Liquidity in FX spot and forward markets*

Ingomar Krohn† Vladyslav Sushko‡

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Abstract

This paper assesses liquidity conditions in foreign exchange (FX) spot and derivatives markets using intra-day data for a period after the global financial crisis. Given that FX forwards and swap markets are by some measures even deeper that the spot market, an assessment of FX liquidity requires taking such instruments into account. We find that spot and forward market liquidity is intimately linked. Furthermore, the co-movement between FX funding and market liquidity, as gleaned from the pricing of both types of instruments, has increased over time. This development is tied to dealer balance sheet capacity. While top dealers dominate liquidity provision in spot throughout the sample period, they tend to pull back from market-making in FX forwards and swaps around regulatory reporting periods. This has shifted market-making activity in FX derivatives onto smaller, more expensive and less informed, dealers, and has also resulted in adverse spillovers to liquidity conditions in spot markets.

JEL classification: F31, G15

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†The author gratefully acknowledges the support of the BIS PhD internship programme and the support from the Economic and Social Research Council (PhD grant no. 15000668). Warwick Business School, Scarman Building, The University of Warwick, Gibbet Hill Road, Coventry, CV4 7AL, United Kingdom, Email: Ingomar.Krohn.14@mail.wbs.ac.uk

‡Economist, Financial Stability Policy, Bank for International Settlements, Centralbahnplatz 2, Basel, CH-4002, Basel, Switzerland, Email: Vladyslav.Sushko@bis.org

1 Introduction

Our paper assesses liquidity conditions in the foreign exchange (FX) market using intra-day data for a period after the global financial crisis. With average daily trading volumes exceeding $5 trillion, FX market is the world's deepest financial market, yet FX liquidity conditions are notoriously difficult to assess. For one, unlike say equity markets, FX trading is fragmented across many venues and is primarily executed over-the-counter (OTC). Furthermore, trading volumes in FX derivatives are an important source of liquidity and price discovery in FX markets. Specifically, daily trading volume in foreign exchange outright forwards and swaps has been increasing significantly in recent years and substantially exceeded spot market turnover in 2016 (BIS, 2016).[1] Hence, it is crucial to account for FX derivatives, in addition to spot trading, when assessing FX liquidity conditions.

This paper contributes to the international finance literature in several ways. First, it adds to the study on liquidity dynamics in the FX market, which only recently witnessed growing attention. Mancini, Ranaldo, and Wrampelmeyer (2013) provide a systematic assessments of FX spot liquidity, highlighting the substantial variation of liquidity across currency pairs. Banti, Phylaktis, and Sarno (2012) combine data on returns and order flows across currencies to construct a measure of systematic FX liquidity risk. Karnaukh, Ranaldo, and Sderlind (2015) provide further evidence for commonality in FX liquidity, using daily data covering a large cross-section of currency pairs for more than twenty years. Hasbrouck and Levich (2017) examine liquidity dynamics across a large number of currencies using one-month of settlement data, complemented with high-frequency data on quotes. In contrast to these studies, we do not limit our analysis to spot market liquidity, but take into account liquidity conditions in the forward market as well.[2] This extension allows us to explicitly account for the joint behavior of FX market liquidity and FX funding liquidity.

The theoretical framework for the interaction of these liquidity measures is grounded in Brunnermeier and Pedersen (2009). Whereas market liquidity broadly refers to the costs of trade execution and the ability to trade large volumes without generating an outsized price impact, funding liquidity refers to the ease with which such trades and the associated market positions can be funded. Importantly, funding instruments are themselves traded, and their pricing can affect market liquidity conditions, which can then feed back to funding costs. While Banti and Phylaktis (2015) do assess this interaction of funding liquidity with

[1] In April 2016, daily average turnover in the foreign exchange spot market was 1,652 billion US dollar-equivalents, compared to 3,078 billion US dollar-equivalent for outright forwards and FX swaps (BIS, 2016).

[2] BIS (2017) covered issues related to the liquidity of currency markets in the Americas, including FX derivatives.

FX market liquidity, they look at funding liquidity conditions in repo markets, whereas our analysis follows a novel approach by constructing all the funding liquidity measures from activity in FX markets themselves. We measure FX funding liquidity by the forward spread (e.g. forward discount computed from quotes of forward points) and, hence, we look at funding liquidity in the proximate market, rather than relying on more removed measures such as Libor-OIS or the TED spread. The FX forward spread can be interpreted as the funding costs of a foreign exchange swap that is used to borrow (lend) US dollar while lending (borrowing) a local currency in the spot market.[3]

Second, we examine intra-day liquidity conditions, using Thomson Reuters Tick History (TRTH) data obtained from Reuters Datascope, while aforementioned analyses are largely conducted at daily or lower frequencies. Huang and Masulis (1999) is another closely related study to have used TRTH data to assess liquidity conditions, but they focused on DM/USD, only on spot, and on one year of data between 1992 and 1993, whereas we cover a much longer and recent time-period, and corroborated our findings in both JPY/USD and EUR/USD.

Third, in line with recent studies examining the market environment against the background of post-crisis regulatory frameworks (e.g. Adrian, Fleming, Or, and Erik, 2017), we analyze current trends of liquidity dynamics and discuss the impact of the changing dealer structure. In this way, we build upon an early stream of literature, such as Huang and Masulis (1999), who examined the relationship between spot market liquidity, measured via bid-ask spreads and dealer competition. We also add to studies relating FX price discovery and dealer informational advantages to dealer size (Rosenberg and Traub, 2009; Bjonnes, Osler, and Rime, 2009; Phylaktis and Chen, 2010; Menkhoff, Sarno, Schmeling, and Schrimpf, 2016). We contribute to the literature by assessing the impact of different types of dealers on liquidity conditions. In particular, we draw a line along a major difference in the regulatory treatment of dealer balance sheets: we distinguish between globally systematically important banks (G-SIBs) and smaller banks, as this captures the different constraints faced by large and smaller dealers for providing liquidity in spot versus the forward markets.

Our main data source for this study is Reuters Datascope. We obtain data for JPY/USD and EUR/USD spot market, 1-month forward points, and 1-month overnight index swap (OIS) rates for the period February 2010 to May 2017. The database documents entries at the milli-second frequency and comprises indicative quotes for the best bid and ask price.

[3]To the extent that measures of FX funding liquidity, particularly when adjusted by benchmark money market rates, are closely related to deviations from covered interest parity (CIP), our work is somewhat related the CIP literature. However, as our aim is neither to measure CIP arbitrage nor to explain CIP failure, we abstract from this literature. Links to a number of recent papers examining the persistent failure of CIP in the period following the global financial crisis can be found here: https://www.bis.org/events/bissymposium0517/programme.htm.

Further, the database stores the name and location of the dealers that are active in spot and forward markets and submit their quotes. The detailed track record allows us to conduct a comprehensive analysis of price and quantity dynamics of quote submissions in both, spot and forward, markets. Our main empirical analysis is conducted at the intra-day frequency leveraging price information with information on how many dealers were active, how many quotes were submitted, how quote submissions varied within a specific time horizon, and how all these metric differed by dealer-type.

Our main results are as follows. First, we find a robust relationship between FX funding and FX market liquidity. A deterioration in FX funding liquidity, measured by the widening of FX swap spreads (CIP deviations) or simple forward spreads (forward discount) is associated with a widening of bid-ask spreads in both currency forward and spot rates.

Second, this link between FX market and FX funding liquidity conditions strengthened significantly since about mid-2014. The regime shift in the liquidity conditions in FX market appears related to the re-occurring liquidity droughts at quarter-ends. During each month corresponding to a quarter-end, controlling for higher variation in liquidity metrics, we find that FX funding and market liquidity exhibit stronger co-movement. Because the origins of quarter-end anomalies can be traced to core bank funding markets, such as unsecured overnight markets and repo markets, this implies stronger transmission of exogenous FX funding liquidity shocks to FX market liquidity. Statistical tests indeed point towards spillover of adverse FX funding liquidity shocks to market liquidity.

Third, we find that liquidity conditions and dealer activity are closely related. Specifically, the positive impact of dealer competition on FX market liquidity has decreased over time. While large dealers still dominate as market-makers in spot at all times and their quoting intensity is associated with improved liquidity dynamics, they have also exhibited a tendency to pull-back from making markets in derivatives, such as FX forward and swaps, around balance sheet reporting periods. As major dealers scale back their activity, funding costs significantly increase, market liquidity declines and volatility increases. For example, we find that funding costs at quarter-ends are approximately three times larger between July 2014 and May 2017 than during the European debt crisis.

Fourth, and related, we find that market-making activity in FX forwards and swaps can significantly diverge from that in spot. Whereas large dealers dominate as principal market-makers in spot throughout the sample period, small dealers largely displace large dealers as market-makers in forwards in times when spreads are wide. Specifically, when liquidity conditions tighten at quarter-ends, small dealers increase their quoting activity. In sub-samples we also find evidence that smaller dealers are consistently quoting inside spreads, hence constantly making-markets. This is because as large dealers, primarily G-SIBs, scale back in FX swaps around balance sheet reporting periods. Yet, small dealers stepping in during these times does not appear to lead to an improvement in liquidity conditions. We identify two reasons for this. One is that small dealers are low volume players, thus require wider bid-ask spreads and forward spreads for their market-making activity to be profitable. The second reason is that quoting activity by small dealers does not contribute to the same extent to price discovery as that by large dealer. Specifically, greater quoting intensity by small dealers does not suppress the dispersion of forward rate quotes in the same way that quoting intensity by large dealers does, indicating greater volatility of quotes around the "true" forward rate in an any given hour.

Finally, consistent with the price spillovers from forward points in FX swap markets to bid-ask spreads in both forwards and spot (eg. FX funding to market liquidity spillovers), starting July 2014 for JPY/USD (January 2015 for EUR/USD) we also find that heightened activity by smaller dealers in FX swap markets has a stronger effect on market liquidity (bid-ask spreads) in the *spot market* compared to smaller dealers in spot. This is noteworthy, especially because more than half of small dealers in FX swaps do not even participate in the spot market directly. In certain times, wider spreads quoted by small dealers in the forward market negatively impact spot market liquidity, and offset some of the positive effects on spot market liquidity from competition by large dealers.

Hence, our analysis suggests that the dealer structure of FX markets has been changing over the span of our sample period and smaller banks appear to act more frequently as market makers in the forward market. This adds nuance to the widely held view that FX liquidity provision is highly concentrated among a handful of largest dealers (King, Osler, and Rime, 2011), while smaller dealers operate an agency model simply passing client flows into the wholesale FX market (Moore, Schrimpf, and Sushko, 2016). While such concentration of liquidity provisions among large dealers appears to largely hold for spot markets, in the markets for FX forwards and swaps smaller dealers tend to turn from running an agency model to a principals model as maker-makers at times when spreads are wide enough to meet their hurdle rates. Since smaller dealers are likely to charge higher mark ups, their increased quoting activity does not necessarily tighten funding and market liquidity spreads, instead allowing the deterioration in FX liquidity conditions to persist until large dealers re-enter as market-makers as the quarter-end turn passes.

This paper proceeds as follows. Section 2 describes the data and our measures of liquidity and dealer activity. Section 3 contains broad overview of liquidity measures at daily frequency. Section 4 contains the core intra-day analysis of FX liquidity dynamics. Section 5 concludes.

2 Data and variable definitions

We obtain data for JPY/USD and EUR/USD spot exchange rate and 1-month forward points from Reuters Datascope for the sample period 1st February 2010 to 31st May 2017. The dataset contains information on dealers' best bid and ask quote submissions, timed at the milli-second frequency. In addition, it documents the name and location of the dealer bank that submitted the quote. We also obtain information on 1-month overnight indexed swap rates for both countries. Table 1 shows the sample of tick history data for a two second window for spot JPY/USD.[4]

[Table 1, about here]

Since quotes are submitted to and documented by Reuters in irregular time intervals, we transform the raw data from the milli-second frequency to 1-min time series, using the last submitted ask and bid quote in each minute. We consider all submitted quotes, irrelevant if a certain dealer submitted more than one quote during each minute. Huang and Masulis (1999) refer to this methodology as quote-weighted price data. We keep a detailed record of the number of submitted quotes and we identify the number of unique dealers that are active in each 1-minute time-interval. In very few cases, in which no quote submission took place, we use the last available information to fill the gap. Next, while activity on FX markets is not restricted to specific trading hours, we clean the data in the spirit of earlier studies (e.g. Andersen, Bollerslev, Diebold, and Vega, 2003) and exclude certain trading hours and holidays. On weekends and in the occasion of a holiday, we delete data entries between 21:00:00 (GMT) of the previous day until 21:00:00 (GMT) of the holiday itself. For example, we drop information on weekends from Friday 21:00:00 until Sunday 21:00:00. We drop data on fixed holidays such as Christmas (24th - 26th December), New Year's (31st December - 2nd January) and July fourth (4th July).[5] In addition, we exclude flexible holidays, such as

[4]While containing important information on quoting activity by FX dealer banks, our dataset is also subject to a number of limitations. First, it is primarily based on quote submissions on the Thomson Reuters Matching platform, which, together with EBS, only represent about 13% of global spot FX trading volume and 12% of global FX swaps trading volume, according to BIS (2016). Second, the data only has information on quotes and not traded prices or volumes, which precludes us from computing a number of popular measures of market liquidity based on the volume-return relationship. Third, the dataset does not contain information on the depth of the order-book, and the observed quotes are top-of-book quotes. Lastly, while Reuters is the main trading platform for commonwealth and emerging market currency pairs, for EUR/USD and JPY/USD it is EBS. As these are the two most frequently traded exchange rates, however, we believe it is pivotal to shed light on the link between liquidity dynamics and dealer activity in spot and forward market of these two currency pairs. Breedon and Vitale (2010) show that dynamics between EBS and Reuters are highly correlated and both markets are closely linked with each other.,

[5]In 2015, the official holiday is 3rd July, since July 4th falls on a Saturday.

Good Friday, Easter Monday, Memorial Day, Labour Day, and Thanksgiving and the day after.

We obtain equally spaced time-series bid and ask prices for spot rate, 1-month forward points, and overnight index swap (OIS) rates, number of quote submissions, and number and names of active dealers. Lastly, we convert the series to the hourly frequency to reduce the impact of market microstructure noise. For the entire sample period, we obtain 44,088 observations.

2.1 Price measures of market liquidity

After these steps of data cleaning, we construct the following variables. Spot dealers quote spot bid and spot ask prices, forward and FX swap dealers quote bid and ask forward points. Following Banti and Phylaktis (2015) we measure market liquidity at the hourly frequency in the foreign exchange spot and forward market by the bid-ask spread

$$Spread_h^S = \frac{S_h^{ask} - S_h^{bid}}{S_h^{mid}} \tag{1}$$

$$Spread_h^F = \frac{F_h^{ask} - F_h^{bid}}{F_h^{mid}} \tag{2}$$

where the mid-price is calculated as the arithmetic average between ask and bid price in each respective market segment. The bid and ask forward exchange rates are implied by the forward points quoted by dealers in FX forwards and FX swaps. We define the 1-month forward rate: $F = S + FP * 10^{-2}$ for USD/JPY and $F = S + FP * 10^{-4}$ for USD/EUR, where S denotes the spot rate and FP are 1-month forward points.

2.2 Price measures of funding liquidity

Forward point quotes from FX forward and swap dealers contain another important piece of information. For example, if the reported forward points are negative, this indicates that USD is trading at a forward discount. Hence, the pricing of FX forwards and swaps reflects the costs of obtaining say USD today at the spot rate S in exchange for say JPY, and reversing this transaction in one month at the pre-agreed forward exchange rate F. This, effectively, represents the cost of term funding of one currency against another.

Hence, our main measure of FX funding liquidity is based on the forward spread, which we calculate as:

$$Fdiscount_h = \frac{F_h^{mid} - S_h^{mid}}{S_h^{mid}} \tag{3}$$

where F^{mid} and S^{mid} refer to the mid-price 1-month forward and spot rates, respectively.

As an alternative measure of funding liquidity, we adjust the forward spread (forward discount) by the level of benchmark interest rates, OIS rates, in the two currencies of the same maturity. This is because, over a longer horizon, the level of the forward-spot differential should change to reflect the relative interest rate differentials in the two currencies, as stipulated by the covered interest parity (CIP). Hence, an alternative measure of FX funding liquidity is based on annualising the implied 1-month interest in the raw forward discount, then adjusting it by the OIS rates in the two currencies. Effectively this comes down to computing deviations from CIP:[6]

$$CIPdev_h = (1 + \frac{r_h^{mid}}{100}) - (1 + \frac{r_h^{mid*}}{100}) \times \left(\frac{F_h^{mid}}{S_h^{mid}}\right)^{(360/30)} \tag{4}$$

where r_h^{mid} and r_h^{mid*} refer to the mid-price OIS rates of both currencies.

By now, it should be fairly obvious that the pricing of FX forwards and swaps is reflective of both market and funding liquidity.[7] First, the quotes for forward ask (bid) points are the quotes for the differential between ask (bid) spot and ask (bid) forward rate, thus implying a price for both. Second, the forward discount implicit in the forward points provides a measure of term funding of one currency against another.

2.3 Quantity measures of FX liquidity

While these price-based measures are used to explore the relationship of liquidity dynamics, we use the following additional quantity-based measures that account for FX dealer structure and quoting activity. First, following Huang and Masulis (1999), we measure dealer competition by tracking the total number of quote submissions. We do this not only for

[6]That said, adjustment of the forward discount by the OIS rates should not be considered as a measure of CIP arbitrage profits (see, for example, Rime, Schrimpf, and Syrstad, 2017), but is simply used to account for the relative cost of funding liquidity via FX swaps in the two currencies taking into account the level of benchmark interest rates.

