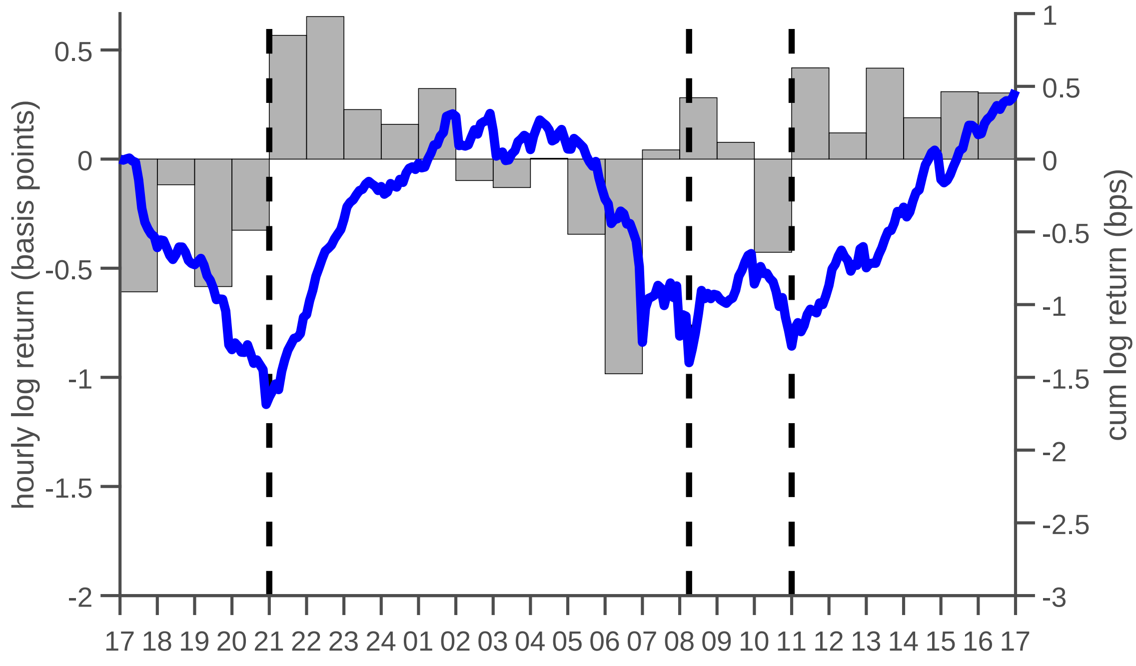
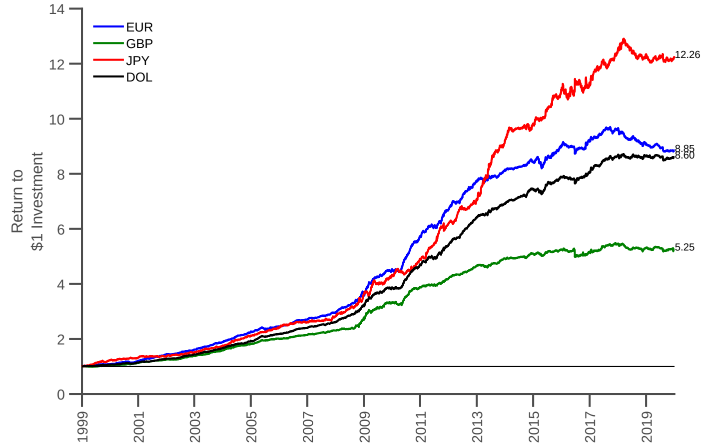
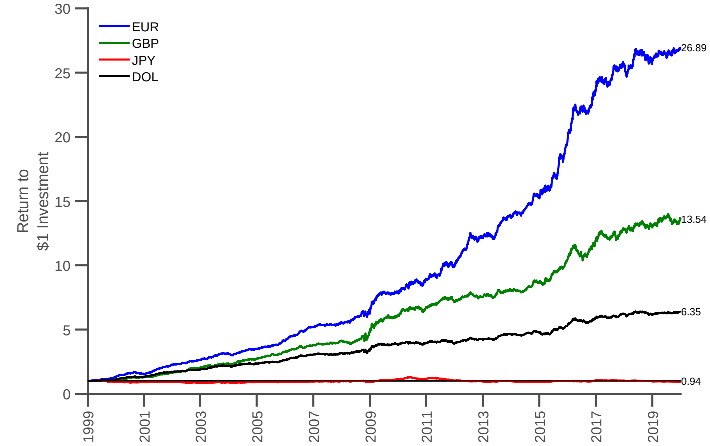


