FX Premia Around the Clock

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ABSTRACT

We dissect return dynamics in the foreign exchange market into high-frequency components over the 24-hour day. Using twenty-five years of data on G10 currencies we show that the dollar portfolio follows a systematic *'W'* shaped return pattern over the trading day. Between U.S. closing and Asian opening the dollar appreciates, in Asian trading hours the dollar depreciates, between European opening and U.S. opening hours the dollar appreciates while during regular U.S trading hours the dollar depreciates. The net effect of this pattern is that investors obtain positive average returns for going long foreign currencies during U.S. trading hours, whereas overnight returns are negative. Exploiting a risk premium decomposition, we show that long and short legs of carry and dollar carry strategies also follow a *'W'* shaped intraday return pattern, albeit with loadings that generate orthogonal components. Tracking these returns throughout the day we find that 80% of carry profits are generated U.S. hours whereas 70% of dollar carry returns are generated during European trading hours. Finally, we show these patterns are exploitable by a subset of investors, such as market makers and large institutional investors, who face lower than average transaction costs.

Keywords: foreign-exchange, intraday and overnight returns, high-frequency data, carry trade, funding costs.

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Empirical work on exchange rates and currency markets is typically based on daily (or monthly) currency returns that are measured at the London fixing time (i.e., 4:00 p.m. U.K. time).[1] However, the foreign exchange market trades continuously on a 24-hour decentralised basis between participants spread across the globe and in different time zones. For example, of the global estimated \$6.6 trillion daily turnover, around \$1.2 trillion is traded during U.S. hours, roughly \$2.4 trillion during London hours, and the remaining volume of \$3.0 trillion is distributed across a large number of local markets (see BIS (2016)).

In this paper, we study currency returns at high-frequency intervals around the clock and ask whether the 24-hour nature of currency trading has a bearing on our understanding of the market. Indeed, given the geographical nature of foreign exchange trade, it is natural to study exchange rate dynamics throughout the trading day. Developing this theme, we begin by documenting the following stylised facts:

1. FX returns vary systematically over the course of a 24-hour period in four distinct regions with turning points that coincide with market opening hours in (*i*) Australia/New Zealand; (*ii*) Asia; (*iii*) Europe and (*iv*) the U.S.

2. Between U.S. closing and Asian opening hours and between European opening and U.S. opening hours the U.S. dollar appreciates versus *all* currencies. During the remaining periods, i.e., between Asian opening and European opening hours and during the intraday period in the U.S., the U.S. dollar depreciates against almost all currencies

3. Taken together, foreign currencies appreciate vis-á-vis the U.S. dollar on average during U.S. trading hours and depreciate overnight, displaying a '*W*'-shaped return pattern within each 24-hour trading period.

4. Exploiting the Hassan and Mano (2018) decomposition we trace returns to well known strategies designed to harvest currency risk premia and show that: (*i*) over 75% of carry returns can be attributed to the U.S. intraday period, while (*ii*) returns to the forward premium and the dollar carry trades are generated during European trading hours and mostly before the U.S. markets open.

[1] See, e.g., Thomson Reuters (2017).

To establish these facts we construct a panel of 5-minute spot returns around the clock using high-frequency data on a set of nine currencies vis-à-vis the U.S. dollar: the Australian dollar (AUD), the Canadian dollar (CAD), the euro (EUR), the British pound (GBP), the Japanese yen (JPY), the New Zealand dollar (NZD), the Norwegian krone (NOK), the Swedish krona (SEK), and the Swiss franc (CHF). Our sample period spans January 1994 to December 2018 during which these pairs cover approximately 67% of the total daily turnover in the foreign exchange market (see BIS (2016)).

Equipped with an intra-day panel of FX returns, we first construct close-to-close returns or spot rate changes sampled at 5:00 p.m. Eastern Standard Time (EST), as opposed to the London fixing time sampling at 4:00 p.m. GMT that is generally used in the literature. We choose 5:00 p.m. EST as our closing time as this coincides with the end of the main trading hours in New York which also coincides with the end of trading of currency derivatives on the Chicago Mercantile Exchange. We label 'intraday' the period that coincides with U.S. trading hours whereas the remaining hours that contain three distinct periods are labelled as 'overnight'. A detailed description of the stylised facts listed above is as follows.