[7]See Baba, Packer, and Nagano (2008) for an exposition of cash flows in an FX swaps.

spot, but also for forward markets, with the number of quotes per hour denoted by Q_h^S and Q_h^F, respectively. In addition, we construct a measure of dealer competition at the extensive margin by counting the total number of active unique dealer banks within each hour. We denote this measure as N_h^S and N_h^F for spot and forward market, respectively. We treat all dealers from one bank, independently of their branch's location, as one market participant. It is worth noting the difference between these two measures. While former one accounts for the quoting activity of banks, the later only takes into account the actual number of banks active in the market. Lastly, we combine these two variables and measure quoting intensity as the ratio of submitted quotes and active banks ($\frac{Q_h^S}{N_h^S}$) and ($\frac{Q_h^F}{N_h^F}$). We interpret this measure as indicator of dealer competition at the intensive margin. An overview of our measures is provided in Table 2.

[Table 2, about here]

2.4 Large vs small dealers

Since we know what dealer is active in the market, we distinguish between small and large dealers as an additional dimension of our analysis. An earlier study that looked at the size dimension is Phylaktis and Chen (2010). These authors relied on the ranking of the Annual Euromoney FX Survey (EMS) to make a dealer classification by size. An alternative approach is to distinguish between large and small dealers in view of recent policy implementations and rely on the classification of global systematically important banks (G-SIBs) by the Financial Stability Board, (BIS, 2011, 2013). Table 3 shows the comparison between the thirty G-SIB bank dealers and the top FX dealers according to the 2016 Euromoney survey. While almost all 30 G-SIBs are ranked as top FX dealers in the Euromoney Survey (Table 3, left column),[8] 32 additional banks would be considered as large dealers by the Euromoney FX Survey but are not included in the list of G-SIBs.

[Table 3 and Figure 1, about here]

Figure 1 shows daily time-series of the percentage share of all top-of-book quotes in spot and forward JPY/USD of large dealers, $Q_t^{S,L}/Q_t^S$, classified according to the G-SIB designation versus dealers that are only part of the Euromoney Survey. During the entire sample

[8] The only exception is Mizuho FG, which is classified as G-SIB but not listed in the Euromoney Survey. Note that non-bank dealers such as Citadel Securities, XTX Markets, Tower Research Capital, or Virtu Financial do not appear in our database by name. This is because their access to Reuters Matching trading platform is prime-brokered by major FX dealers banks. Therefore the quotes of such non-bank market-makers on Reuters Matching appear under their prime-broker's name and not their own. Dealers that are not appear in our database are marked in grey in Table 3.

period, large dealers categorised according to the G-SIB classification were responsible for 37.2% of daily spot quote submissions, on average, whereas using the broader Euromoney Survey for classification would raise that share to 49.8%. Figure 1a points towards an increased concentration of spot liquidity provision by tier-1 and tier-2 dealers. The share of spot quotes in JPY/USD submitted by large dealers approximately doubles between 2011 and 2014. Yet, as both figures show, the trends of both classifications are very different from each other. First, quoting activity by tier-1 dealers becomes increasingly volatile in the second half of our sample. Second, in periods when tier-1 dealers (G-SIBs) pull back and decrease their market making activity (e.g. December 2016), tier-2 dealers increase the number of quote submissions.

Moving to FX forward markets, the substitution effect between tier-1 and tier-2 quotes is even stronger in forward markets than in spot, as indicated by the counter-cyclical activity of tier-1 and tier-2 dealers. The pull-back by tier-1 dealers from market making is particularly pronounced in FX forwards and swaps, Figure 1b. The decreasing quoting activity in FX forwards points at general FX dealer aversion to making-markets in FX derivatives around regulatory reporting periods, because, unlike cash, derivatives exposures are costly in terms of capital and collateral requirements under Basel III and national leverage and liquidity regulations. Tier-1 dealers are also subject to the annual G-SIB surcharge.

During the entire sample period, large dealers categorised according to the G-SIB classification where responsible for 52.2% of daily quote submissions, on average. Whereas, using the broader Euromoney Survey for classification would raise that share to 73.5%. This implies that the majority of dealers classified as small in the forward market are still the type to make it into the Euromoney Survey, unlike most of the small dealers in the spot market. Hence, it may be more accurate to think of small dealers in FX swaps as tier-2 dealers, while many more small dealers in spot are better thought of as tier-3 dealers, because they would not feature in the Euromoney Survey.

[Figure 2, about here]

Indeed, the comparison of Figures 2a and 2b shows that most small (tier-3) dealers are only active in the spot market in both sub-sample periods, while tier-2 banks increase their activity in FX forwards and swaps markets since about mid-2014. In contrast, tier-1 dealer behavior changes from quoting in both markets to greater liquidity provision in spot markets only. We interpret the Venn diagrams as further evidence that quoting activity between tier-1 and tier-2 banks differ significantly from each other in spot and forward markets, with tier-1 dealer shifting away from quoting FX swaps to only quoting spot as bank adopted to the new regulatory reporting templates as of January 2015. As Figure 2c shows, the tier-1 dealer shifting away from quoting both FX forwards and spot (eg FX swaps) to only quoting spot are particularly pronounced around the quarter-end and year-end regulatory reporting periods.

3 Liquidity measures at daily frequency

This section looks at daily trends in liquidity and dealer competition measures over the sample period February 2010 to May 2017. Figures 3a and 3b show the dynamics of the price-based liquidity measures for JPY/USD and EUR/USD, respectively. Market liquidity in the spot and forward market move very closely (correlation of 0.97 for JPY/USD and 0.98 for EUR/USD) over most of the sample period. For both currency pairs, bid-ask spreads increase during the European debt crisis at the end of 2011 and beginning of 2012. They remain comparably low afterwards and start to increase gradually for both currencies from mid-2014 until the end of the sample. Since a higher bid-ask spread is associated with more illiquid market conditions, both Figures seem to suggest that market liquidity has declined towards the end of our sample.

[Figure 3, about here]

For funding liquidity, we observe a similar pattern. As indicated by the black plot, there is an increase in (absolute) forward spreads in the middle of 2011 and relatively stable funding costs in the period after the European debt crisis. From the third quarter in 2014 onward, funding liquidity drops on a re-occurring basis. These liquidity droughts are particularly prevalent during quarter-end periods, indicated by the grey areas. Clearly, the level of funding liquidity since about mid-2014 follows a different pattern compared to the 2010 to 2014 period.

Table 4 shows summary statistics for price-based FX liquidity measures across the months falling on quarter-ends (QE), versus those on month before (BQE) and after (AQE). The sample is split according to the apparent regime change in FX liquidity conditions with the emergence of the quarter-end turn in forward points in September 2014 for JPY/USD and March 2015 for EUR/USD; hence we pick the second sub-sample cut-off two month prior to the QE month for each currency pair. For each liquidity measure, Panel A shows the average level as well as p-values of a one-sided t-test that the liquidity measures are significantly worse than in the rest of the months in each sub-sample. Panel B shows the volatility of each liquidity measure as well as the p-values of the variance ratio test that volatilities are significantly different compared to the rest of the months in each sub-sample.

[Table 4, about here]

Quarter-end anomalies of the type picked-up in this paper are a recent phenomenon that has emerged since about September 2014 for JPY/USD (March 2015 for EUR/USD). Their origins are exogenous to the FX market as such, attributed to the window dressing by global banks, as some banks shrink their balance sheets so as to manage their regulatory costs associated with the new post-crisis capital and liquidity requirements. Such balance sheet window-dressing appears to have first-and-foremost affected short-term money markets and on balance sheet funding instruments, such as repurchase agreements (CGFS, 2017). However, strong effects have also been documented for off-balance sheet instruments, such as FX swaps (see Arai, Makabe, Okawara, and Nagano, 2016 and Du, Tepper, and Verdelhan, 2017).

Takeaways from the results reported in the table are as follows. First, FX funding liquidity, as measured by either forwards points, $Fdiscount$, or forward points adjusted by the level of benchmark interest rates, $CIPdev$, deteriorates significantly at quarter-end months over the entire period (both wider spreads and higher spread volatility), but the magnitudes of the fall in liquidity at quarter-ends are several times larger in the most recent period. Second, market liquidity in JPY/USD has began exhibiting significant deteriorations at quarter-ends in the most recent period, as indicated by wider level and volatility of bid-ask spreads in spot and forwards. Market liquidity in EUR/USD appears less affected, although the volatility of bid-ask spreads particularly in the forward market, but also to a lesser extent in spot, has risen.

[Figure 4, about here]

Further, Figures 4a and 4b show the dynamics of quantity-based measures of market activity. They show FX dealer quoting intensity in spot (blue) and forward market (red) as well as the moving average for both markets. Spot market trading intensity is up to five to ten times higher than in the forward market. In addition, in both markets, we observe an increase in market activity towards the end of our sample. The moving averages indicate a rise in quote submissions compared to the number of banks. The spiking of dealer quoting intensity is particularly pronounced for FX forwards for both currency pairs.

[Figure 5, about here]

The steep increase in quoting intensity in the forward markets is driven by increased activity of smaller dealers. Figures 5a and 5b plot the quoting intensity of smaller dealers in forwards against CIP deviations that take account of transaction costs (measured by bid-ask spreads). As the figures show, whenever bid-ask spreads and forwards spreads widen, as measured by the transaction cost-adjusted CIP deviations, small dealers tend to increase their quoting intensity. This was temporarily the case during the euro area sovereign debt crisis, but became more persistent since about mid-2014 as price-based measures of FX liquidity conditions deteriorated first in JPY/USD and then in EUR/USD.

From Figures 3 through 5 we draw the following conclusions. First, liquidity dynamics, market participation, and trading activity vary to a great extent over our sample period. For example, while market liquidity in spot and forward market appears to be greatly impacted by the European debt crisis during the first years of our sample, bid-ask spreads and funding costs decrease significantly between 2013 to mid-2014. From mid-2014 until the end of our sample liquidity dynamics are tightening again, despite an overall calm market environment compared to the crisis years. Second, liquidity droughts appear to emerge on a re-occurring basis and are stronger towards the end of a quarter. Third, as is also empirically established later, the rise in total quoting activity by FX dealers is not necessarily associated with an improvement in liquidity conditions.

4 Intraday analysis of FX liquidity

In this section, we move to the analysis at the hourly frequency, using measures constructed from tick-level data and described in Table 2. Figures 6 and 7 show the variation in FX market and funding liquidity in spot and forward markets during the trading hours for the two sub-sample periods for JPY/USD and EUR/USD, respectively. Market liquidity (measured by bid-ask spreads) tends to be lower during the beginning and end of the trading day, resembling a reversed J-shaped form of liquidity (blue bars). Measures of FX funding liquidity, both $Fdiscount$ and $CIPdev$, in turn exhibit an inverted J-shape, also indicating worse liquidity conditions when London and New York based traders are largely absent.

Red lines indicate averages for each trading hour during quarter-end months. As shown in Figure 6a, market liquidity changed little during quarter-ends in the February 2010 to June 2014 period, but FX funding liquidity conditions were usually worse. During the second sub-sample period, from July 2014 to May 2017, shown in Figure 6b, FX funding liquidity measures are considerably worse in levels (blue bars), and their deterioration at quarter-ends is much larger in relative terms, with spreads in both $Fdiscount$ and $CIPdev$ about two times wider (red lines). Furthermore, unlike the earlier period, bid-ask spreads exhibit widening at quarter ends for both spot at forward markets, indicating possible spillovers from FX funding to FX market liquidity at quarter-ends during the most recent period. Figures 7a and 7b show qualitatively similar results for EUR/USD.

[Figures 6 and 7, about here]

Statistical tests confirm that intraday co-movement between FX market and funding liquidity has strengthened since the appearance of quarter-end anomalies in funding markets in mid-2014 for JPY/USD and early 2015 for EUR/USD. Table 5 shows that pairwise correlations as well as percentage of variation explained by a common factor has increased across all combinations of bid-ask spreads in spot and forwards with FX funding liquidity measures, for both currency pairs.

[Table 5, about here]

4.1 Short- and long-run liquidity dynamics

The descriptive statistics point towards time-varying liquidity dynamics across sub-sample periods. They also indicate that the co-movement between FX market and FX funding liquidity conditions intensified in the last sub-sample period. While funding liquidity has tended to deteriorate at quarter-ends even in the pre-2014 period, these funding liquidity droughts have intensified since mid-2014. Furthermore, it is only in the latest sub-sample period that FX funding liquidity droughts appear to spillover to market liquidity conditions.

To formally examine the relationship between liquidity conditions in spot and forward markets, and the interaction between their market liquidity and funding liquidity components, we estimate a conditional error correction model (ECM), derived from an autoregressive distributed lag model specification for the two sub-sample periods. Following Pesaran, Shin, and Smith (2001) the specification allows to assess the long- and short-run specification between a set of variables independent of the order of integration of the variables in our system. As the dynamics of variables vary across the sample period, displaying mean-reversion in some months but high persistence in others, inferences about non-stationarity from standard unit root tests are highly dependent on the chosen time-period. Modelling the relationship between dealer activity and liquidity in an ARDL model, however, allows us to take an agnostic view about the order of integration, and to model long- and short-run dynamics without classifying variables as either stationary or non-stationary We formulate the following two conditional ECMs as:

$$\Delta Spread_h^P = \alpha + \sum_{i=1}^{23} \delta_i H_i + \theta_0 Spread_{h-1}^P + \boldsymbol{\theta x_{h-1}} + \sum_{i=1}^{p-1} \boldsymbol{\gamma_i \Delta z_{h-i}^P} + \boldsymbol{\beta \Delta x_h^P} + u_h \tag{5}$$

where $\mathbf{z_h^S} = (Spread_h^P, |Fdiscount|_h, Q_{LD,h}^P/N_{LD,h}^P, Q_{SD,h}^P/N_{SD,h}^P, Vol_h^P) = (Spread_h^P, \mathbf{x_h^P})'$ is a vector of endogenous variables. LD, SD denote large and small dealers, for both spot and forward markets, $P = S, F$. The vector contains bid-ask spread as a measure of market liquidity, forward points as a measure of funding liquidity, quoting intensity of large and smaller dealers, and realized volatility as control variables. α denotes an intercept and the term $\sum_{i=1}^{23} \delta_i H_i$ refers to hourly dummy variables and their associated coefficients. Long-run dynamics are captured by the lagged terms of the dependent and independent variables while short run dynamics are driven by the contemporaneous and lagged differenced terms. We test for the existence of a long-run relationship applying Pesaran, Shin, and Smith (2001) bound testing procedure. First, we test if all long-run coefficients are significantly different from zero using a F-test ($H_0 : \theta_i = 0$). Second, we test if the coefficient of the cointegrating relationship is smaller and significantly different from zero. We estimate the identical model specification for every sub-sample period and only vary the number of lags p. Then we examine the significance of the long-run coefficients. If both null hypotheses are rejected, we conclude that there exists a long-run relationship between variables in vector $\boldsymbol{z^S}$ and $\boldsymbol{z^F}$.

Table 6 shows the coefficients estimates of the long-run equations, expressed in terms of economic magnitudes by scaling by the standard deviations of the regressors. Table 7 and Table 8 show the complete test results for the long-run relationship among the variables for JPY/USD and EUR/USD, respectively. The reported F-statistics of the Pesaran, Shin, and Smith (2001) bounds test exceed I(1) critical values for all equation, indicating the presence of a statistically significant long-run relationship among the selected measures of liquidity and volatility.

[Tables 6, 7 and 8, about here]

Focusing on Table 6, the ECM-ARDL model estimation results point at several takeaways. First, there is a strong and robust relationship between FX market liquidity, as proxied by bid-ask spreads in both forwards ($Spread^F$) and spot ($Spread^S$), with FX funding liquidity, as proxies by the forward discount ($Fdiscount$). For example, a one standard deviation widening in $Fdiscount$ is associated with $0.42bp$ ($0.26bp$) wider bid-ask in JPY/USD (EUR/USD) forward, and a $0.28bp$ ($0.19bp$) wider bid-ask spread in JPY/USD (EUR/USD) spot. The link between funding and market liquidity strengthened in the second sub-sample, particularly for EUR/USD where economic magnitude of the coefficient on $Fdiscount$ approximately doubled in the spot bid-ask spread equation, and increased more than fivefold in the forward bid-ask spread equation.

Second, the positive net effect of dealer competition on market liquidity in FX forwards has all but disappeared. A one standard deviation increase in the quoting intensity by large dealers in the forward market, Q^F_{LD}/N^F_{LD} used to be associated with a $0.30bp$ ($0.22bp$) narrowing of bid-ask spreads on JPY/USD forwards (EUR/USD forwards) in the 2010 to mid-2014 (December 2015 for EUR/USD), but the effect becomes small and not statistically significant in the mid-2014 to 2017 period. In contrast, the negative association between quoting intensity of smaller dealers, Q^F_{SD}/N^F_{SD}, and market liquidity in FX forwards has persisted for both currency pairs, and even strengthened significantly in the case of EUR/USD. Thus, a one standard deviation increase in Q^F_{SD}/N^F_{SD} is associated with $0.13bp$ ($0.15bp$) wider bid-ask spread in FX forwards in JPY/USD (EUR/USD).

Third, in contrast to the forward market, dealer competition in the spot market has continued to contribute to significant narrowing of bid-ask spreads also in the post-2014 period. An one standard deviation increase in quoting intensity by large dealers in spot, Q^S_{LD}/N^S_{LD}, is associated with $0.17bp$ ($0.28bp$) narrower bid-ask spreads in in JPY/USD (EUR/USD) spot. In the case of EUR/USD, even small dealer (primarily tier-3 bank) competition contributes to the narrowing of spot bid-ask spreads, while their effects are not significant for JPY/USD.

Fourth, rises in small dealer (primarily tier-2 bank) activity in forwards appears to have negative spillovers on spot market liquidity. Specifically, even though small dealer competition in spot markets does not seem to have a statistically significant effect on market liquidity in JPY/USD, higher quoting intensity by small dealers in forwards is associated with wider bid-ask spreads in the spot (Table 6, top-panel, last column). Similarly, when small dealer quoting intensity in EUR/USD spot is replaced with small dealer quoting intensity in forwards in the $Spread^S$ equation, the coefficient is two times larger in magnitude and takes on a positive sign. This is noteworthy especially because approximately half of small dealers in FX forwards and swap do not even participate in spot market directly (see, Figure 2, above).

These results are obtained controlling for time-of-day effects with hourly dummies, as well as for intraday volatility in both spot and forwards. The results are also robust to measuring FX funding liquidity using CIP deviations instead of the un-adjusted forward discount (see Tables A5 and A6).