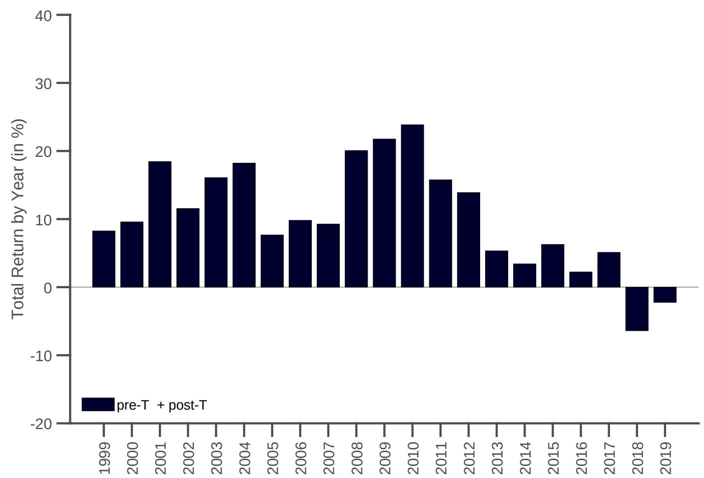
Figure 3. Intraday Returns Dynamics: Dollar Portfolio
This figure displays cumulative average 5-min returns (Δs) in basis points for the dollar portfolio over the course of a trading day. An increase means the basket of foreign currencies appreciates against the U.S. dollar. The three black dashed lines at 20:55, 8:15, and 11:00 refer to the Tokyo, the ECB, and the London fix, respectively. Returns are expressed in basis points. The time is measured in Eastern Time (ET). The sample period is January 1999 to December 2019.