G10 currency pairs display a systematic sequence of appreciation and depreciation marked by the opening and closing times of major trading venues. After trading in New York closes and the trading day in Sydney starts, all foreign currencies in the sample depreciate vis-à-vis the U.S. dollar. Between the start of the trading day in Southeast Asia (Singapore/Hong Kong) and Europe (London/Frankfurt) a distinct reversal in the return patterns occurs. All currencies show a strong appreciation vis-à-vis the U.S. dollar that lasts until the early morning hours of the next day. Then, coinciding with the opening of trading venues in Europe, foreign currencies depreciate until New York trading begins. This trend is particularly strong for European currencies, but it is quite pervasive qualitatively across the entire currency cross-section. With the beginning of trading activity in New York, a last significant return reversal can be observed and (almost) all foreign currencies exhibit a strong appreciation vis-à-vis the U.S. dollar. The relative increase in the value of foreign currencies against the U.S. dollar lasts until New York trading activity ceases and, with the start of a new trading day, foreign currencies depreciate again. These systematic reversal patterns are striking in both economic and statistical terms.

In particular, a portfolio that invests in all foreign currencies in equal amounts (i.e., the dollar portfolio) also inherits the *'W'*-shaped return pattern. Furthermore, a principal components analysis also reveals the robustness of the main result across various sampling frequencies. We extract principal components not only from the high-frequency data but also from daily and monthly foreign exchange returns. Regardless of the sampling frequency, the first principal component remains virtually unchanged and the estimated correlation coefficient is above 99% as we move from higher to lower frequency. Moreover, the correlation between the first principal component and the dollar portfolio is also as high as 99%. While we know from the existing literature that the first principal component extracted from monthly data essentially picks up the average appreciation or depreciation of foreign currencies against the U.S. dollar, it is not immediately obvious that the first principal components from different sampling frequencies should be as highly correlated as they are. In this regard, our paper is related to Fourel, Rime, Sarno, Schmeling, and Verdelhan (2018) who show that the dollar portfolio is a strong predictor of currency returns during the day and across different sampling frequencies. However, we highlight the diverging return patterns during the day and overnight, and document how the returns patterns exhibited by the dollar portfolio differ from the patterns of conditional currency strategies.

Next we exploit the Hassan and Mano (2018) decomposition that largely encompasses the existing traditional literature with regards to violations of the expectations hypothesis, the forward premium puzzle, the carry trade, and the dollar carry trade (see, e.g., Fama (1984), Lustig, Roussanov, and Verdelhan (2011), and Lustig, Roussanov, and Verdelhan (2014)). We find that returns to the carry trade are mostly generated during the intraday period. On the other hand, returns to the forward premium trade that is designed to exploit the failure of uncovered interest rate parity are generated before U.S. markets open but while European markets are already trading. Returns to the dollar carry trade follow the same pattern as we show that the dollar carry portfolio largely coincides with the forward premium portfolio over our sample period. We also revisit some early results with regards to the forward premium puzzle and the carry trade and show that the expectations hypothesis thesis is rejected using close-to-close returns exactly because the loading in the forecasting regression is far from one, in both economic and statistical terms, during the intraday period while we cannot reject a loading of one overnight. Furthermore, we show that sorting currencies into portfolios based on their forward discount as in Lustig, Roussanov, and Verdelhan (2011) leads to a significant spread between the high and the low interest rate portfolio during intraday periods only.

The intraday behaviour of the various currency strategies is quite distinct on average from the behaviour of the unconditional dollar portfolio. In fact, neither the carry trade, the forward premium trade, nor the dollar carry trade exhibit a distinct *'W'*-shaped pattern. However, all the currency strategies have a short and a long leg even though not all of them are zero cost strategies. And, given the results for the dollar portfolio, it is not very surprising that both the short and the long leg exhibit very clear *'W'* patterns. The fact that the net effect for any of the long-short strategies is not zero informs about how returns to the well-known trading strategies are generated over the course of a 24 hour period.

In summary, we find distinctly different foreign exchange return dynamics depending on whether we consider intraday or overnight periods within a 24-hour window. Some of the known results based on daily data are almost entirely due to what happens during the intraday or overnight periods, respectively. As we show in an extensive set of robustness tests, these price dynamics of the U.S. dollar vis-á-vis foreign currencies are robust across trading days, different periods of the year, and largely consistent across the sample period of twenty-four years. Further, the systematic up- and downswings of the dollar portfolio are not driven by one particular currency pair, but hold independent of the sub-set of G10 currencies that we consider. Further, find a *'W'*-shaped return pattern in U.S. dollar denominated futures traded on the Chicago Mercantile Exchange (CME), highlighting that the diverging intraday and overnight pattern is not solely limited to spot markets, but representative of wider intraday return dynamics across foreign exchange instruments priced vis-á-vis the U.S. dollar.