4.2 Adverse liquidity effects of small dealer competition

What are the possible economic reasons behind the negative relationship between FX market liquidity and small dealer competition? The first reason is that small dealers charge higher spreads. This can be gleaned from Table 9, which shows simple average of the median hourly bid-ask spreads and forward discounts computed from forward quotes by large and small dealers. For both JPY/USD and EUR/USD, the bid-ask spreads of forward rates (expressed as a percentage of mid-forward rate, in basis points) are significantly higher for small dealers compared to large dealers. Similarly, the forward discount (forward spread, expressed as a percentage of mid-spot rate) is also also somewhat wider for small dealers compared to large dealers. This is consistent with smaller dealers facing higher hurdle rates to enter as market-makers in the forward market, presumably due to being smaller volume players. Hence, their competition does not lead to the narrowing of the spreads to the levels that can be supported by large dealers.

[Table 9, about here]

The second reason for the negative relationship between FX market liquidity and small dealer competition in the forward market relates to the relative informational disadvantage of small dealers compared to large dealers. Bjonnes, Osler, and Rime (2009) find that order flow of large dealer banks is more informative than that of small banks, in terms of return predictability. Menkhoff, Sarno, Schmeling, and Schrimpf (2016) find evidence that informative order-flow of sophisticated investors affects foreign exchange rate via the intermediation of large dealers. Our logic is consistent with this literature. Large dealers intermediate the lion share of customer flows inside their internal liquidity pools. As a result, their activity on anonymous primary interdealer venues, such as Reuters Matching, is largely driven by the hedging of any residual inventory imbalances reflective of aggregate informed trading of their client base. This would suggest that, on average, large dealers possess more precise information about the "true" market forward exchange rate at any point in time (again, because they observe the FX hedging activity of their diverse client base) compared to small dealers.

In order to test this, we follow recent studies which assess the distribution of quote submissions. For example, Corsetti, Lafarguette, and Mehl (2017) use information on both quotes and trades to construct a quote dispersion measure that accounts for market participants' reaction to new information based on the speed of trade execution. As we do not possess information on trades but only on quote submissions, our measure of dispersion follows Jankowitsch, Nashikkar, and Subrahmanyam (2011) and is applied to forward quotes within each hour:

$$Disp_h^F = \sqrt{\sum_{i=1}^{h_i} \frac{q_i^F}{Q_h^F} \left(\frac{F_i - \bar{F}_h}{\bar{F}_h} \right)} \tag{6}$$

where q_i^F accounts for the number of forward quote submissions within a minute, Q_h^F denotes the total number of submissions within the hour, F_i denotes the forward mid price in minute i and $\bar{F}_h$ is the average forward price of each hour. In times of higher volatility and low liquidity, we expect the dispersion of quotes to be comparably larger and $Disp_h^F$ to increase.

We then once again formulate a conditional ECM, but for the system that includes $Disp_h^F$, quoting intensity by large and small dealers, and hourly volatility of the forward rate, Vol_h^P, as control:

$$\Delta Disp_h^F = \alpha + \sum_{i=1}^{23} \delta_i H_i + \theta_0 Disp_{h-1}^F + \boldsymbol{\theta x_{h-1}} + \sum_{i=1}^{p-1} \boldsymbol{\gamma_i \Delta z_{h-i}^P} + \boldsymbol{\beta \Delta x_h^P} + u_h \tag{7}$$

where $\mathbf{z_h^S} = (Disp_h^F, Q_{LD,t}^F / N_{LD,h}^F, Q_{SD,h}^F / N_{SD,h}^F, Vol^F) = (Disp_h^F, \mathbf{x_h^P})'$. Table 10 shows the results. Consistent with the hypothesis outlined above, large dealer quoting intensity is associated with a reduction in the dispersion of forward quotes in both JPY/USD and EUR/USD. In contrast, smaller dealer quoting intensity is not associated with a reduction in the forward quote dispersion in JPY/USD, while their marginal effect on dispersion is less than half of that of large dealers in the EUR/USD forward market.

[Table 10, about here]

To summarise, the results reported in Tables 9 and 10 indicate that two effects are at play in generating the negative relationship between liquidity in FX forward market and competition by small dealers. The first one relates to their wider required intermediation spreads, both bid-ask spreads and the forward spread (forward discount). The second one relates to their informational disadvantage and hence greater uncertainty about the actual market mid-rate for pricing FX forwards, which leads to greater dispersion and volatility of the forward quotes.

4.3 Contagion versus interdependence

In this subsection, we test for the presence of contagion from funding markets to market liquidity at quarter-end balance sheet reporting periods, when large dealers pull back and small dealers increase their quoting intensity in FX forwards and swaps.

We follow Forbes and Rigobon (2002) and calculate an adjusted correlation coefficient using hourly data. We then test for regime shifts between quarter-end and non-quarter end months.[9] Adjusting the correlation coefficient for heteroskedastic levels of volatility allows us to make further statements about about contagions and spillovers, rather than simple co-movement. To this end, we estimate the following bivariate vector autoregressive model:

$$\Delta y_h = \phi(L)\Delta y_{h-1} + \eta_h \tag{8}$$

$$\Delta y_h = \left[\Delta Fdiscount_h, \Delta Spread_h^P\right] \text{ where } P = F, S \tag{9}$$

where Δy_h refers to the first differenced and de-seasonalized measures of funding and market liquidity. First, we de-seasonalise the FX liquidity metrics by regressing their changes on hourly dummies. Second, we estimate Equation (8) using a 200-hour rolling window and store the variance-covariance matrix for every single estimation.[10] Third, based on the obtained variance-covariance matrices from the hourly VAR regressions, we follow the approach in Forbes and Rigobon (2002) and construct an unconditional correlation coefficient as follows:

$$\rho = \frac{\rho^*}{\sqrt{(1 + \delta[1 - (\rho^*)^2])}} \tag{10}$$

$$\text{with } \delta = \frac{\sigma^{QE}_{Fdiscount}}{\sigma^{NQE}_{Fdiscount}} - 1$$

where ρ^* refers to the standard correlation coefficient between funding and market liquidity, and $\sigma^{QE}_{Fdiscount}$ and $\sigma^{NQE}_{Fdiscount}$ refer to the average variance of FX funding liquidity in quarter-end months (QE) and the two preceding non quarter-end months (NQE), respec-

[9] Using a vector autoregression framework, Moinas, Nguyen, and Valente (2017) exploit regime shifts of volatility levels to examine liquidity dynamics in the European treasury bond markets.

[10] Every rolling estimation initially allows for 8 lags but we increase the lag length in a step-wise fashion until residuals are free of serial correlation.

tively. Since the intra-day data allows us to construct the measure of co-movement for every rolling window estimation, we are able to obtain a time series of unconditional correlation coefficients for each QE and NQE period.

Having obtained the time-series of the adjusted correlation coefficients between funding and market liquidity measures in quarter-end months and the preceding two months, we then employ a one-sided t-test to examine for the following hypothesis:

$$H_0\text{: } \rho_{NQE} < \rho_{QE} \mid \rho_{QE} < 0 \qquad\qquad H_A\text{: } \rho_{NQE} > \rho_{QE} \mid \rho_{QE} < 0$$

where ρ_{NQE} and ρ_{QE} refer to the average of the adjusted correlation coefficients in the non-quarter-end and quarter-end months. Rejecting the null hypothesis indicates that the shocks to $Fdiscount$ in a quarter-end month lead to spillover to bid-ask spreads, even after adjusting for the higher level of volatility of funding conditions during these periods.[11]

[Table 11, about here]

Table 11 shows the results for JPY/USD. The average adjusted correlation coefficient is negative in a number of quarter-end as well as non-quarter-end months in both spot (upper panel) and forward (lower panel). Based on the t-test conducted on the adjusted correlation coefficients, we are able to reject the null of no spillovers in 3 out of 11 quarter-end months considered for spot, and 4 out of 11 quarter-end months for forwards. Hence, the evidence in favour of contagion from FX funding to FX market liquidity in JPY/USD is strongest for December 2015, June 2016, and December 2016.

[Table 12, about here]

Table 12 shows the analogous test results for EUR/USD. Similar to JPY/USD, the number of months in which the null is reject in favour of contagious spillovers is higher for forward bid-ask spreads than for spot bid-ask spreads. At the same time, the overall number of months, in which the results point towards contagion from FX funding liquidity to FX market liquidity, is slightly less that for JPY/USD. Still, both December 2015 and December 2016 turn out to be the quarter-end periods with the most robust evidence in favour of contagions, rather

[11] Qualitatively the same conclusions are drawn when shocks to CIP deviations at quarter-end months are considered. Results are summarized in Table A7 and A8 for JPY/USD and EUR/USD, respectively.

than simple co-movement. It is noteworthy that these months also fall on year-ends, when additional G-SIB surcharges apply to large dealer banks' balance sheets.

Overall, the empirical evidence suggests that a deterioration in funding liquidity at quarter-ends can spillover to market liquidity in spot and forward market. Taken together with our previous results on dealer activity, these findings suggest that the pull-back by G-SIBs from dealing in FX forwards and swaps at quarter- and year-ends can have a particularly contagious implications for spot market liquidity, as they are displaced by more expensive and less informed dealers.

4.4 Small dealer market-making: case study of December 2016

In this sub-section we provide evidence that small dealers displaced large dealers as market-makers in the market of JPY/USD FX forwards and swaps in December 2016. However, because these smaller volume players require higher hurdle rates, in terms of both bid-ask spreads on the forward points that they quote as well as wider forward discount, the increased competition by smaller dealers allows the low FX liquidity environment to persist. In contrast, large banks continued to dominate as market-makers in spot, indicating that it is likely their balance sheet constraints on the exposures to FX derivatives that explains their pullback from quoting inside spreads in the forward market.

The left-hand panels of Figures 8 and 9 show the median hourly JPY/USD quotes of small dealers and large dealers during December 2016, for spot and forwards, respectively. Top is ASK and bottom is BID quotes. The right-hand panels show the hypothetical location of small dealer quotes relative to large dealer quotes in the case that small dealers are actively making markets by quoting inside spreads. If the actual quotes correspond to the inside spread scenario, then this indicates that small dealers, not large dealers, would have been making markets on average during this month. The comparison of actual data (left) to the scenarios (right) in Figure 8 indicates that in December 2016, despite the pull-back by large dealers (G-SIBs) form the market in the aggregate, large dealers continued to make markets in spot. However, the comparison of actual data (left) to the scenarios (right) in Figure 9 of the forward quotes indicates that small dealers entered as market-makers in the forward market.

The results for EUR/USD, shown in Figure 10 and 11, are qualitatively similar. That said, spot quotes among large and small dealers do not show systematic differences. In the forward market, similar to JPY/USD, there is evidence that small dealers act as market markers, particularly during European trading hours.

A hypothesis that we so far reject is that smaller banks enter the market to source liquidity in one of the currencies. If this was the case, our test of inside versus outside spread by dealer category would have shown smaller dealers providing skewed quotes relative to large dealers. Data indicate that this is not the case.

Such entry of small dealers in forwards rather than spot as market-makers is consistent with large dealers pulling back from trading in derivatives (eg forwards and FX swaps) but continuing to make markets in spot. Hence, the results indicate that small (primarily tier-2) dealers can play an important role in market-making in FX forwards when funding conditions are tight and spreads are wide enough for smaller-volume players to profitably engage as market-makers. This adds nuance to the recently documented changes in FX market structure, whereby liquidity provision is bifurcated between the few large dealers making markets as principals and smaller dealers that operate an agency model simply passing client flows into the wholesale FX market. In this context, special periods, like quarter-ends, can be used for identification of funding liquidity effect on dealer competition and FX market activity.

5 Conclusion

Trading volumes in FX forwards and swaps are larger than spot, making these instruments crucial for price discovery in currency markets, yet there is hardly any literature on FX market liquidity taking the pricing of FX derivatives into account. In this paper, we measure the joint evolution of FX spot and forward market liquidity conditions. We draw on the pricing of both types of instruments to study the relationship between FX market liquidity and FX funding liquidity. The assessment of liquidity conditions also takes into account information on the number of dealers active at a given point in time, their quoting intensity, as well as dealer characteristics such as size. The empirical strategy makes particular use of month-end and quarter-end dynamics in the FX swap market for the identification of exogenous FX funding liquidity shocks, and their impact on FX market liquidity.

The results based on intraday data for JPY/USD and EUR/USD point at the presence of liquidity spirals in FX markets, a la Brunnermeier and Pedersen (2009). Furthermore, the co-movement between market and funding liquidity has increased in recent years, and the instances of extreme liquidity droughts have also risen. Statistical tests also point towards contagion of adverse FX funding liquidity shocks to market liquidity in both forward and spot markets in the most extreme periods.

Competitive dynamics of FX dealers play an important role in these liquidity dynamics.

Specifically, the positive impact of dealer competition on FX market liquidity has decreased over time. While large dealers still dominate market-making in spot markets at all times, and their quoting intensity is associated with improved liquidity dynamics, they have also exhibited a tendency to pull-back from market-making in derivatives, namely FX forward and swaps, around balance sheet reporting periods. Yet, as large dealers are displaced by smaller, and as such more expensive and less informed, dealers in the forward markets, spot market liquidity appears to also suffer because liquidity conditions in spot and forward markets are tightly linked.

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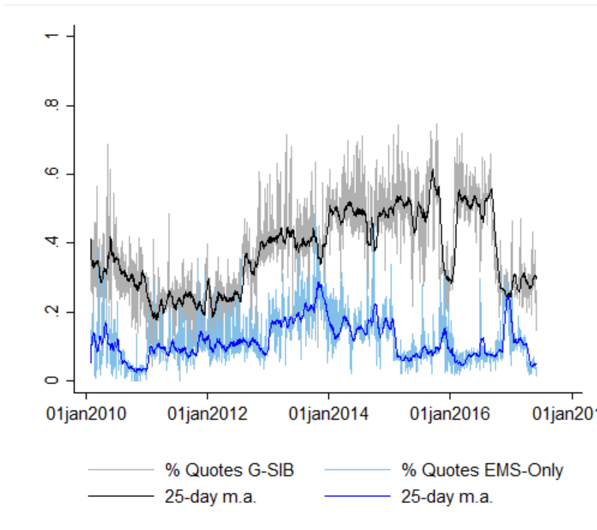
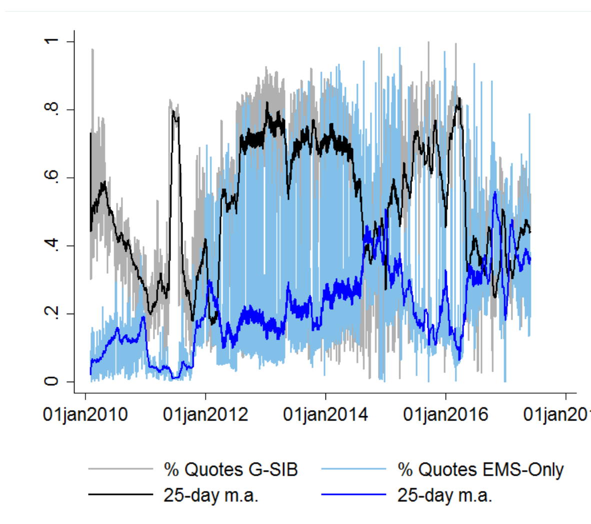
Figures

Figure 1: Large and small dealer characteristics in JPY/USD

(a) Daily percentage quotes from large dealers in spot: G-SIB vs Euromoney classification



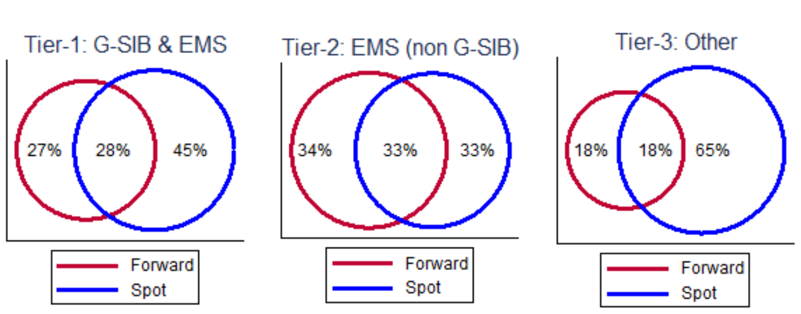
(b) Daily percentage quotes from large dealers in forward: G-SIB vs Euromoney classification



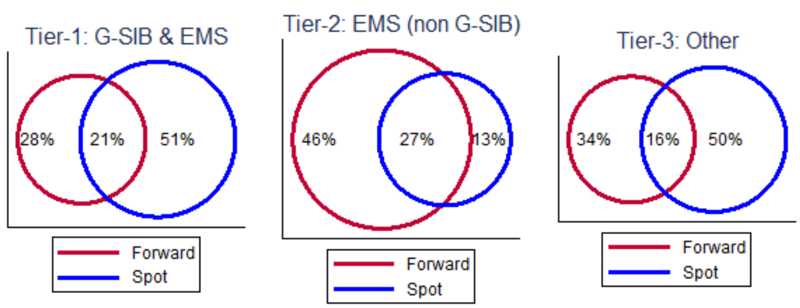
See Table 3 for the corresponding list of dealers. G-SIB (tier-1) dealers refer to banks that are classified as globally systematically important banks. EMS are banks that are listed as large dealers by the FX Euromoney Survey but that are not part of the G-SIB classification.