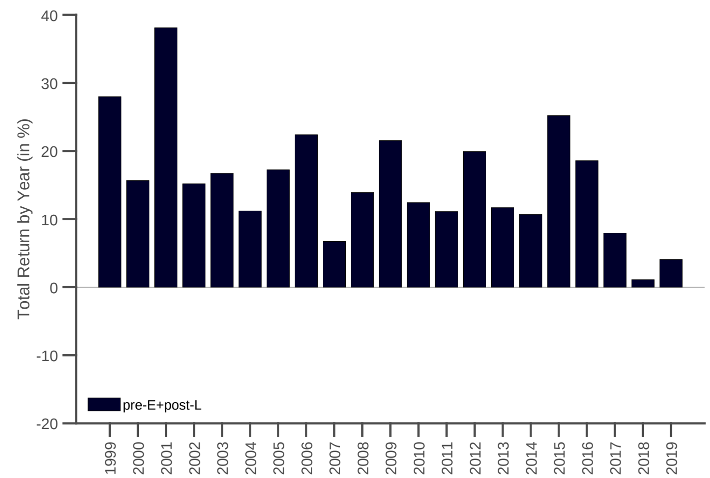
(a) Total Return Index: Tokyo Fix



(b) Total Return Index: Europe Fix

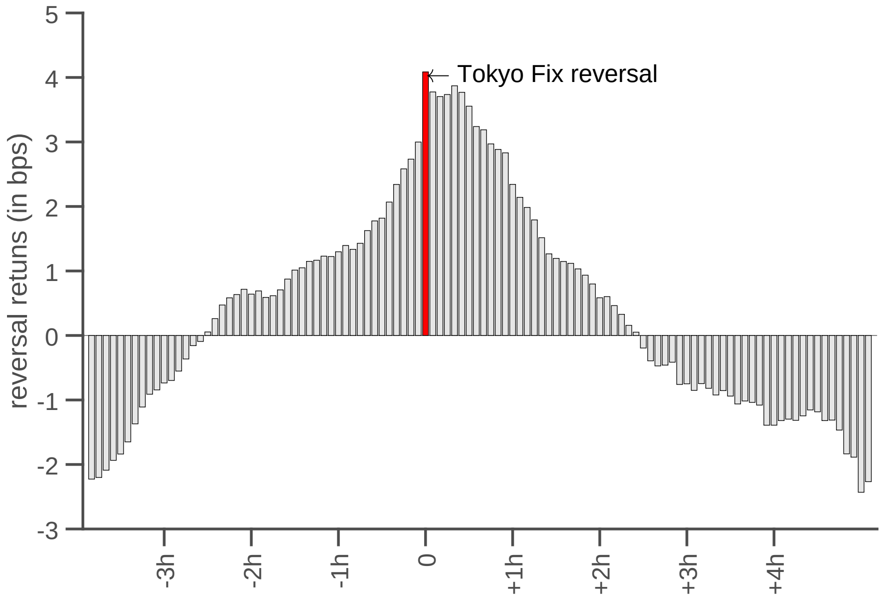


(c) DOL around Tokyo Fix

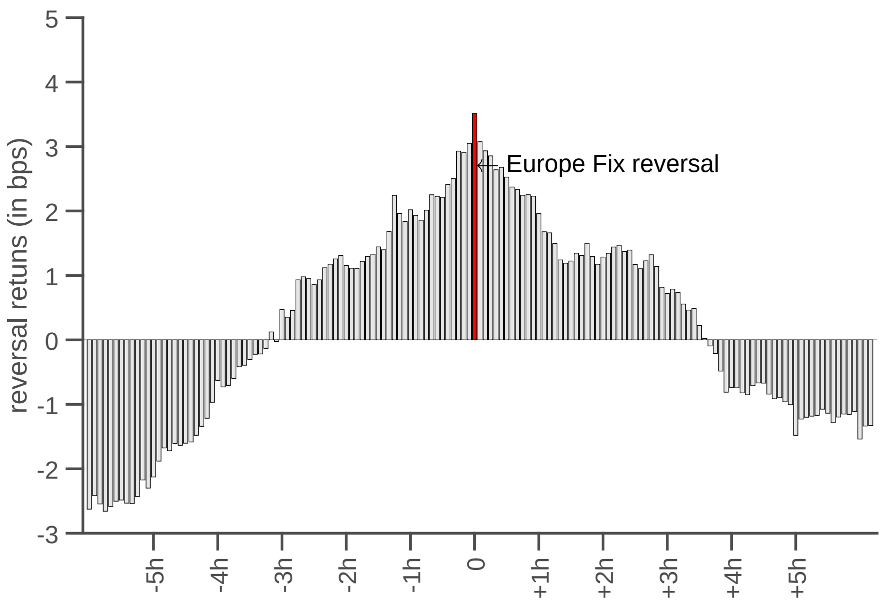


(d) DOL around Europe Fix

Figure 4. Total Return Indices and Year-By-Year Performance: Trading the *Vs*
The figures show the performance of a trading strategy around the Tokyo and ECB/London fix, where an investor takes a short-position during the pre-fix and a long-position during the post-fix, respectively. The top panels show the total return indices for the three major currencies (EUR, GBP, JPY) and the dollar portfolio (DOL) with an initial investment of one U.S. dollar. The bottom panels show the total returns split year by year for the dollar portfolio. The sample period is January 1999 to December 2019.