Finally, we assess the profitability of simple intraday trading strategies that require daily rebalancing and exploit systematic overnight and intraday price trends of foreign currencies vis-à-vis the U.S. dollar. In line with previous studies (e.g., Menkhoff, Sarno, Schmeling, and Schrimpf (2012), Lustig, Roussanov, and Verdelhan (2011)) we use the bid-ask spread as a proxy of transaction costs and we consider different magnitudes of the spread that have been argued to accurately proxy trading costs faced by dealers in the FX market (Gilmore and Hayashi (2011), Gargano, Riddiough, and Sarno (2017)). Even though intraday trading strategies require daily rebalancing of the intraday and overnight portfolio, we document that the most liquid exchange rates (CHF, EUR, GBP) generate positive net returns in both intraday periods. An equally-weighted portfolio of these currency pairs leads to 3.50% and 2.41% average annualized net returns during the day and overnight, respectively. These profits are obtained by holding long foreign currency positions during the day and by investing into the dollar during the night and result in annualized Sharpe ratios between 0.12 (CHF) and 0.43. Further, if one adjusts the bid-ask spread to the least conservative magnitude suggested by the literature and more representative of competitive spreads of market makers and large institutions, we document positive Sharpe ratios for six out of the nine currencies. The annualized risk-adjusted returns range between 0.17 (JPY) and 0.77 (GBP) during the day, while short positions over night lead to Sharpe ratios between 0.13 (AUD) and 0.77 (GBP). Our simple assessment points toward the profitability of intraday trading strategies in the FX spot market and it indicates that persistent intraday price trends can be successfully exploited by market participants.

The structure of this paper is organized as follows: In Section I we describe the data, while Section II presents the empirical design and discusses how we choose the sub-periods over the 24-hour window. Section III summarizes an extensive set of robustness checks. Section IV describes the results with respect to currency risk premia during the intraday versus overnight period. Section V shows whether the *'W'*-pattern can be exploited in a trading strategy and Section VI concludes.

Literature Review

Our work is related to a recently growing literature that assesses the diverging intraday and overnight returns in U.S. equity markets. Cliff, Cooper, and Gulen (2008) document that individual stocks, stock indices and stock index futures yield higher returns during the overnight non-trading period compared to the regular U.S. trading-hours. They examine potential causes for the large overnight return and find that neither volatility nor liquidity premia can explain this finding. Kelly and Clark (2011) also study overnight returns in the context of ETFs and shows that risk adjusted returns of stocks held overnight vastly exceeds the returns during regular trading hours. They argue that undiversified semi-professional/noise traders could possibly explain their finding if they liquidate their positions before market close. Relatedly, Della Corte, Kosowski, and Wang (2015) assess the impact of market openings and closures on returns of international stocks and futures across various asset classes. They show that a overnight-intraday strategy that forms intraday portfolios based on overnight signals outperforms conventional short-term reversal strategies.

More recently, Lou, Polk, and Skouras (2017) document a diverging return pattern between intraday and overnight returns for equities and they provide evidence for strong reversal patterns between intraday and overnight returns. Bogousslavsky (2018) reports large variations in intraday and overnight stock returns for various portfolio compositions: Portfolios based on size and illiquidity earn their return just before the market close while others accrue their return gradually throughout the day. The author argues some of these patterns can be explained by information asymmetry around market closures. Related to these papers, Hendershott, Livdan, and Rösch (2018) discuss the implications of the intraday return pattern for the capital asset pricing model (CAPM) and confirm its validity during overnight hours.

In contrast to studies on equity markets, comprehensive empirical evidence on intraday return patterns in the FX market is limited. What is more, to the best of our knowledge no study up to today has explored the implications of systemic intraday return patterns for widely-applied FX trading strategies. While it has been proven that strategies such as carry or dollar carry are profitable at daily or lower frequencies, it is unknown what hour of the day most of the currency risk premia are generated. Our paper aims to fill these gaps and seeks to improve our understanding of intraday FX returns. Furthermore, as the determinants of the intraday return pattern are largely unknown to academics and practitioners, we discuss underlying driving forces of returns and identify the most profitable trading hours of the day for carry and dollar carry.