Figure 2: Activity of small and large dealers by market segment in JPY/USD

(a) Average share of dealers active in spot and derivative markets: Feb 2010 - Jun 2014



(b) Average share of dealers active in spot and derivative markets: Jul 2014 - May 2017



(c) Percentage of large dealer activity in spot and derivative markets

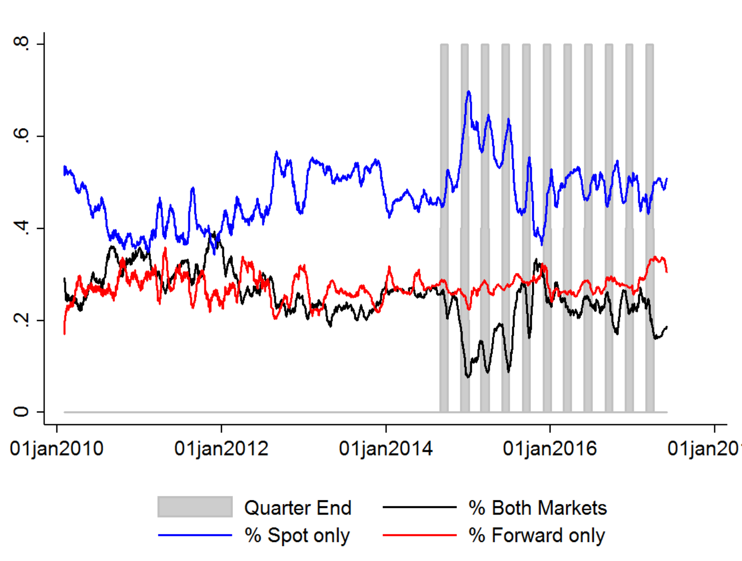
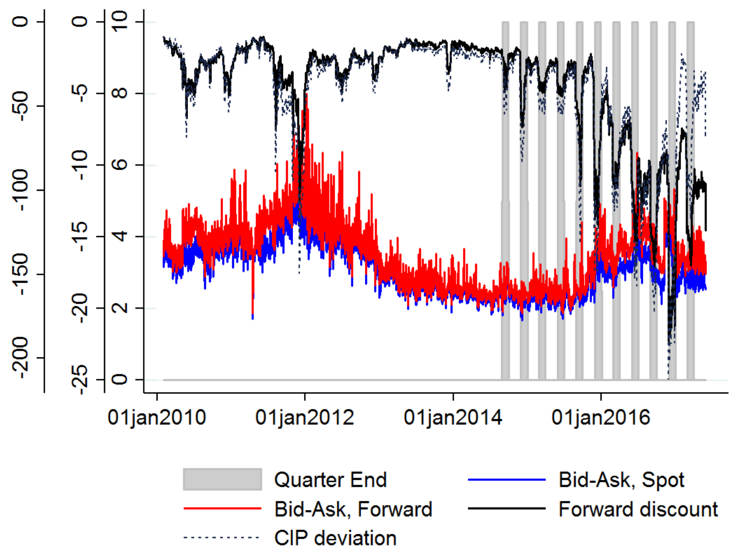


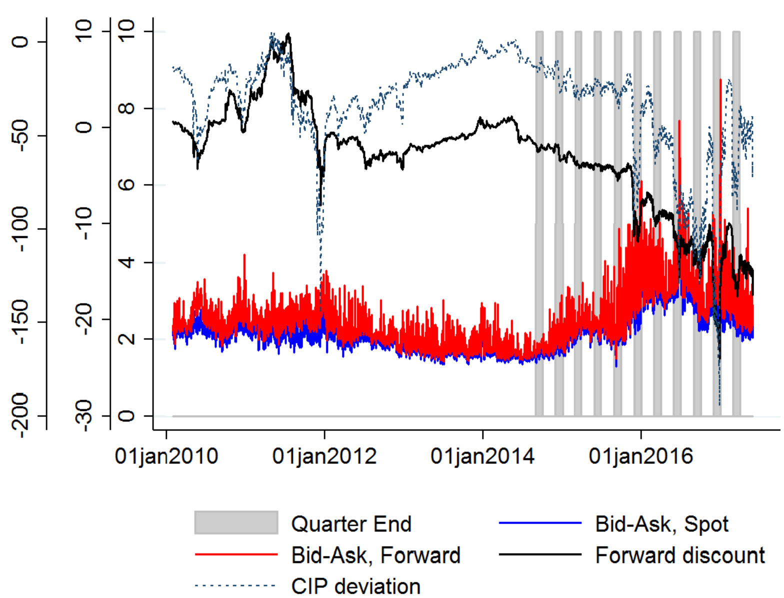
Figure 2a and 2b show the average share of dealers active in different market segments for the period February 2010 - June 2014 and July 2014 to May 2017, respectively. Red refers to dealers active only in forward, blue to dealers active only in spot, and the intersection refers to dealers active in both markets. Figure 2c shows the 25-day moving average of large dealers (tier-1) that are only active in spot markets, only in forward markets, or in both markets.

Figure 3: Bid-ask spreads in spot and forwards, forward discount, and CIP deviations

(a) JPY/USD



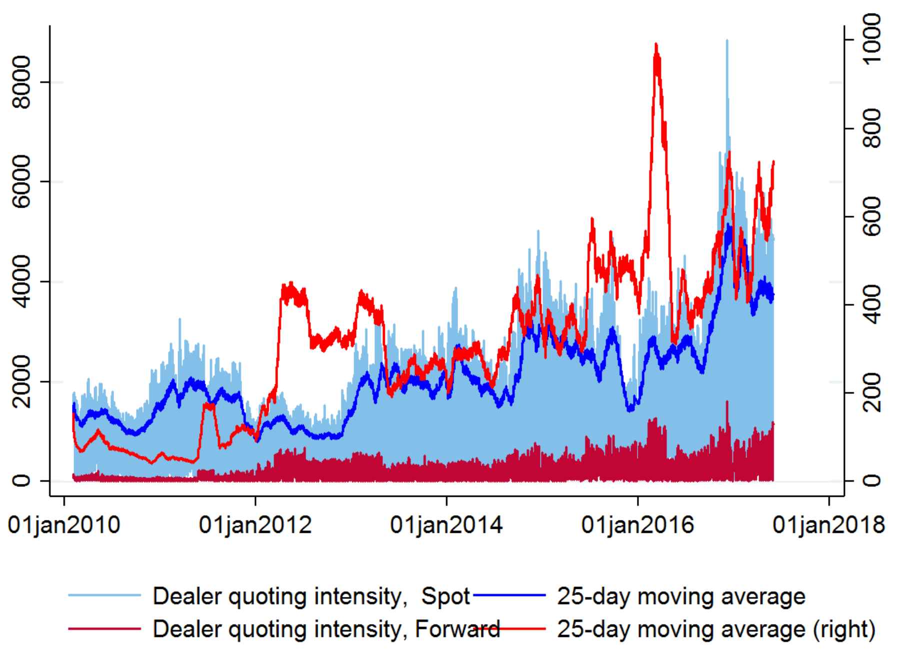
(b) EUR/USD



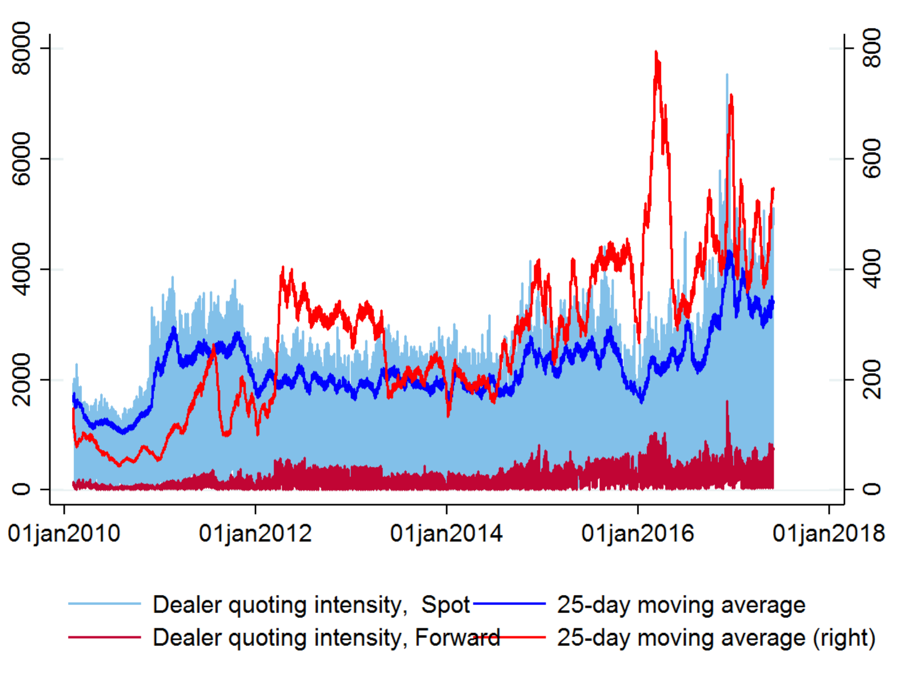
The outside y-axis shows OIS-based 1-month CIP deviations, in basis points; the middle y-axis shows 1-month forward discount, in basis points as a percentage of spot price; the inner y-axis shows bid-ask spreads, in basis points as a percentage of mid price.

Figure 4: Measures of dealer competition in spot and forwards

(a) JPY/USD



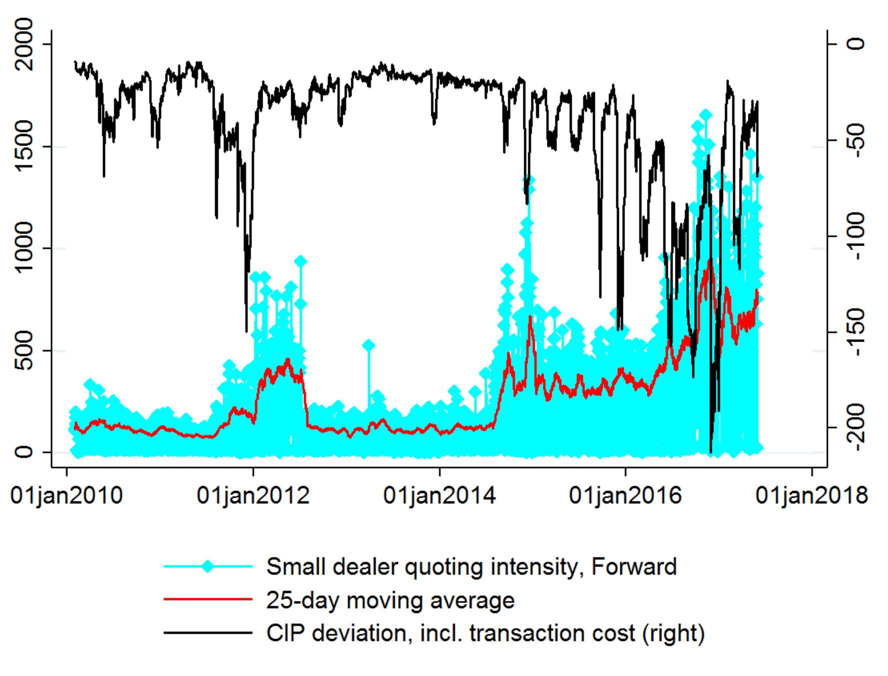
(b) EUR/USD



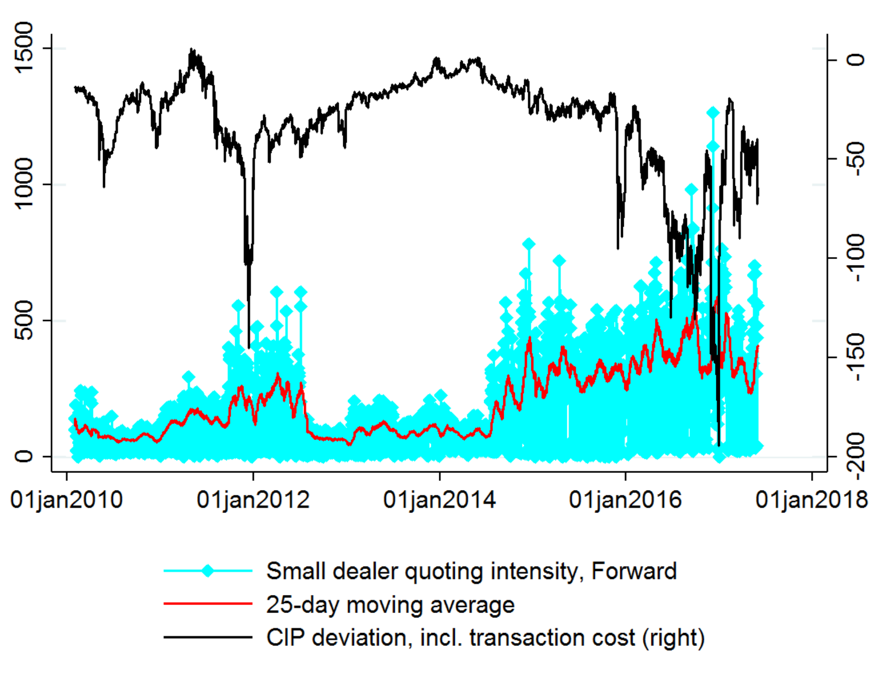
The figure shows daily dealer quoting intensity, defined as the total number of quotes divided by the total number of active dealers in a given day t, in spot and forwards, Q_t^S/N_t^S and Q_t^F/N_t^F; all measures based on the top of the order book.

Figure 5: Small dealer quoting intensity in the forward markets

(a) JPY/USD



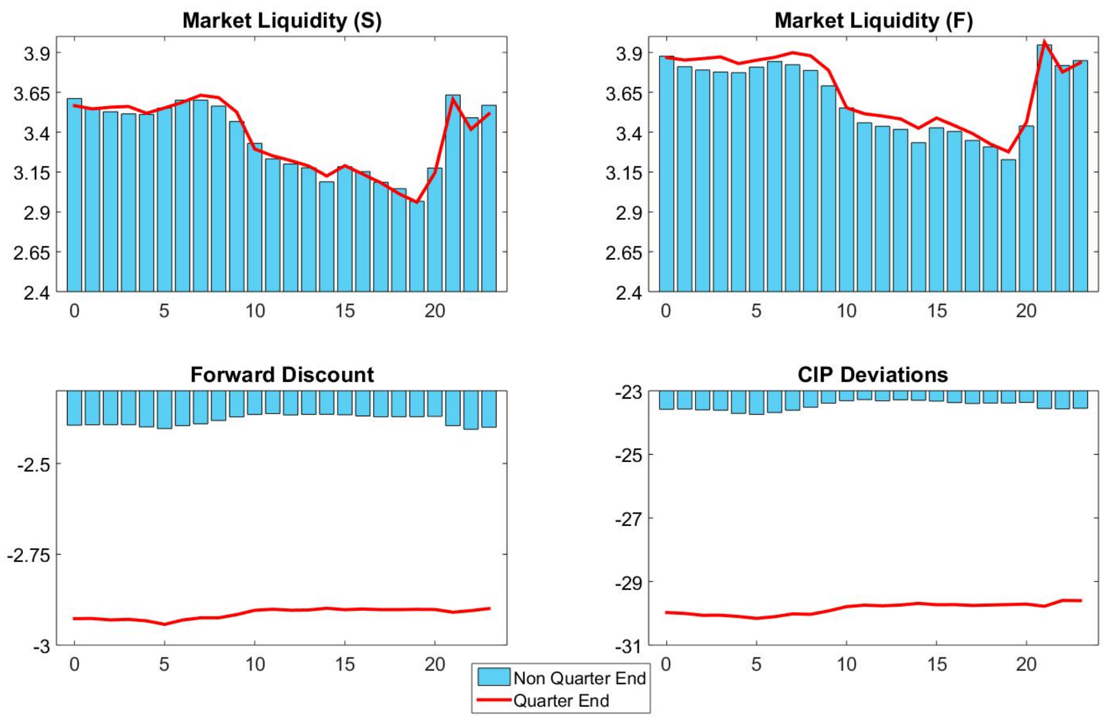
(b) EUR/USD



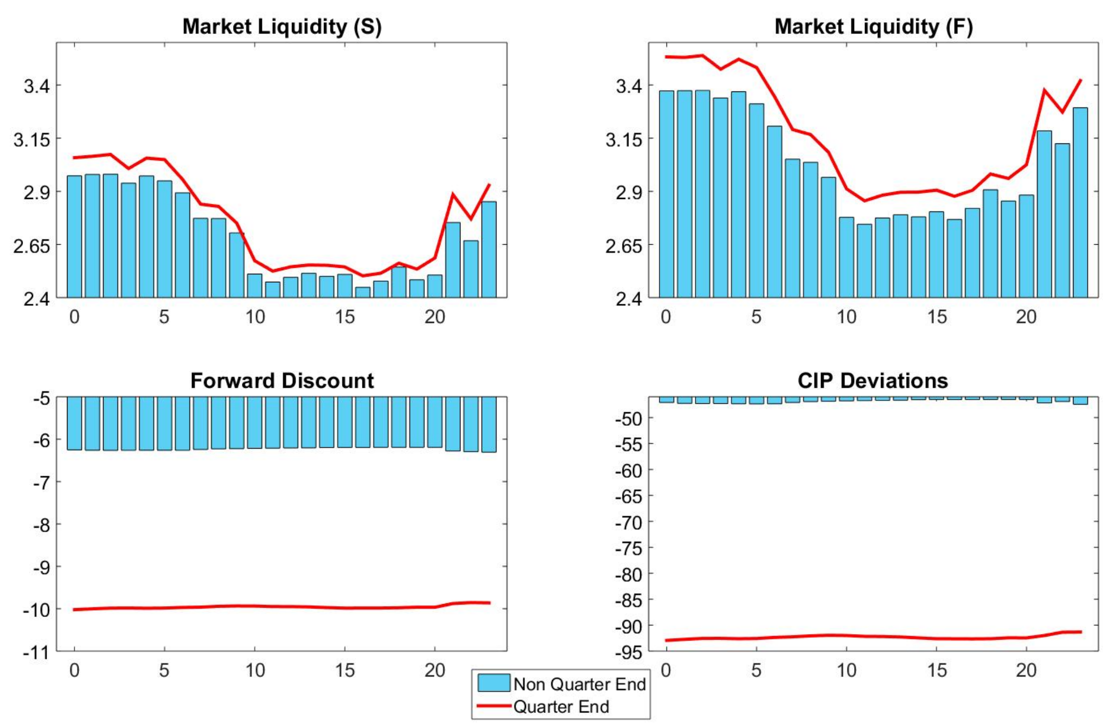
The figure shows daily dealer quoting intensity of small dealers in forwards, defined as the total number of quotes divided by the total number of active dealers in a given day t, $Q_t^{F,SD}/N_t^{F,SD}$; all measures based on the top of the order book.