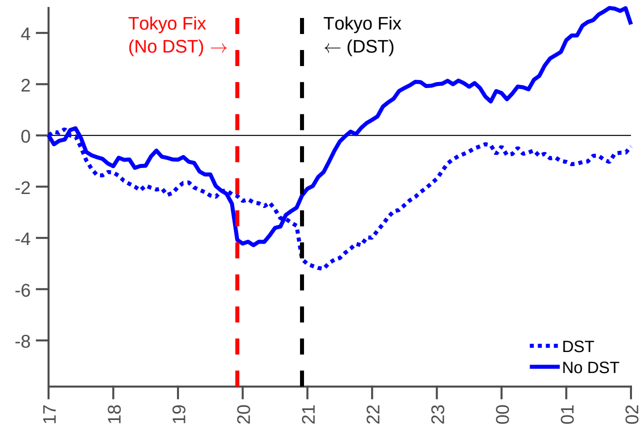
(a) TOK Fix



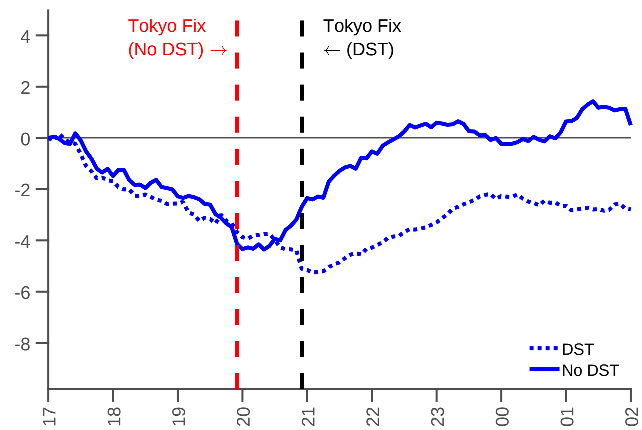
(b) Europe Fix

Figure 5. Reversal Returns: Alternative Reversal Times

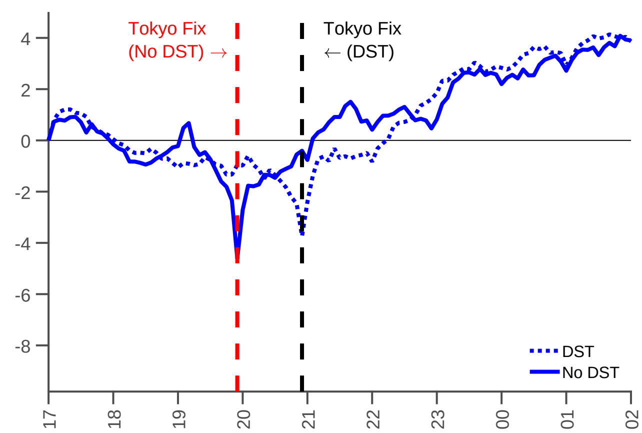
The figure shows reversal returns with different reversal times during the main Tokyo (Panel (a)) and European (Panel (b)) trading hours. Returns are measured in basis points (y-axis). The x-axis shows the timing of the reversal point relative to the Tokyo and the European fixes, respectively (indicated by the value "0" and marked by the red bar). Values to the left (right) of the red bars indicate the point in time of the reversal occurs earlier (later) than the fix. See note 2 for the definitions of the reversal returns. The sample period is January 1999 to December 2019.



(a) EUR



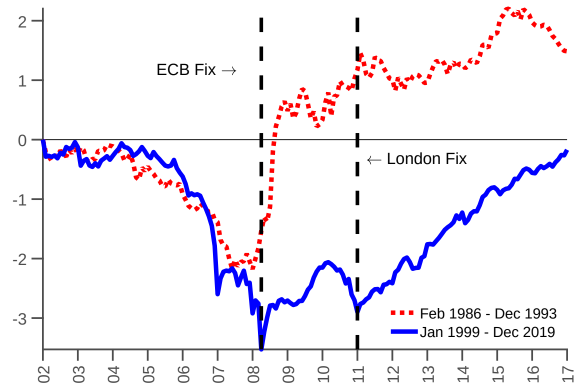
(b) GBP



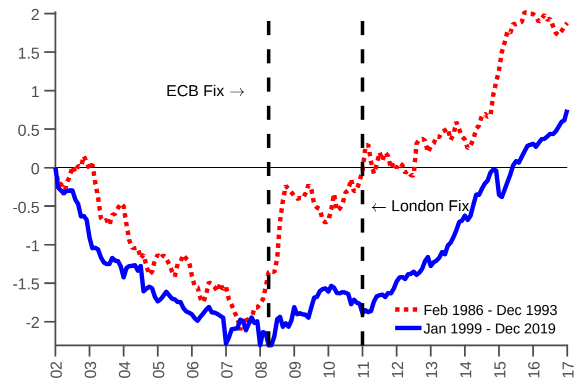
(c) JPY

Figure 6. Intraday Returns Dynamics: Daylight Saving Changes

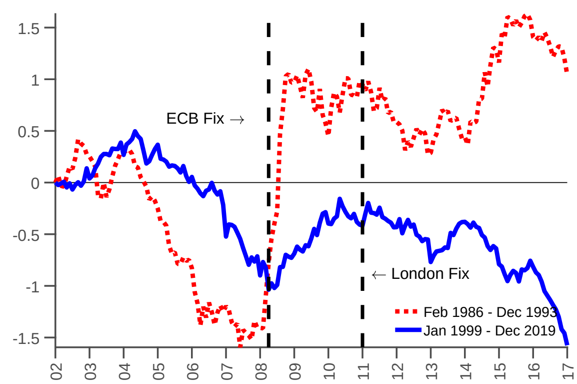
This figure displays cumulative average 5-min returns (Δs), expressed in basis points, for EUR (Panel a)), GBP (Panel b)), and JPY (Panel c)) over during the main trading hours in Japan on days when the time zone in New York is Eastern Daylight Saving time (DST, dotted line) and Eastern Standard time (No DST, solid line). An increase means foreign currencies appreciates against the U.S. dollar. The two dashed lines at 19:55 and 20:55 refer to the time of the Tokyo fix in both time zones, respectively. The sample period is January 1999 to December 2019.



(a) EUR



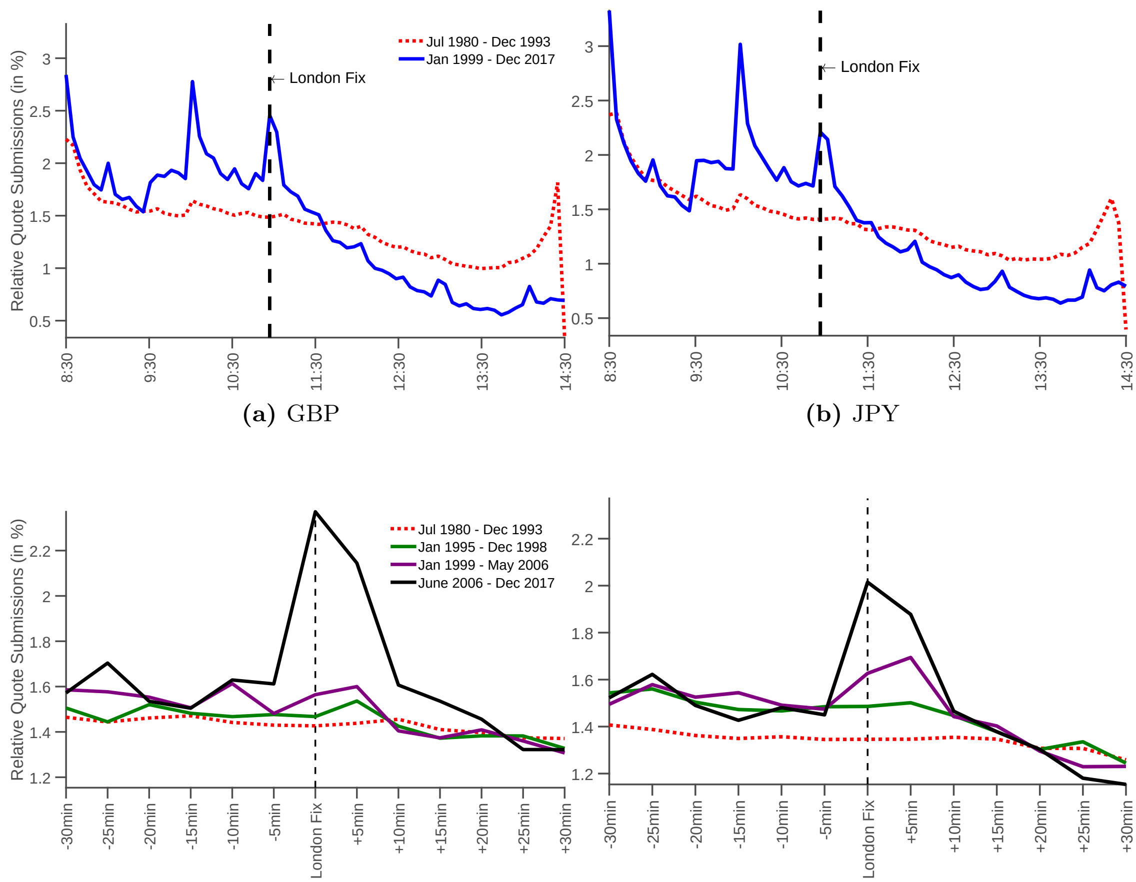
(b) GBP



(c) JPY

Figure 7. Intraday Returns Dynamics: Introduction of the London Fix

This figure displays cumulative average 5-min returns (Δs), expressed in basis points, for EUR (Panel a)), GBP (Panel b)), and JPY (Panel c)) over the course of the entire trading day. The red dotted line refers to the period February 1986 to December 1993, before the London fix was introduced. The blue line refers to the period January 1999 to December 2019. We exclude the year 1994 when the London fix was introduced. Data is sourced from Olsen for the years prior to 1999, while data is sourced from RTH for the years from 1999 onwards. The two black-dashed line vertical lines refer to the ECB fix (8:15) and the London fix (11:00) Eastern time.