Figure 6: Intraday liquidity dynamics: JPY/USD

(a) Feb 2010 - Jun 2014



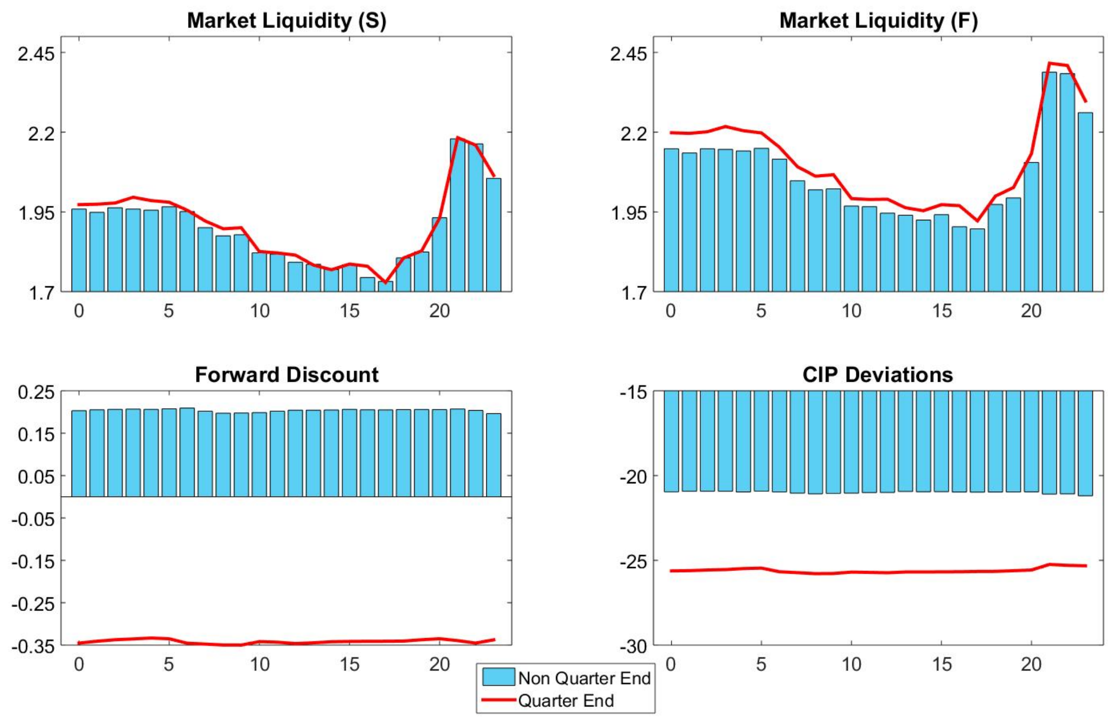
(b) Jul 2014 - May 2017



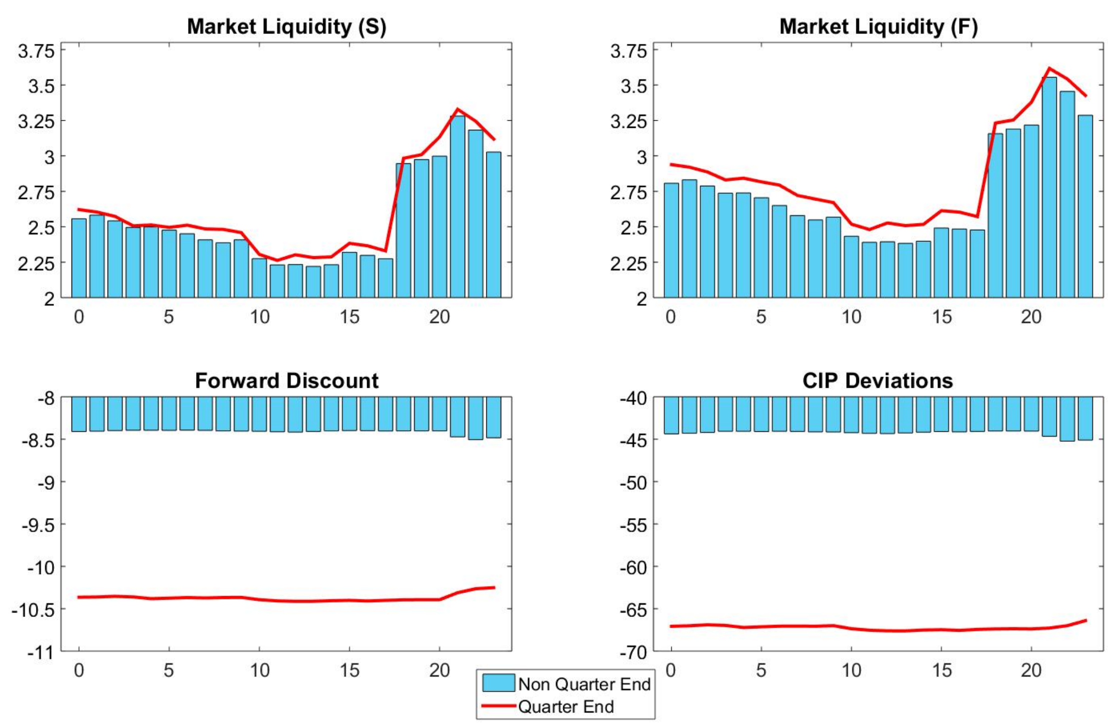
Figures (6a) and (6b) display average intraday levels of market liquidity in spot (S, top left), forwards (F, top right), funding liquidity ($Fdiscount$, bottom left) and CIP deviations ($CIPdev$, bottom right). Blue bars refer to non quarter-end months wand red lines refer quarter-end months; GMT time-stamps.

Figure 7: Intraday liquidity dynamics: EUR/USD

(a) Feb 2010 - Dec 2014

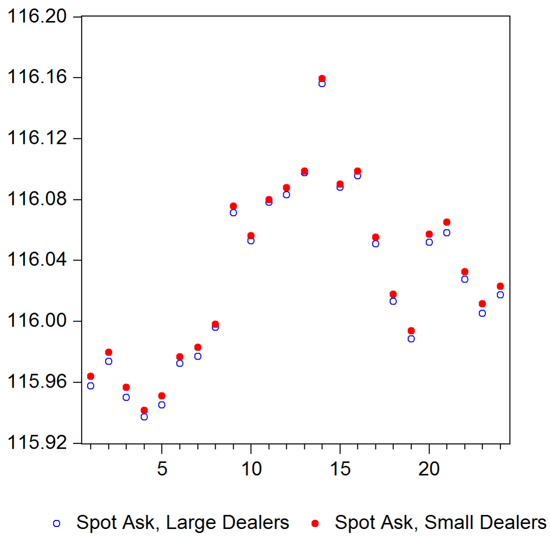


(b) Jan 2015 - May 2017



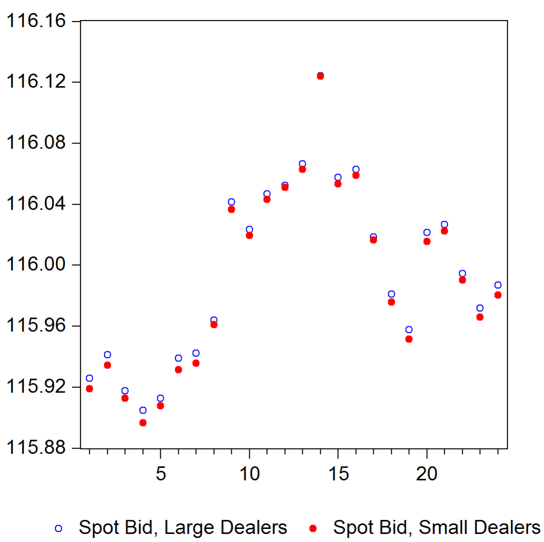
Figures (7a) and (7b) isplay average intraday levels of market liquidity in spot (S, top left), forwards (F, top right), funding liquidity ($Fdiscount$, bottom left) and CIP deviations ($CIPdev$, bottom right). Blue bars refer to non quarter-end months wand red lines refer quarter-end months; GMT time-stamps.

Figure 8: Median quote submissions in JPY/USD spot (December 2016)

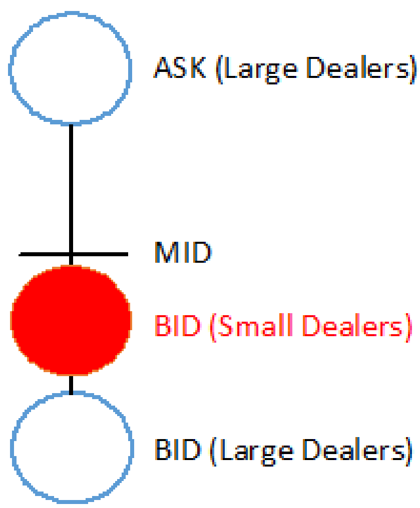


(a) Actual spot ASK

(b) Hypothetical: Smaller Dealers Short USD spot



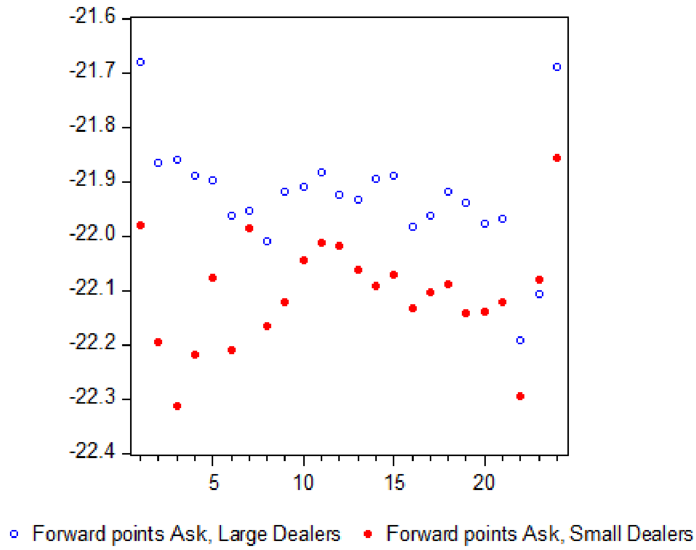
(c) Actual Spot BID



(d) Hypothetical: Smaller Dealers Long USD spot

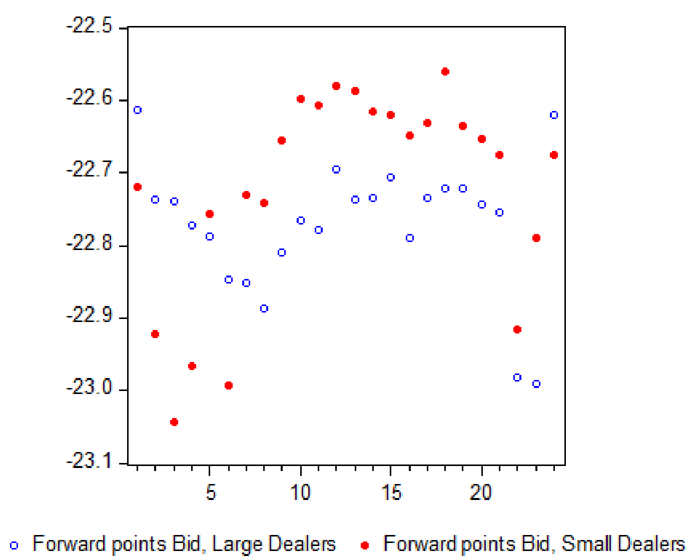
Spot quotes of small dealers compared to forward quotes of large dealers. Indicates that small dealers did not act as market-makers in spot in December 2016. *Top-left:* Actual spot ask; *Top-right:* Hypothetical: Smaller Dealers Short USD spot scenario (ASK: SELL USD @ 116.160). *Bottom-left:* Actual spot bid; *Bottom-right:* Hypothetical: Smaller Dealers Long USD spot scenario (BID: BUY USD @ 116.124). GMT time-stamps.

Figure 9: Median quote submissions in JPY/USD forwards (December 2016)

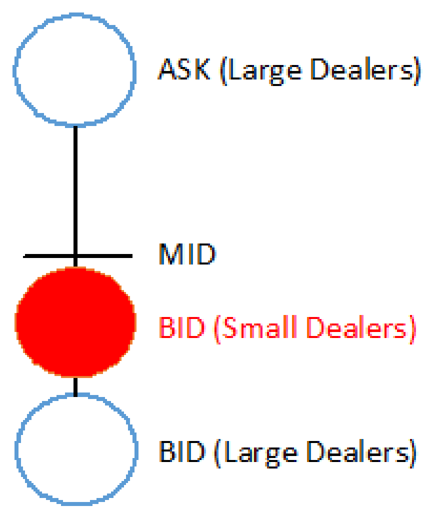


(a) Actual forward points ASK

(b) Hypothetical: Smaller Dealers Short USD forward



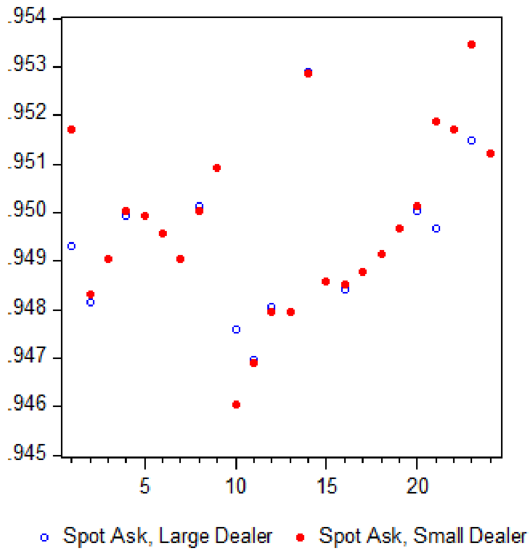
(c) Actual forward points BID



(d) Hypothetical: Smaller Dealers Long USD forward

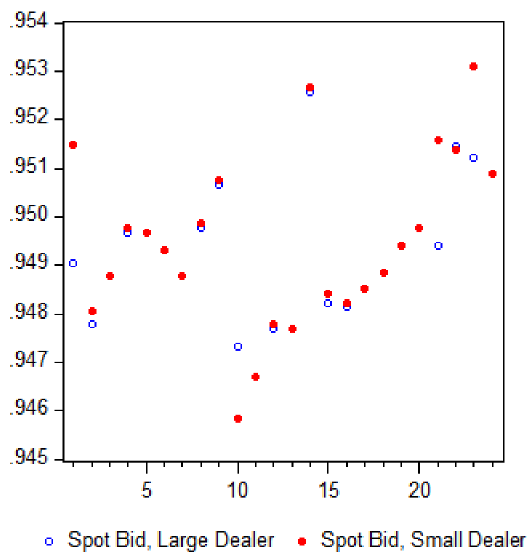
Forward quotes of small dealers compared to forward quotes of large dealers. Indicates that small dealers acted as market-makers in forwards in December 2016. *Top-left:* Actual forward points ask; *Top-right:* Hypothetical: Smaller Dealers Short USD forward scenario (ASK: SELL USD @ 116.160 - 0.220). *Bottom-left:* Actual forward points bid; *Bottom-right:* Hypothetical: Smaller Dealers Long USD forward scenario (BID: BUY USD @ 116.124 - 0.221). GMT time-stamps.

Figure 10: Median quote submissions in EUR/USD spot (December 2016)



(a) Actual Spot ASK

(b) Hypothetical: Smaller Dealers Short USD spot

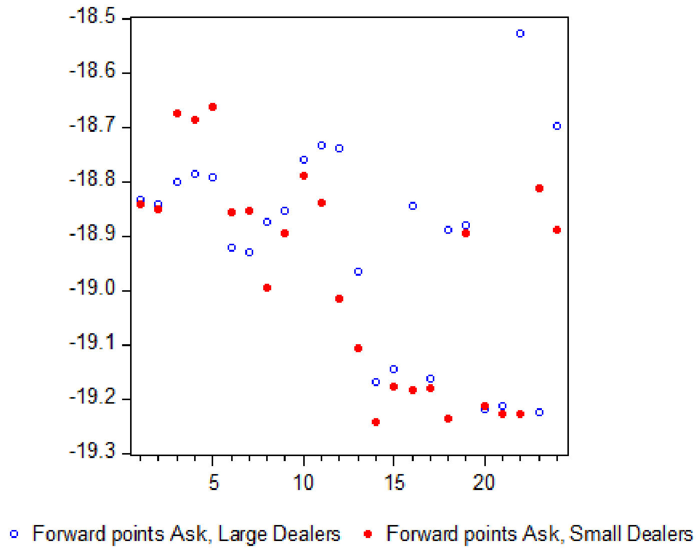


(c) Actual Spot BID

(d) Hypothetical: Smaller Dealers Long USD spot

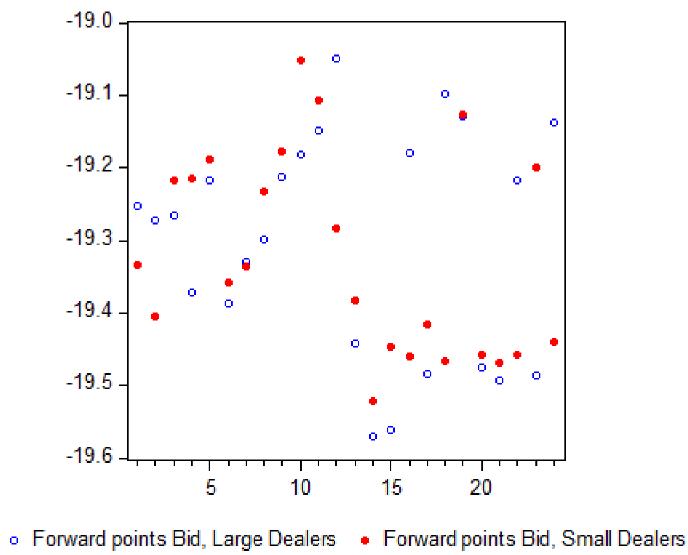
Spot quotes of small dealers compared to forward quotes of large dealers. Indicates that small and large dealers act as market-makers in spot in December 2016. *Top-left:* Actual spot ask; *Top-right:* Hypothetical: Smaller Dealers Short USD spot scenario (ASK: SELL USD @ 0.9529). *Bottom-left:* Actual spot bid; *Bottom-right:* Hypothetical: Smaller Dealers Long USD spot scenario (BID: BUY USD @ 0.9526). GMT time-stamps.