(a) GBP **(b)** JPY

(c) GBP **(d)** JPY

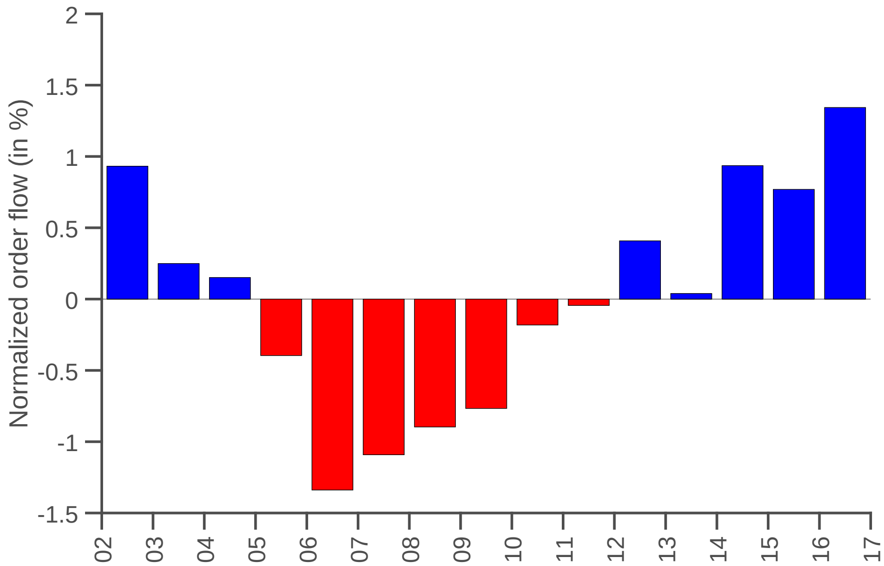
Figure 8. Changes in Quoting Activity Around the London Fix

The figure shows the number of quote updates in each 5-minute interval in currency futures traded on the CME relative to the daily total number of submitted quotes between 8:30 and 14:30 (ET) for the currencies GBP, and JPY. Panel a) and b) (top row) contrast futures market activity in the period July 1980 to December 1993 (dotted red line) with the period January 1999 to December 2017 (solid blue line). Panel c) and d) (bottom row) show the quoting activity 30-minutes before and after the London fix during the period July 1980 to December 1993 (red dotted line), between January 1995 to December 1998 (solid green line), between January 1999 to May 2006 (solid purple line), and June 2006 to December 2017 (solid black line). The sample period is July 1980 to December 2017. Data is from Refinitiv's Tick History database.