Figure 11: Median quote submissions in EUR/USD forwards (December 2016)



(a) Actual Forward Points ASK

(b) Hypothetical: Smaller Dealers Short USD spot



(c) Actual Forward Points BID

(d) Hypothetical: Smaller Dealers Long USD spot

Forward quotes of small dealers compared to forward quotes of large dealers. Indicates that small dealers acted as market-makers in forwards in December 2016. *Top-left:* Actual forward points ask; *Top-right:* Hypothetical: Smaller Dealers Short USD forward scenario (ASK: SELL USD @ 0.9529 - 0.00192). *Bottom-left:* Actual forward points bid; *Bottom-right:* Hypothetical: Smaller Dealers Long USD forward scenario (BID: BUY USD @ 0.9526 - 0.00195). GMT time-stamps.

Tables

Table 1: **Example: two-second window for JPY/USD spot on 5 May 2017**

INSTRUMENT	DATE	TIME	DEALER	BID	ASK
'JPY='	'5-May-17'	'14:47:29.348944'	'BKofNYMellon NYC'	112.620003	112.6399994
'JPY='	'5-May-17'	'14:47:29.381124'	'BARCLAYS LON'	112.610001	112.6399994
'JPY='	'5-May-17'	'14:47:29.640943'	'SOC GENERALE PAR'	112.599998	112.6399994
'JPY='	'5-May-17'	'14:47:30.065053'	'KASPI BANK ALA'	112.620003	112.6399994
'JPY='	'5-May-17'	'14:47:31.277082'	'SEB STO'	112.599998	112.6500015
'JPY='	'5-May-17'	'14:47:32.260157'	'RBS LON'	112.599998	112.6399994
'JPY='	'5-May-17'	'14:47:32.301189'	'RABOBANKGFM LON'	112.589996	112.6399994

Source: Thomson Reuters Tick History (TRTH) data, available via Reuters Datascope.

Table 2: **Benchmark hourly measures and their daily transformations**

Measure (hourly)	Definition	Daily
$Spread_h^S = \frac{S_h^{ask} - S_h^{bid}}{S_h^{mid}}$	market liquidity, S; $S_h^{ask} \equiv 1/h_i \sum_{i=1}^{h_i} S_i^{ask}$	mean
$Spread_h^F = \frac{F_h^{ask} - F_h^{bid}}{F_h^{mid}}$	market liquidity, F; $F_h^{bid} = S_h^{bid} + FP_h^{bid} \times 10^{-2}$	mean
$Fdiscount_h = \frac{F_h^{mid} - S_h^{mid}}{S_h^{mid}}$	FX funding liquidity	mean
$CIPdev_h = (1 + \frac{r_h^{mid}}{100}) - (1 + \frac{r_h^{mid*}}{100}) \times \left(\frac{F_h^{mid}}{S_h^{mid}}\right)^{360/30}$		mean
$Q_h^P = \#Quotes_h^P$	dealer competition, *intensive margin*	sum
$N_h^P = \#Dealers_h^P$	dealer competition, *extensive margin*	sum
Q_h^P / N_h^P	dealer competition, *quoting intensity*	sum
$Disp_h^P = \sqrt{\sum_{i=1}^{h_i} \frac{q_i}{Q_h} \left(\frac{P_i - \bar{P}_h}{\bar{P}_T}\right)}$	weighted quote dispersion; $P \equiv S, F$	mean
$Vol_h^P = \frac{\sum (r_P - \bar{r}_{P,h})^2}{n-1}$	hourly variance; $r_P = ln(P_h) - ln(P_{h-1})$; $P \equiv S, F$	-

Table 3: **G-SIB classification vs 2016 Euromoney FX Survey rankings**

This table reports the comparison between large dealer categorisation based on G-SIB classification with that based on Euromoney FX Survey rankings.

2016 G-SIB Classification	2016 Euromoney FX Survey (EMS)
Agricultural Bank of China	Alfa Bank
Bank of America Merrill Lynch	ANZ Banking Group
Bank of China	Bank of Montreal
Bank of New York Mellon	BBVA
Barclays	CIBC
BNP Paribas	Citadel Securities
China Construction Bank	Commerzbank
Citigroup	Commonwealth Bank of Australia
Credit Suisse	Danske Bank
Deutsche Bank	Den norske Bank
Goldman Sachs	Jump Trading
Groupe BPCE	Lloyds Banking Group
Groupe Credit Agricole	Lucid Markets
HSBC	National Australia Bank
ICBC	Natixis
ING Bank	Nomura
JP Morgan Chase	Rabobank
Mitsubishi UFJ FG	RBC Capital Markets
(Mizuho FG)	Saxo Bank
Morgan Stanley	Scotiabank
Nordea	SEB
Royal Bank of Scotland	Standard Bank
Santander	State Bank of India
Societe Generale	Svenska Handelsbanken
Standard Chartered	Swedbank
State Street	TD Securities
Sumitomo Mitsui FG	Tower Research Capital
UBS	Virtu Financial
Unicredit Group	VTB
Wells Fargo	Westpac Banking
	Woori Bank
	XTX Markets
	Zurich Cantonalbank

Notes: Banks that are classified as large dealers according to G-SIB classification are also considered as large dealers according to the Euromoney FX Survey (EMS). Banks marked in grey are not available in our database and banks that are only part of the G-SIB classifaction but not listed in EMS are marked with parenthesis.

Table 4: **Summary Statistics: Liquidity dynamics (price-based) at quarter end**

This table reports the average and standard deviation of spot market ($Spread^S$), forward market ($Spread^F$), and funding liquidity ($Fdiscount$) for JPY/USD and EUR/USD for two different sub-sample periods. QE refers to months at quarter-ends (March, June, September, December), BQE are months before quarter-end (February, May, August, November), and AQE refer to the first month after quarter-end (January, April, July, Octobers). In Panel A, numbers in parentheses refer to the p-value of a one-sided t-test that market and funding liquidity in the respective months is larger than in the rest of the months in each sub-sample. In Panel B, numbers in parentheses denote the p-value of a variance ratio test.

	JPY/USD						EUR/USD					
	02/2010 - 06/2014			07/2014 - 05/2017			02/2010 - 12/2015			01/2015 - 05/2017		
	QE	BQE	AQE	QE	BQE	AQE	QE	BQE	AQE	QE	BQE	AQE
Panel A: Average and t-test												
$Fdiscount$	-2.91***	-2.4	2.4	-9.93***	-6.24	-6.28	-0.37***	0.12	0.31	-10.38***	-8.38	-8.46
	(0.00)	(1.00)	(1.00)	(0.00)	(1.00)	(1.00)	(0.00)	(0.83)	(1.00)	(0.00)	(1.00)	(1.00)
$CIPdev$	-29.85***	-23.69	-23.52	-92.20***	-45.56	-48.92	-25.37***	-21.02	-20.98	-67.47***	-42.14	-46.70
	(0.00)	(1.00)	(1.00)	(0.00)	(1.00)	(1.00)	(0.00)	(0.99)	(1.00)	(0.00)	(1.00)	(1.00)
$Spread^S$	3.41	3.47	3.41	2.79*	2.80**	2.75	1.97	1.99	1.95	2.74	2.75	2.7
	(0.69)	(0.12)	(0.76	(0.05)	(0.02)	(1.00)	(0.46)	(0.12)	(0.91)	(0.38)	(0.27)	(0.81)
$Spread^F$	3.72	3.73	3.67	3.22***	3.15	3.03	2.18	2.17	2.12	3.01	2.94	2.95
	(0.36)	(0.27)	(0.84)	(0.01)	(0.28)	(0.99)	(0.12)	(0.21)	(0.98)	(0.15)	(0.74)	(0.67)
Panel B: Standard deviation and ratio test												
$Fdiscount$	1.76***	1.29	0.88	5.23***	3.89	3.89	2.89	2.72	3.21***	5.37***	4.13	4.25
	(0.00)	(0.99)	(1.00)	(0.00)	(1.00)	(1.00)	(0.76)	(1.00)	(0.00)	(0.00)	(1.00)	(1.00)
$CIPdev$	21.40***	15.43	10.20	44.72***	29.85	28.83	21.85***	14.08	12.68	40.18***	24.87	27.34
	(0.00)	(1.00)	(1.00)	(0.00)	(1.00)	(1.00)	(0.00)	(1.00)	(1.00)	(0.00)	(1.00)	(1.00)
$Spread^S$	0.78	0.83*	0.79	0.58***	0.55	0.46	0.39	0.37	0.37	0.69	0.66	0.76**
	(0.87)	(0.06)	(0.67)	(0.00)	(0.21)	(1.00)	(0.11)	(0.65)	(0.80)	(0.68)	(0.97)	(0.01)
$Spread^F$	0.91	0.96	0.92	0.78***	0.69	0.65	0.47*	0.45	0.44	0.84*	0.69	0.85***
	(0.80)	(0.13)	(0.60)	(0.00)	(0.76)	(0.99)	(0.09)	(0.67)	(0.83)	(0.07)	(1.00)	(0.03)

Notes: Results are based on daily data. Numbers in parentheses refer to p-values. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 5: **Intraday conditional co-movement of liquidity measures**

This table reports the average co-movement between spot market and forward market liquidity with funding liquidity in two sub-sample periods for JPY/USD and EUR/USD. Funding liquidity is measured either by forward points or by CIP deviations. ρ refers to the average correlation coefficients across trading hours and PCA refers to the proportion of variation explained by the first principal component.

	JPY/USD			
	02/2010 00:00:00 - 06/2014 23:00:00		07/2014 00:00:00 - 05/2017 23:00:00	
	$Spread^S$	$Spread^F$	$Spread^S$	$Spread^F$
$\rho_{Fdiscount}$	-0.44	-0.50	-0.51	-0.63
ρ_{CIPdev}	-0.41	-0.47	-0.48	-0.57
$PCA_{Fdiscount}$	72.23	74.93	75.62	81.70
PCA_{CIPdev}	70.52	73.31	73.97	78.52
	EUR/USD			
	02/2010 00:00:00 - 12/2014 23:00:00		01/2015 00:00:00 - 05/2017 23:00:00	
	$Spread^S$	$Spread^F$	$Spread^S$	$Spread^F$
$\rho_{Fdiscount}$	0.24	0.27	-0.28	-0.40
ρ_{CIPdev}	-0.34	-0.46	-0.33	-0.45
$PCA_{Fdiscount}$	62.00	63.54	64.16	69.81
PCA_{CIPdev}	67.15	72.85	66.75	72.44

Notes: Hourly sample; GMT time-stamps.

Table 6: **Intraday conditional co-movement of liquidity measures**

This table is based on estimation results of the long-run equation of a conditional error correction model (ECM) derived from an autoregressive distributed lag (ARDL) model specification. Specifically, for the two sub-sample periods, for spot and forward markets, $P = S, F$, we estimate:

$$\Delta Spread_h^P = \alpha + \sum_{i=1}^{23} \delta_i H_i + \theta_0 Spread_{h-1}^P + \boldsymbol{\theta x_{h-1}} + \sum_{i=1}^{p-1} \boldsymbol{\gamma_i \Delta z_{h-i}^P} + \boldsymbol{\beta \Delta x_h^P} + u_t$$

where a vector $\mathbf{z_h^S} = (Spread_h^P, |Fdiscount|_t, Q_{LD,h}^P/N_{LD,h}^P, Q_{SD,h}^P/N_{SD,h}^P, Vol_h^P) = (Spread_h^P, \mathbf{x_h^P})'$ and LD, SD denotes large and small dealers. The coefficients are scaled by the standard deviation of the explanatory variables in each sub-sample.

	JPY/USD					
	02/2010 00:00:00 - 06/2014 23:00:00			07/2014 00:00:00 - 05/2017 23:00:00		
Variable	$Spread^F$	$Spread^S$	$Spread^S$	$Spread^F$	$Spread^S$	$Spread^S$
$\|Fdiscount\|$	0.405***	0.228***	0.217**	0.420***	0.278***	0.278***
Q_{LD}^F/N_{LD}^F	-0.299***			-0.050		
Q_{SD}^F/N_{SD}^F	0.234***		0.127***	0.126**		0.095**
Vol^F	0.113			0.436***		
Q_{LD}^S/N_{LD}^S		-0.606***	-0.496***		-0.172***	-0.173***
Q_{SD}^S/N_{SD}^S		0.141***			0.051	
Vol^S		0.263***	0.303***		0.370***	0.403***
	EUR/USD					
	02/2010 00:00:00 - 12/2014 23:00:00			01/2015 00:00:00 - 05/2017 23:00:00		
Variable	$Spread^F$	$Spread^S$	$Spread^S$	$Spread^F$	$Spread^S$	$Spread^S$
$\|Fdiscount\|$	0.044***	0.086***	0.103***	0.259***	0.193***	0.193***
Q_{LD}^F/N_{LD}^F	-0.223***			0.048		
Q_{SD}^F/N_{SD}^F	0.079***		0.042***	0.154***		0.208***
Vol^F	0.416***			0.493***		
Q_{LD}^S/N_{LD}^S		-0.201***	-0.154***		-0.279***	-0.372***
Q_{SD}^S/N_{SD}^S		0.104***			-0.109**	
Vol^S		0.347***	0.362***		0.352***	0.359***

Hourly sample; GMT time-stamps. ARDL lags chosen based on the Schwarz (Bayes) criterion (SC). P-values assigned based on HAC robust standard errors: *** p<0.01, ** p<0.05, * p<0.1.

Table 7: **Long-run liquidity dynamics in JPY/USD**

This table reports coefficients from the long-run equation of a conditional error correction model (ECM) derived from an autoregressive distributed lag (ARDL) model specification. Specifically, for the two sub-sample periods, for spot and forward markets, $P = S, F$, we estimate:

$$\Delta Spread_h^P = \alpha + \sum_{i=1}^{23} \delta_i H_i + \theta_0 Spread_{h-1}^P + \boldsymbol{\theta x_{t-1}} + \sum_{i=1}^{p-1} \boldsymbol{\gamma_i \Delta z_{h-i}^P} + \boldsymbol{\beta \Delta x_h^P} + u_t$$

where a vector $\mathbf{z_h^S} = (Spread_h^P, |Fdiscount|_h, Q_{LD,h}^P/N_{LD,h}^P, Q_{SD,h}^P/N_{SD,h}^P, Vol_h^P) = (Spread_h^P, \mathbf{x_h^P})'$ and LD, SD denotes large and small dealers. F-statistics based on the results of the bound testing procedure for long-run relationship, robust to variables being in between I(0) and I(1). Constant and coefficients on short-run effects omitted for brevity.

Sample:	2/01/2010 00:00-6/30/2014 23:00			7/01/2014 00:00-5/31/2017 23:00		
Variable:	$Spread^F$	$Spread^S$	$Spread^S$	$Spread^F$	$Spread^S$	$Spread^S$
$\|Fdiscount\|$	-0.291***	-0.164***	-0.156**	-0.090***	-0.060***	-0.061 ***
	(0.038)	(0.024)	(0.024)	(0.007)	(0.006)	(0.005)
Q_{LD}^F/N_{LD}^F	-0.007 ***			-0.001		
	(0.001)			(0.001)		
Q_{SD}^F/N_{SD}^F	0.014***		0.008***	0.005**		0.004**
	(0.005)		(0.003)	(0.002)		(0.002)
Vol^F	1.065			2.324***		
	(0.817)			(0.330)		
Q_{LD}^S/N_{LD}^S		-0.008***	-0.007***		-0.002***	-0.002***
		(0.000)	(0.000)		(0.000)	(0.000)
Q_{SD}^S/N_{SD}^S		0.003***			0.001	
		(0.001)			(0.001)	
Vol^S		2.465***	2.843***		1.975***	2.148***
		(0.514)	(0.552)		(0.251)	(0.259)
Hour dummies	yes	yes	yes	yes	yes	yes
Adj. R^2	0.804	0.754	0.755	0.820	0.749	0.746
Log likelihood	-15,592	-15,259	-15,211	-5,744	-5,005	-5,073
F-statistic	64.540	101.316	105.574	105.284	85.146	82.805
Observations	26,484	26,484	26,484	17,592	17,592	17,592

Hourly sample; GMT time-stamps. ARDL lags chosen based on the Schwarz (Bayes) criterion (SC). HAC robust standard errors in parentheses: *** p<0.01, ** p<0.05, * p<0.1. F-statistic based on the Pesaran et al (2001) bounds test: 1% critical values 3.29 for I(0) and 4.37 for I(1).

Table 8: **Long-run liquidity dynamics in EUR/USD**

This table reports coefficients from the long-run equation of a conditional error correction model (ECM) derived from an autoregressive distributed lag (ARDL) model specification. Specifically, for the two sub-sample periods, for spot and forward markets, $P = S, F$, we estimate:

$$\Delta Spread_h^P = \alpha + \sum_{i=1}^{23} \delta_i H_i + \theta_0 Spread_{h-1}^P + \boldsymbol{\theta x_{h-1}} + \sum_{i=1}^{p-1} \boldsymbol{\gamma_i \Delta z_{h-i}^P} + \boldsymbol{\beta \Delta x_h^P} + u_h$$

where a vector $\mathbf{z_h^S} = (Spread_t^P, |Fdiscount|_t, Q_{LD,h}^P/N_{LD,h}^P, Q_{SD,h}^P/N_{SD,h}^P, Vol_h^P) = (Spread_t^P, \mathbf{x_h^P})'$ and LD, SD denotes large and small dealers. F-statistics based on the results of the bound testing procedure for long-run relationship, robust to variables being in between I(0) and I(1). Constant and coefficients on short-run effects omitted for brevity.