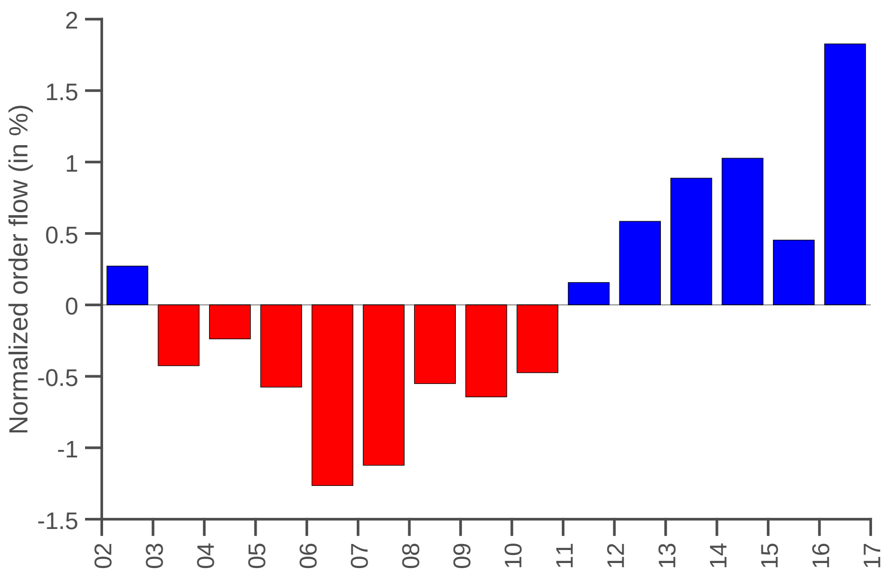
	AUD	CAD	CHF	EUR	GBP	JPY	NOK	NZD	SEK
17:00 - 18:00	1.03	0.68	0.42	0.15	0.54	0.48	0.21	1.66	0.21
18:00 - 19:00	1.61	0.60	0.33	0.21	0.53	0.86	0.27	2.21	0.24
19:00 - 20:00	3.35	0.86	0.88	0.38	0.85	2.13	0.40	3.25	0.38
20:00 - 21:00	4.71	1.21	1.38	0.61	1.30	4.25	0.58	4.34	0.48
21:00 - 22:00	5.15	1.09	0.98	0.62	1.11	3.40	0.62	4.51	0.54
22:00 - 23:00	3.75	0.91	0.98	0.54	0.91	2.34	0.53	3.60	0.52
23:00 - 00:00	3.00	0.71	0.66	0.47	0.77	2.01	0.47	2.90	0.51
00:00 - 01:00	2.93	0.67	1.00	0.51	0.81	2.08	0.40	2.60	0.40
01:00 - 02:00	3.44	1.01	1.38	1.18	1.38	3.00	0.77	2.95	0.92
02:00 - 03:00	5.38	2.39	4.16	4.94	4.27	5.15	3.95	5.05	4.24
03:00 - 04:00	6.06	3.46	7.17	8.73	6.61	6.15	6.80	5.90	8.64
04:00 - 05:00	5.23	3.25	6.56	8.69	8.35	5.42	7.59	5.23	7.75
05:00 - 06:00	4.33	3.01	6.07	7.73	6.80	4.27	6.09	4.31	7.30
06:00 - 07:00	3.70	3.22	5.42	6.74	6.07	3.67	5.54	3.72	5.56
07:00 - 08:00	3.94	4.62	6.17	7.23	6.46	4.43	6.19	4.11	6.65
08:00 - 09:00	7.04	10.95	10.47	12.25	9.16	8.98	9.22	6.89	8.55
09:00 - 10:00	7.40	11.65	10.48	11.66	9.30	8.97	12.27	7.51	11.32
10:00 - 11:00	9.63	15.61	11.29	11.69	12.29	10.47	14.64	10.11	12.62
11:00 - 12:00	6.71	11.66	8.69	6.70	9.20	7.17	9.38	6.89	8.38
12:00 - 13:00	3.23	6.52	5.14	3.18	4.54	4.25	4.49	3.30	4.64
13:00 - 14:00	2.27	4.56	3.36	1.97	2.93	3.29	3.31	2.14	3.76
14:00 - 15:00	2.80	4.94	3.16	1.95	2.78	3.27	2.65	2.60	2.78
15:00 - 16:00	2.07	3.65	2.28	1.16	1.87	2.39	2.54	2.28	2.45
16:00 - 17:00	1.24	2.77	1.57	0.69	1.17	1.55	1.07	1.94	1.16

Figure 9. Relative Trading Volume Around the Clock

The figure displays the hourly trading volume over the course of the trading day relative to daily total trading volume expressed in percent. The values in each column add up to 100. The sample period is June 2006 to December 2019. Data is from Refinitiv's Matching (RM) trading platform.



(a) AUD



(b) GBP

Figure 10. Normalized Order Flow Dynamics

The figures show the average normalized order flow dynamics in every hourly interval over the course of the main trading hours in Europe and the United States for the Australian dollar and the British pound on Refinitiv's Matching trading platform. Normalized order flow is defined as buyer- minus seller-initiated traded volume, relative to total trading volume. The sample period is June 2006 to December 2019.

References

Andrade, S. C., C. Chang, and M. S. Seasholes (2008): "Trading Imbalances, Predictable Reversals, and Cross-Stock Price Pressure," *Journal of Financial Economics*, 88(2), 406–423.

BIS (2019): "Triennial Central Bank Survey–Foreign Exchange Turnover in April 2019," Discussion paper, Bank for International Settlements.

Bjønnes, G. H., C. L. Osler, and D. Rime (2021): "Price Discovery in Two-Tier Markets," *International Journal of Finance and Economics*, 26(2), 3109–3133.

Breedon, F., and A. Ranaldo (2013): "Intraday Patterns in FX Returns and Order Flow," *Journal of Money, Credit and Banking*, 45(5), 953–965.

Breedon, F., and P. Vitale (2010): "An Empirical Study of Portfolio-Balance and Information Effects of Order Flow on Exchange Rates," *Journal of International Money and Finance*, 29(3), 504–524.