Sub-sample period:	2/01/2010 00:00-12/31/2014 23:00			01/01/2015 00:00-5/31/2017 23:00		
Variable:	$Spread^F$	$Spread^S$	$Spread^S$	$Spread^F$	$Spread^S$	$Spread^S$
$\|Fdiscount\|$	0.015 ***	0.029 ***	0.035 ***	-0.056 ***	-0.041 ***	-0.016 ***
	(0.006)	(0.004)	(0.004)	(0.008)	(0.010)	(0.006)
Q_{LD}^F/N_{LD}^F	-0.005 ***			0.001		
	(0.000)			(0.001)		
Q_{SD}^F/N_{SD}^F	0.004 ***		0.002 ***	0.006 ***		0.008 ***
	(0.001)		(0.001)	(0.002)		(0.002)
Vol^F	1.227 ***			0.555 ***		
	(0.149)			(0.191)		
Q_{LD}^S/N_{LD}^S		-0.002 ***	-0.002 ***		-0.003 ***	-0.004 ***
		(0.000)	(0.000)		(0.001)	(0.001)
Q_{SD}^S/N_{SD}^S		0.002 ***			-0.002 **	
		(0.001)			(0.001)	
Vol^S		1.022 ***	1.064 ***		0.395 ***	0.402 ***
		(0.104)	(0.108)		(0.076)	(0.073)
Hour dummies	yes	yes	yes	yes	yes	yes
Adj. R^2	0.276	0.277	0.276	0.348	0.361	0.353
Log likelihood	1059	1633.199	1623.145	-4900.235	-4471.512	-4562.982
F-statistic	168.86	151.13	105.57	121.20	119.04	114.97
Observations	29457	29,457	29,457	14,619	14,619	14,619

Hourly sample; GMT time-stamps. ARDL lags chosen based on the Schwarz (Bayes) criterion (SC). HAC robust standard errors in parentheses: *** p<0.01, ** p<0.05, * p<0.1. F-statistic based on the Pesaran et al (2001) bounds test: 1% critical values 3.29 for I(0) and 4.37 for I(1).

Table 9: **Forward rate bid-ask spreads and forward discounts quoted by large vs small dealers**

	JPY/USD		EUR/USD	
Dealer category:	$Spread^F$	$Fdiscount$	$Spread^F$	$Fdiscount$
Large dealers	3.344bp	-4.471bp	2.291bp	-2.950bp
Small dealers	3.517bp	-4.472bp	2.324bp	-2.952bp

Notes: Average median hourly quotes. Large dealer are banks classified as G-SIBs and appearing in the Euromoney FX Survey rankings. 2/01/2010 00:00 to 5/31/2017 23:00 sample period.

Table 10: **Forward quote dispersion of large vs small dealer quoting intensity**

This table reports coefficients from the long-run equation of a conditional error correction model (ECM) derived from an autoregressive distributed lag (ARDL) model specification. Specifically, for the two sub-sample periods, for forward markets, F, we estimate:

$$\Delta Disp^F_h = \alpha + \sum_{i=1}^{23} \delta_i H_i + \theta_0 Disp^F_{h-1} + \boldsymbol{\theta x_{h-1}} + \sum_{i=1}^{p-1} \boldsymbol{\gamma_i \Delta z^P_{h-i}} + \boldsymbol{\beta \Delta x^P_h} + u_h \tag{11}$$

where a vector $\mathbf{z^S_h} = (Disp^F_h, Q^F_{LD,t}/N^F_{LD,h}, Q^F_{SD,h}/N^F_{SD,h}, Vol^F) = (Disp^F_h, \mathbf{x^P_h})'$, $Disp^F_h$ is quote-weighted dispersion of forward rate quotes, and LD, SD denotes large and small dealers. F-statistics based on the results of the bound testing procedure for long-run relationship, robust to variables being in between I(0) and I(1). Constant and coefficients on short-run effects omitted for brevity.

Variable	$Disp^F$, JPY/USD	$Disp^F$, EUR/USD
Q^F_{LD}/N^F_{LD}	-0.002 **	-0.009 ***
	(0.001)	(0.001)
Q^F_{SD}/N^F_{SD}	-0.002	-0.004 ***
	(0.002)	(0.001)
Vol^F	23.972 ***	5.856 ***
	(5.034)	(0.782)
Hour dummies	yes	yes
Adj. R^2	0.514	0.754
Log likelihood	-101,823	-86,262
F-statistic	317.029	344.875
Observations	43,701	43,396

Hourly sample: 2/01/2010 00:00 to 5/31/2017 23:00; GMT time-stamps. ARDL lags chosen based on the Schwarz (Bayes) criterion (SC). HAC robust standard errors in parentheses: *** p<0.01, ** p<0.05, * p<0.1. F-statistic based on the Pesaran et al (2001) bounds test: 1% critical values 3.65 for I(0) and 4.66 for I(1).

Table 11: **Contagion from FX funding to market liquidity in JPY/USD**

The table shows tests for contagion from FX funding liquidity to FX market liquidity in spot and forwards. We follow Forbes and Rigobon (2002), and conduct a t-test of whether the correlations between $\Delta Fdiscount$ and $\Delta Spread^P$ is significantly more negative at quarter-ends, where $P = S, F$. The correlation coefficients are estimated using a 200-hour rolling window bi-variate VAR, and adjusted for heteroskedastic levels of volatility, thus allowing to make statements about contagions rather than a simple co-movement.

To spot market:	$\Delta Fdiscount \rightarrow \Delta Spread^S$					
	Q-end month		Prior 2 months		Contagion	
QEs:	ρ_{QE}	σ_{QE}	ρ_{NQE}	σ_{NQE}	t-stat	Reject H_0
09/14	0.004	0.009	-0.004	0.006	-14.13	
12/14	0.015	0.020	-0.019	0.015	-25.18	
03/15	0.075	0.022	0.018	0.046	-27.35	
06/15	-0.023	0.051	0.009	0.064	8.94	Yes
09/15	0.008	0.008	-0.011	0.020	-22.89	
12/15	0.020	0.057	0.013	0.066	-1.61	
03/16	0.067	0.042	-0.009	0.100	-17.41	
06/16	-0.078	0.062	-0.012	0.021	18.66	Yes
09/16	-0.007	0.053	-0.093	0.094	-19.36	
12/16	-0.044	0.046	0.014	0.058	17.36	Yes
03/17	0.024	0.081	-0.053	0.072	-15.36	
Avg. contagion	**-0.048**	**0.053**			**14.987**	**3/11 QEs**

To forward market:	$\Delta Fdiscount \rightarrow \Delta Spread^F$					
	Q-end month		Prior 2 months		Contagion	
QEs:	ρ_{QE}	σ_{QE}	ρ_{NQE}	σ_{NQE}	t-stat	Reject H_0
09/14	0.002	0.008	-0.005	0.007	-13.44	
12/14	0.012	0.019	-0.021	0.015	-25.1	
03/15	0.078	0.023	0.023	0.047	-25.66	
06/15	-0.028	0.052	0.011	0.061	10.71	Yes
09/15	0.016	0.014	-0.013	0.02	-26.63	
12/15	-0.011	0.025	0.03	0.067	14.61	Yes
03/16	0.053	0.057	-0.023	0.106	-15.23	
06/16	-0.078	0.061	-0.008	0.022	20.17	Yes
09/16	-0.008	0.076	-0.071	0.084	-12	
12/16	-0.06	0.05	-0.009	0.071	13.37	Yes
03/17	0.021	0.077	-0.059	0.066	-16.95	
Avg. contagion	**-0.044**	**0.047**			**14.715**	**4/11 QEs**

Hourly samples. Bivariate VAR, $\Delta y_h = \phi(L)\Delta y_{h-1} + \eta_h$ with $\Delta y_h = \left[\Delta Fdiscount_h, \Delta Spread_h^P\right]$, where $P = F, S$ and all endogenous variables de-seasonalised of hourly effects.

Table 12: **Contagion from FX funding to market liquidity in EUR/USD**

The table shows tests for contagion from FX funding liquidity to FX market liquidity in spot and forwards. We follow Forbes and Rigobon (2002), and conduct a t-test of whether the correlations between $\Delta Fdiscount$ and $\Delta Spread^P$ is significantly more negative at quarter-ends, where $P = S, F$. The correlation coefficients are estimated using a 200-hour rolling window bi-variate VAR, and adjusted for heteroskedastic levels of volatility, thus allowing to make statements about contagions rather than a simple co-movement.

To spot market:	$\Delta Fdiscount \rightarrow \Delta Spread^S$					
	Q-end month		Prior 2 months		Contagion	
QEs:	ρ_{QE}	σ_{QE}	ρ_{NQE}	σ_{NQE}	t-stat	Reject H_0
03/15	0.029	0.052	-0.055	0.09	-19.33	
06/15	0.086	0.089	0.082	0.126	-0.65	
09/15	0.041	0.027	-0.012	0.048	-22.99	
12/15	-0.027	0.036	-0.006	0.069	6.44	Yes
03/16	0.123	0.062	0.053	0.049	-17.68	
06/16	0.011	0.007	-0.002	0.025	-13.6	
09/16	0.039	0.03	-0.082	0.064	-42.74	
12/16	-0.106	0.081	0.039	0.047	29.35	Yes
03/17	-0.031	0.096	-0.113	0.161	-10.77	
Avg. contagion	**-0.067**	**0.059**			**17.90**	**2/9 QEs**

To forward market:	$\Delta Fdiscount \rightarrow \Delta Spread^F$					
	Q-end month		Prior 2 months		Contagion	
QEs:	ρ_{QE}	σ_{QE}	ρ_{NQE}	σ_{NQE}	t-stat	Reject H_0
03/15	0.031	0.049	-0.075	0.1	-23.54	
06/15	0.077	0.096	0.005	0.102	-11.08	
09/15	0.04	0.028	-0.04	0.058	-31.32	
12/15	-0.026	0.034	-0.025	0.066	0.32	Yes
03/16	0.152	0.067	0.052	0.046	-23.83	
06/16	-0.01	0.029	-0.003	0.027	3.58	Yes
09/16	0.053	0.031	-0.078	0.058	-48.82	
12/16	-0.105	0.08	0.025	0.047	26.43	Yes
03/17	-0.017	0.098	-0.113	0.171	-12.04	
Avg. contagion	**-0.047**	**0.048**			**10.11**	**3/9 QEs**

Hourly samples. Bivariate VAR, $\Delta y_h = \phi(L)\Delta y_{h-1} + \eta_h$ with $\Delta y_h = \left[\Delta Fdiscount_h, \Delta Spread_h^P\right]$, where $P = F, S$ and all endogenous variables de-seasonalised of hourly effects.

A Additional tables & robustness checks

Table A1: **Intraday correlation coefficient of liquidity measures by trading hour**

This table reports the average correlation coefficient by trading hour between spot market and funding liquidity ($\rho^{Fdiscount}_{Spread^S}$) and forward market and funding liquidity ($\rho^{Fdiscount}_{Spread^F}$) in two subsample periods for the JPY/USD and EUR/USD exchange rates.

	JPY/USD				EUR/USD			
GMT	Feb 2010 - Jun 2014		Jul 2014 - May 2017		Feb 2010 - Dec 2014		Jan 2015 - May 2017	
	$\rho^{Fdiscount}_{Spread^S}$	$\rho^{Fdiscount}_{Spread^F}$	$\rho^{Fdiscount}_{Spread^S}$	$\rho^{Fdiscount}_{Spread^F}$	$\rho^{Fdiscount}_{Spread^S}$	$\rho^{Fdiscount}_{Spread^F}$	$\rho^{Fdiscount}_{Spread^S}$	$\rho^{Fdiscount}_{Spread^F}$
0	-0.41	-0.47	-0.50	-0.65	0.30	0.30	-0.28	-0.40
1	-0.44	-0.50	-0.48	-0.63	0.28	0.29	-0.29	-0.41
2	-0.44	-0.50	-0.48	-0.63	0.30	0.31	-0.27	-0.40
3	-0.44	-0.49	-0.45	-0.62	0.29	0.30	-0.22	-0.35
4	-0.43	-0.49	-0.48	-0.64	0.30	0.30	-0.20	-0.34
5	-0.38	-0.44	-0.47	-0.62	0.22	0.24	-0.18	-0.34
6	-0.42	-0.47	-0.51	-0.64	0.12	0.17	-0.26	-0.41
7	-0.46	-0.50	-0.39	-0.55	0.11	0.17	-0.15	-0.32
8	-0.45	-0.48	-0.30	-0.49	0.14	0.20	-0.18	-0.33
9	-0.49	-0.52	-0.34	-0.51	0.15	0.21	-0.14	-0.30
10	-0.49	-0.51	-0.53	-0.63	0.18	0.24	-0.34	-0.45
11	-0.46	-0.49	-0.54	-0.63	0.19	0.24	-0.41	-0.51
12	-0.45	-0.50	-0.57	-0.65	0.18	0.22	-0.38	-0.48
13	-0.43	-0.50	-0.54	-0.63	0.19	0.23	-0.31	-0.42
14	-0.44	-0.51	-0.55	-0.63	0.25	0.28	-0.32	-0.42
15	-0.40	-0.47	-0.58	-0.65	0.33	0.35	-0.37	-0.46
16	-0.46	-0.52	-0.63	-0.68	0.26	0.29	-0.52	-0.58
17	-0.45	-0.52	-0.63	-0.69	0.27	0.30	-0.57	-0.61
18	-0.47	-0.53	-0.63	-0.68	0.20	0.25	-0.33	-0.41
19	-0.47	-0.53	-0.60	-0.67	0.23	0.27	-0.35	-0.42
20	-0.44	-0.51	-0.56	-0.66	0.34	0.36	-0.23	-0.31
21	-0.41	-0.47	-0.52	-0.66	0.33	0.33	-0.30	-0.39
22	-0.49	-0.54	-0.52	-0.68	0.30	0.32	-0.14	-0.27
23	-0.45	-0.50	-0.49	-0.66	0.32	0.32	-0.06	-0.20
Avg.	**-0.44**	**-0.50**	**-0.51**	**-0.63**	**0.24**	**0.27**	**-0.28**	**-0.40**

Hourly sample: 2/01/2010 00:00 to 5/31/2017 23:00; GMT time-stamps.

Table A2: **Intraday correlation coefficient of liquidity measure, by trading hour incl. CIP deviations**

This table reports the average correlation coefficient by trading hour between spot market and funding liquidity ($\rho^{CIPdev}_{Spread^S}$) and forward market and funding liquidity ($\rho^{CIPdev}_{Spread^F}$) in two sub-sample periods for the JPY/USD and EUR/USD exchange rates.

	JPY/USD				EUR/USD			
GMT	Feb 2010 - Jun 2014		Jul 2014 - May 2017		Feb 2010 - Dec 2014		Jan 2015 - May 2017	
	$\rho^{CIPdev}_{Spread^S}$	$\rho^{CIPdev}_{Spread^F}$	$\rho^{CIPdev}_{Spread^S}$	$\rho^{CIPdev}_{Spread^F}$	$\rho^{CIPdev}_{Spread^S}$	$\rho^{CIPdev}_{Spread^F}$	$\rho^{CIPdev}_{Spread^S}$	$\rho^{CIPdev}_{Spread^F}$
0	-0.37	-0.43	-0.50	-0.60	-0.41	-0.50	-0.31	-0.44
1	-0.41	-0.47	-0.49	-0.59	-0.41	-0.50	-0.33	-0.45
2	-0.42	-0.47	-0.50	-0.60	-0.38	-0.48	-0.34	-0.46
3	-0.41	-0.46	-0.47	-0.58	-0.42	-0.51	-0.28	-0.42
4	-0.41	-0.46	-0.50	-0.60	-0.40	-0.49	-0.29	-0.44
5	-0.36	-0.41	-0.48	-0.58	-0.40	-0.51	-0.26	-0.42
6	-0.39	-0.44	-0.49	-0.58	-0.38	-0.50	-0.32	-0.47
7	-0.43	-0.47	-0.40	-0.54	-0.33	-0.46	-0.24	-0.41
8	-0.41	-0.45	-0.33	-0.49	-0.30	-0.42	-0.28	-0.42
9	-0.46	-0.49	-0.37	-0.50	-0.28	-0.41	-0.25	-0.40
10	-0.45	-0.48	-0.49	-0.57	-0.29	-0.41	-0.40	-0.51
11	-0.42	-0.45	-0.50	-0.57	-0.36	-0.46	-0.44	-0.54
12	-0.41	-0.46	-0.52	-0.59	-0.35	-0.47	-0.42	-0.53
13	-0.40	-0.47	-0.48	-0.55	-0.33	-0.46	-0.37	-0.48
14	-0.40	-0.47	-0.48	-0.55	-0.27	-0.40	-0.37	-0.48
15	-0.36	-0.44	-0.51	-0.57	-0.27	-0.41	-0.43	-0.52
16	-0.41	-0.48	-0.54	-0.60	-0.37	-0.49	-0.50	-0.58
17	-0.41	-0.48	-0.54	-0.60	-0.38	-0.50	-0.53	-0.58
18	-0.43	-0.50	-0.53	-0.59	-0.33	-0.47	-0.35	-0.43
19	-0.43	-0.50	-0.50	-0.57	-0.32	-0.46	-0.36	-0.43
20	-0.40	-0.47	-0.49	-0.57	-0.33	-0.45	-0.29	-0.37
21	-0.38	-0.45	-0.44	-0.56	-0.28	-0.39	-0.27	-0.36
22	-0.46	-0.51	-0.47	-0.57	-0.29	-0.39	-0.22	-0.33
23	-0.42	-0.46	-0.49	-0.59	-0.33	-0.43	-0.18	-0.31
Avg.	**-0.41**	**-0.47**	**-0.48**	**-0.57**	**0.34**	**0.46**	**-0.33**	**-0.45**

Hourly sample: 2/01/2010 00:00 to 5/31/2017 23:00; GMT time-stamps.

Table A3: **First principal component of liquidity measures by trading hour**

This table reports the variation explained by the first principal component by trading hour between spot market and funding liquidity ($\frac{Fdiscount}{Spread^S}$) and forward market and funding liquidity ($\frac{Fdiscount}{Spread^F}$) in two sub-sample periods for the JPY/USD and EUR/USD exchange rates.

	JPY/USD				EUR/USD			
GMT	Feb 2010 - Jun 2014		Jul 2014 - May 2017		Feb 2010 - Dec 2014		Jan 2015 - May 2017	
	$\frac{CIPdev}{Spread^S}$	$\frac{CIPdev}{Spread^F}$	$\frac{CIPdev}{Spread^S}$	$\frac{CIPdev}{Spread^F}$	$\frac{CIPdev}{Spread^S}$	$\frac{CIPdev}{Spread^F}$	$\frac{CIPdev}{Spread^S}$	$\frac{CIPdev}{Spread^F}$
0	70.42	73.35	75.10	82.29	65.00	65.17	63.99	69.95
1	72.09	75.17	74.21	81.58	64.02	64.68	64.56	70.27
2	72.15	74.82	73.83	81.54	65.14	65.32	63.75	69.79
3	71.82	74.63	72.44	81.13	64.45	64.77	60.75	67.43
4	71.48	74.40	74.18	82.22	64.94	65.23	59.94	67.09
5	69.06	71.96	73.28	81.23	60.86	61.89	59.10	66.90
6	71.13	73.68	75.53	82.18	56.05	58.37	62.92	70.56
7	73.21	75.16	69.34	77.62	55.46	58.52	57.63	66.21
8	72.27	74.24	64.96	74.63	56.75	59.84	59.24	66.56
9	74.62	76.19	67.01	75.53	57.45	60.71	57.08	64.95
10	74.55	75.68	76.70	81.55	58.83	62.12	67.07	72.74
11	73.00	74.55	77.20	81.65	59.28	62.14	70.30	75.28
12	72.28	74.83	78.52	82.73	58.76	61.24	68.94	73.95
13	71.64	74.98	77.00	81.31	59.63	61.52	65.59	70.87
14	72.04	75.36	77.45	81.71	62.73	63.95	65.80	70.95
15	70.20	73.66	79.20	82.74	66.31	67.30	68.31	73.00
16	72.97	75.90	81.27	84.08	63.00	64.59	75.87	78.97
17	72.61	75.97	81.72	84.41	63.51	65.01	78.65	80.66
18	73.35	76.43	81.32	84.14	60.07	62.63	66.58	70.32
19	73.27	76.48	79.95	83.67	61.32	63.45	67.34	70.85
20	71.96	75.27	78.17	82.85	67.23	68.08	61.57	65.74
21	70.29	73.59	75.81	83.22	66.28	66.59	65.06	69.32
22	74.48	77.04	76.13	84.01	65.06	65.85	56.92	63.30
23	72.50	74.97	74.46	82.84	65.82	66.02	52.82	59.82
Avg.	**72.23**	**74.93**	**75.62**	**81.70**	**62.00**	**63.54**	**64.16**	**69.81**

Hourly sample: 2/01/2010 00:00 to 5/31/2017 23:00; GMT time-stamps.

Table A4: **First principal component of liquidity measures, by trading hour incl. CIP deviations**

This table reports the variation explained by the first principal component by trading hour between spot market and funding liquidity ($\frac{Fdiscount}{Spread^S}$) and forward market and funding liquidity ($\frac{Fdiscount}{Spread^F}$) in two sub-sample periods for the JPY/USD and EUR/USD exchange rates.

	JPY/USD				EUR/USD			
GMT	Feb 2010 - Jun 2014		Jul 2014 - May 2017		Feb 2010 - Dec 2014		Jan 2015 - May 2017	
	$\frac{Fdiscount}{Spread^S}$	$\frac{Fdiscount}{Spread^F}$	$\frac{Fdiscount}{Spread^S}$	$\frac{Fdiscount}{Spread^F}$	$\frac{Fdiscount}{Spread^S}$	$\frac{Fdiscount}{Spread^F}$	$\frac{Fdiscount}{Spread^S}$	$\frac{Fdiscount}{Spread^F}$
0	68.67	71.52	75.18	79.79	70.68	74.96	65.73	71.89
1	70.67	73.62	74.56	79.27	70.40	74.95	66.42	72.40
2	70.97	73.50	75.14	79.90	69.09	74.19	66.91	73.00
3	70.39	73.06	73.35	78.77	70.77	75.33	64.20	71.03
4	70.26	73.03	75.21	79.98	69.95	74.55	64.61	71.92
5	67.86	70.58	73.95	78.81	70.23	75.68	63.15	70.81
6	69.41	71.97	74.44	79.25	68.92	75.10	65.98	73.50
7	71.64	73.59	70.04	76.81	66.52	72.81	62.21	70.61
8	70.74	72.61	66.47	74.36	64.99	71.16	64.24	71.16
9	72.82	74.36	68.40	75.22	63.88	70.50	62.52	69.95
10	72.66	73.84	74.45	78.45	64.64	70.45	69.80	75.44
11	71.06	72.73	74.83	78.46	68.01	72.96	71.80	77.00
12	70.26	73.06	75.79	79.31	67.38	73.35	70.85	76.33
13	69.85	73.46	74.15	77.72	66.48	72.89	68.55	74.04
14	70.10	73.71	74.14	77.56	63.45	70.19	68.70	73.96
15	68.19	71.97	75.27	78.53	63.73	70.54	71.33	76.09
16	70.73	74.02	77.04	79.89	68.65	74.53	75.20	78.94
17	70.45	74.15	77.01	79.85	69.23	74.94	76.54	79.22
18	71.49	74.86	76.54	79.41	66.74	73.73	67.48	71.51
19	71.59	75.06	75.04	78.59	66.18	73.03	67.79	71.43
20	69.93	73.53	74.34	78.47	66.65	72.52	64.55	68.66
21	69.04	72.39	71.83	77.81	64.14	69.41	63.67	67.76
22	72.91	75.58	73.67	78.73	64.37	69.30	60.77	66.39
23	70.86	73.18	74.40	79.64	66.57	71.34	58.94	65.61
Avg.	**70.52**	**73.31**	**73.97**	**78.52**	**67.15**	**72.85**	**66.75**	**72.44**

Hourly sample: 2/01/2010 00:00 to 5/31/2017 23:00; GMT time-stamps.

Table A5: **Long-run dynamics in JPY/USD incl. CIP Deviation**

This table reports coefficients from the long-run equation of a conditional error correction model (ECM) derived from an autoregressive distributed lag (ARDL) model specification. Specifically, for the two sub-sample periods, for spot and forward markets, $P = S, F$, we estimate:

$$\Delta Spread_h^P = \alpha + \sum_{i=1}^{23} \delta_i H_i + \theta_0 Spread_{h-1}^P + \boldsymbol{\theta x_{h-1}} + \sum_{i=1}^{p-1} \boldsymbol{\gamma_i \Delta z_{h-i}^P} + \boldsymbol{\beta \Delta x_h^P} + u_h$$

where a vector $\mathbf{z_h^S} = (Spread_h^P, |CIPdev|_h, Q_{LD,h}^P/N_{LD,h}^P, Q_{SD,h}^P/N_{SD,h}^P, Vol_h^P) = (Spread_h^P, \mathbf{x_h^P})'$ and LD, SD denotes large and small dealers. F-statistics based on the results of the bound testing procedure for long-run relationship, robust to variables being in between I(0) and I(1). Constant and coefficients on short-run effects omitted for brevity.

	2/01/2010 00:00 6/30/2014 23:00			7/01/2014 00:00 5/31/2017 23:00		
Variable:	$Spread^F$	$Spread^S$	$Spread^S$	$Spread^F$	$Spread^S$	$Spread^S$
$\|CIPdev\|$	-0.022 ***	-0.013 ***	-0.013 ***	-0.009 ***	-0.005 ***	-0.006 ***
	(0.003)	(0.002)	(0.002)	(0.001)	(0.001)	(0.001)
Q_{LD}^F/N_{LD}^F	-0.007 ***			-0.001		
	(0.001)			(0.001)		
Q_{SD}^F/N_{SD}^F	0.015 ***		0.008 ***	0.011 ***		0.009 ***
	(0.005)		(0.003)	(0.003)		(0.002)
Vol^F	1.202			2.453 ***		
	(0.862)			(0.382)		
Q_{LD}^S/N_{LD}^S		-0.008 ***	-0.007 ***		-0.002 ***	-0.002 ***
		(0.000)	(0.000)		(0.000)	(0.000)
Q_{SD}^S/N_{SD}^S		0.003 ***			0.002 ***	
		(0.001)			(0.000)	
Vol^S		2.635 ***	3.005 ***		1.981 ***	2.183 ***
		(0.524)	(0.565)		(0.265)	(0.289)
Hour dummies	yes	yes	yes	yes	yes	yes
Adj. R^2	0.276	0.280	0.282	0.264	0.280	0.273
Log likelihood	-15598.35	-15256.36	-15209.2	-5756.013	-5011.41	-5095.461
F-statistic	143.269	152.287	158.901	89.809	104.496	92.531
Observations	26,484	26,484	26,484	17,592	17,592	17,592

Hourly sample; GMT time-stamps. ARDL lags chosen based on the Schwarz (Bayes) criterion (SC). HAC robust standard errors in parentheses: *** p<0.01, ** p<0.05, * p<0.1. F-statistic based on the Pesaran et al (2001) bounds test: 1% critical values 3.29 for I(0) and 4.37 for I(1).

Table A6: **Long-run dynamics in EUR/USD incl. CIP Deviation**

This table reports coefficients from the long-run equation of a conditional error correction model (ECM) derived from an autoregressive distributed lag (ARDL) model specification. Specifically, for the two sub-sample periods, for spot and forward markets, $P = S, F$, we estimate:

$$\Delta Spread_h^P = \alpha + \sum_{i=1}^{23} \delta_i H_i + \theta_0 Spread_{h-1}^P + \boldsymbol{\theta x_{h-1}} + \sum_{i=1}^{p-1} \boldsymbol{\gamma_i \Delta z_{h-i}^P} + \boldsymbol{\beta \Delta x_h^P} + u_h$$

where a vector $\mathbf{z_h^S} = (Spread_h^P, |CIPdev|_h, Q_{LD,h}^P/N_{LD,h}^P, Q_{SD,h}^P/N_{SD,h}^P, Vol_h^P) = (Spread_h^P, \mathbf{x_h^P})'$ and LD, SD denotes large and small dealers. F-statistics based on the results of the bound testing procedure for long-run relationship, robust to variables being in between I(0) and I(1). Constant and coefficients on short-run effects omitted for brevity.

Sub-sample period:	2/01/2010 00:00-12/31/2014 23:00			01/01/2015 00:00-5/31/2017 23:00		
Variable	$Spread^F$	$Spread^S$	$Spread^S$	$Spread^F$	$Spread^S$	$Spread^S$
$\|CIPdev\|$	-0.009 ***	-0.005 ***	-0.006 ****	-0.009 ***	-0.005 ***	-0.003 ***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Q_{LD}^F/N_{LD}^F	-0.005 ***			0.002 **		
	(0.000)			(0.001)		
Q_{SD}^F/N_{SD}^F	0.002 **		0.0004	0.005 **		0.008 ***
	(0.001)		(0.001)	(0.002)		(0.002)
Vol^F	0.836 ***			0.430 ***		
	(0.117)			(0.149)		
Q_{LD}^S/N_{LD}^S		-0.002 ***	-0.001 ***		-0.003 ***	-0.004 ***
		(0.000)	(0.000)		(0.001)	(0.001)
Q_{SD}^S/N_{SD}^S		0.003 ***			-0.001	
		(0.001)			(0.000)	
Vol^S		0.875 ***	0.891 ***		0.304 ***	0.379 ***
		(0.102)	(0.108)		(0.063)	(0.069)
Hour dummies	yes	yes	yes	yes	yes	yes
Adj. R^2	0.279	0.277	0.276	0.349	0.361	0.353
Log likelihood	1108.006	1633.038	1614.414	-4896.476	-4469.675	-4559.083
F-statistic	181.748	157.440	171.008	127.282	120.854	113.515
Observations	29,457	29,457	29,457	14,619	14,619	14,619

Hourly sample; GMT time-stamps. ARDL lags chosen based on the Schwarz (Bayes) criterion (SC). HAC robust standard errors in parentheses: *** p<0.01, ** p<0.05, * p<0.1. F-statistic based on the Pesaran et al (2001) bounds test: 1% critical values 3.29 for I(0) and 4.37 for I(1).

Table A7: **Contagion from FX funding to market liquidity in JPY/USD**, incl. CIP Deviations

The table shows tests for contagion from FX funding liquidity to FX market liquidity in spot and forwards. We follow Forbes and Rigobon (2002), and conduct a t-test of whether the correlations between $\Delta CIPDev$ and $\Delta Spread^P$ is significantly more negative at quarter-ends, where $P = S, F$. The correlation coefficients are estimated using a 200-hour rolling window bi-variate VAR, and adjusted for heteroskedastic levels of volatility, thus allowing to make statements about contagions rather than a simple co-movement.

To spot market:	$\Delta CIPDev \rightarrow \Delta Spread^S$					
	Q-end month		Prior 2 months		Contagion	
QEs:	ρ_{QE}	σ_{QE}	ρ_{NQE}	σ_{NQE}	t-stat	Reject H_0
09/14	0.007	0.012	-0.006	0.011	-17	
12/14	0.019	0.021	-0.02	0.024	-24.53	
03/15	0.035	0.045	0.024	0.059	-3.16	
06/15	-0.01	0.054	0	0.058	2.63	Yes
09/15	0.005	0.008	-0.009	0.02	-17.2	
12/15	0.029	0.042	0.027	0.054	-0.55	
03/16	0.027	0.05	-0.008	0.097	-7.8	
06/16	-0.075	0.087	-0.008	0.021	13.74	Yes
09/16	0.005	0.052	-0.081	0.081	-20.75	
12/16	-0.077	0.047	0.004	0.049	24.97	Yes
03/17	-0.015	0.08	-0.051	0.068	-7.3	
Avg. contagion	**-0.054**	**0.063**			**13.78**	**3/11 QEs**

To forward market:	$\Delta CIPDev \rightarrow \Delta Spread^F$					
	Q-end month		Prior 2 months		Contagion	
QEs:	ρ_{QE}	σ_{QE}	ρ_{NQE}	σ_{NQE}	t-stat	Reject H_0
09/14	0.005	0.011	-0.007	0.011	-16.37	
12/14	0.015	0.02	-0.023	0.022	-25.04	
03/15	0.037	0.044	0.03	0.06	-2.04	
06/15	-0.015	0.056	0.002	0.055	4.39	Yes
09/15	0.014	0.014	-0.011	0.02	-23.29	
12/15	0.004	0.02	0.044	0.052	17.92	
03/16	0.029	0.064	-0.012	0.093	-8.24	
06/16	-0.059	0.099	-0.01	0.03	8.71	Yes
09/16	0.035	0.081	-0.029	0.086	-11.64	
12/16	-0.088	0.045	-0.013	0.059	22.45	Yes
03/17	-0.021	0.075	-0.054	0.065	-7.18	
Avg. contagion	**-0.054**	**0.067**			**11.85**	**3/11 QEs**

Hourly samples. Bivariate VAR, $\Delta y_h = \phi(L)\Delta y_{h-1} + \eta_h$ with $\Delta y_h = \left[\Delta CIPDev_h, \Delta Spread_h^P\right]$, where $P = F, S$ and all endogenous variables de-seasonalised of hourly effects.

Table A8: **Contagion from FX funding to market liquidity in EUR/USD**, incl. CIP Deviations

The table shows tests for contagion from FX funding liquidity to FX market liquidity in spot and forwards. We follow Forbes and Rigobon (2002), and conduct a t-test of whether the correlations between $\Delta CIPDev$ and $\Delta Spread^P$ is significantly more negative at quarter-ends, where $P = S, F$. The correlation coefficients are estimated using a 200-hour rolling window bi-variate VAR, and adjusted for heteroskedastic levels of volatility, thus allowing to make statements about contagions rather than a simple co-movement.

To spot market:	$\Delta CIPDev \rightarrow \Delta Spread^S$					
	Q-end month		Prior 2 months		Contagion	
QEs:	ρ_{QE}	σ_{QE}	ρ_{NQE}	σ_{NQE}	t-stat	Reject H_0
03/15	0.015	0.034	-0.064	0.108	-18.150	
06/15	0.112	0.051	0.043	0.123	-12.910	
09/15	0.021	0.043	-0.003	0.053	-7.860	
12/15	-0.033	0.044	-0.005	0.067	7.810	Yes
03/16	0.126	0.053	0.054	0.046	-21.090	
06/16	0.011	0.007	-0.002	0.023	-14.040	
09/16	0.044	0.037	-0.080	0.065	-40.060	
12/16	-0.123	0.072	0.040	0.058	35.020	
03/17	-0.039	0.041	-0.074	0.150	-6.120	Yes
Avg. contagion	**-0.078**	**0.058**			**21.42**	**2/9 QEs**

To forward market:	$\Delta CIPDev \rightarrow \Delta Spread^F$					
	Q-end month		Prior 2 months		Contagion	
QEs:	ρ_{QE}	σ_{QE}	ρ_{NQE}	σ_{NQE}	t-stat	Reject H_0
03/15	0.019	0.034	-0.073	0.11	-20.89	
06/15	0.101	0.049	0.009	0.114	-18.58	
09/15	0.021	0.042	-0.027	0.062	-15.2	
12/15	-0.04	0.04	-0.021	0.064	5.46	Yes
03/16	0.153	0.058	0.053	0.043	-27.12	
06/16	-0.01	0.029	-0.003	0.025	3.64	Yes
09/16	0.057	0.036	-0.07	0.063	-42.09	
12/16	-0.11	0.071	0.029	0.057	30.59	Yes
03/17	-0.043	0.039	-0.074	0.159	-5.14	
Avg. contagion	**-0.053**	**0.047**			**13.23**	**3/9 QEs**

Hourly samples. Bivariate VAR, $\Delta y_h = \phi(L)\Delta y_{h-1} + \eta_h$ with $\Delta y_h = \left[\Delta CIPDev_h, \Delta Spread_h^P\right]$, where $P = F, S$ and all endogenous variables de-seasonalised of hourly effects.