Brunnermeier, M., S. Nagel, and L. H. Pedersen (2009): "Carry Trades and Currency Crashes," *NBER Macroeconomics Annual 2008*, 23, 313–347.

Campbell, J. Y., S. J. Grossman, and J. Wang (1993): "Trading Volume and Serial Correlation in Stock Returns," *Quarterly Journal of Economics*, 108(4), 905–939.

Choi, J., O. Shachar, and S. S. Shin (2019): "Dealer Liquidity Provision and the Breakdown of the Law of One Price: Evidence From the CDS–Bond Basis," *Management Science*, 65(9), 4100–4122.

Cornett, M. M., T. V. Schwarz, and A. C. Szakmary (1995): "Seasonalities and Intraday Return Patterns in the Foreign Currency Futures Market," *Journal of Banking and Finance*, 19(5), 843–869.

Coval, J., and E. Stafford (2007): "Asset Fire Sales (and Purchases) in Equity Markets," *Journal of Financial Economics*, 86(2), 479–512.

Da, Z., P. Gao, and R. Jagannathan (2011): "Impatient Trading, Liquidity Provision, and Stock Selection by Mutual Funds," *The Review of Financial Studies*, 24(3), 675–720.

Duffie, D., P. Dworczak, and H. Zhu (2017): "Benchmarks in Search Markets," *The Journal of Finance*, 72(5), 1983–2044.

ECB (2019): "Framework for the Euro Foreign Exchange Reference Rates," Discussion paper, European Central Bank.

Evans, M. (2018): "Forex Trading and the WMR Fix," *Journal of Banking and Finance*, 87, 233–247.

Evans, M. D., P. O'Neill, D. Rime, and J. Saakvitne (2020): "Forex Trading and the WMR Fix: Assessing the E?ects of Rigging and Reform," Working Paper, Georgetown University.

Evans, M. D. D., and R. K. Lyons (2002): "Order Flow and Exchange Rate Dynamics," *Journal of Political Economy*, 110(1), 170–180.

FSB (2014): "Foreign Exchange Benchmarks," Financial Stability Board, Final Report.

Grossman, S. J., and M. H. Miller (1988): "Liquidity and Market Structure," *The Journal of Finance*, 43(3), 617–633.

Heston, S. L., R. A. Korajczyk, and R. Sadka (2010): "Intraday Patterns in the Cross-Section of Stock Returns," *The Journal of Finance*, 65(4), 1369–1407.

Ito, T., and M. Yamada (2016): "Puzzles in the Forex Tokyo "Fixing": Order Imbalances and Biased Pricing by Banks," Discussion paper, Center on Japanese Economy and Business, No. 352.

——— (2017): "Puzzles in the Tokyo Fixing in the Forex Market: Order Imbalances and Bank Pricing," *Journal of International Economics*, 109, 214–234.

Jiang, Z., A. Krishnamurthy, and H. Lustig (2021): "Foreign Safe Asset Demand and the Dollar Exchange Rate," *The Journal of Finance*, 76(3), 1049–1089.

Jylhä, P., K. Rinne, and M. Suominen (2014): "Do Hedge Funds Supply or Demand Liquidity?," *Review of Finance*, 18(4), 1259–1298.

Lou, D., C. Polk, and S. Skouras (2017): "A Tug of War: Overnight Versus Intraday Expected Returns," Working Paper, London School of Economics.

Melvin, M., and J. Prins (2015): "Equity Hedging and Exchange Rates at the London 4 p.m. Fix," *Journal of Financial Markets*, 22, 50–72.

Nagel, S. (2012): "Evaporating Liquidity," *The Review of Financial Studies*, 25(7), 2005–2039.

Osler, C., and A. Turnbull (2020): "Dealer Trading at the Fix," Working Paper, Brandeis International Business School.

Ranaldo, A. (2009): "Segmentation and Time-of-Day Patterns in Foreign Exchange Markets," *Journal of Banking and Finance*, 33, 2199–2206.

Rinne, K., and M. Suominen (2016): "Short-Term Reversals, Returns to Liquidity Provision and the Costs of Immediacy," SSRN abstract N. 1537923.

Stoll, H. R. (1978): "The Supply of Dealer Services in Securities Markets," *The Journal of Finance*, 33(4), 1133–1151.

Wasserfallen, W. (1989): "Flexible Exchange Rates: A Closer Look," *Journal of Monetary Economics*, 23, 511–521.