Related to our study is early existing work on FX intraday returns such as Cornett,Schwarz, and Szakmary (1995) who document similar patterns using hourly data for the period 1977 to 1991. Further, Ranaldo (2009) argues that currencies tend to depreciate during local trading hours, and appreciate during the main trading hours of foreign markets. Breedon and Ranaldo (2013) extend the same result for the period 1997 to 2007 and link return patterns to order flow dynamics. Similarly, Jiang (2017) relates systematic return dynamics to different time zones of local markets and argues intraday patterns are driven by market segmentation and costs of financial intermediation. With respect to these papers, our contribution is at least three-fold: First, we provide a more granular dissection of close-to-close returns into daily sub-periods and unveil a 'W' shaped intraday return pattern for most individual currencies and for an unconditional dollar portfolio; Second, we make the connection that close-to-close returns, exclusively employed by the extant empirical literature, provide a distorted view of currency risk premia since they are the sum of potentially drastically different return dynamics. Third, we document that foreign currencies do not only depreciate during the opening hours of their respective local market, but that G10 currencies almost collectively follow return reversals at similar points in time over the day.

Further, our work distinguishes itself from aforementioned studies by examining the dynamics of currency premia from trading strategies over the course of the day. We first build upon Lyons and Rose (1995) and Chaboud and Wright (2005) and re-visit the Fama (1984) regressions in view of the documented intraday-overnight spread. We find that the expectation hypothesis largely holds overnight, and that differences between forward rates and expected future spot rates appears to largely emerge during the day.

Next, in contrast to all earlier work on intraday returns, we re-visit conventional trading strategies such as carry (Lustig and Verdelhan (2007)) and dollar carry (Lustig, Roussanov, and Verdelhan (2014)). While the original empirical assessments are based on conventional close-to-close returns and largely conducted at the monthly frequency, we examine the return generating process of portfolio returns over the course of the trading day. In particular, we discuss differences between overnight and intraday returns of carry and dollar carry portfolios and document how these strategies perform at specific hours of the day. As our data includes information until December 2017, we also re-assess the profitability of these strategies in the post-financial crisis period and link our findings to institutional characteristics of the foreign exchange market.

I. Data

The empirical analysis is based on one of the most comprehensive high-frequency foreign exchange quotes data set analysed to date and is constructed from two high-quality data sources. Our full sample starts in January 1994 and ends in December 2018, covering 25 years of high-frequency tick-by-tick data for the G10 currencies, including the Australian dollar (AUD), the Canadian dollar (CAD), the euro (EUR), the Japanese yen (JPY), the New Zealand dollar (NZD), the Norwegian krona (NOK), the Swedish krona (SEK), the Swiss franc (CHF), and the British pound (GBP), vis-à-vis the U.S. dollar. These currencies are consistently among the most liquid currencies over the sample period and together they account for approximately 67% of the total daily turnover in the foreign exchange market according the latest triannual BIS survey (see BIS (2016)). Our main data source for exchange rate data is the Thomson Reuters Tick History (TRTH) database which provides indicative quotes for all G10 currencies from January 1999 to December 2018. To extend the length of our sample period, we supplement the TRTH data for the January 1994 to December 1998 period with quotes from Olsen & Associates.[2] For both data sets we obtain the best bid and ask quote recorded to the nearest even second. After applying a number of filters to correct the data for outliers, the price at each five-minute tick is obtained by linearly interpolating from the average of the bid and ask quotes for the two closest ticks. If no quote was submitted during a specific interval, we fill the gap with the most recent available price. The quotes are then used to construct the mid prices as well as the currencies' net returns at five minute intervals. In addition, the bid-ask prices also allow to calculate returns net of transaction costs. Following previous studies (e.g. Andersen, Bollerslev, Diebold, and Vega (2003)) we exclude quotes that are submitted on days that are associated with low trading activity. We remove all quotes on weekends between Friday 5:00 p.m. and Sunday 5:05 p.m. (Eastern Standard Time, EST). Similarly, we drop information around fixed holidays, i.e., Christmas (24 to 26 December), New Year (31 December to 2 January), and 4 July, and around flexible holidays, such as Good Friday, Easter Monday, Memorial Day, Labor Day, and Thanksgiving (including the day after). We express all spot rates in U.S. dollar per foreign currency. Hence, an increase of the (log) exchange rate s_t can be interpreted as an appreciation of the U.S. dollar vis-à-vis the foreign currency.

In addition to the data on quoted spot prices, we also use daily spot and 1-month forward rates from WM/Reuters via *Datastream* to calculate the monthly forward discounts at the daily frequency.[3] The WM/Reuters data is based on the London fixing time and, thus, sampled at 4:00 p.m. GMT. As we sample daily spot rates at 5:00 p.m. (EST) using data from TRTH, it arises a slight disconnect in the sampling time between the spot and the forward discount from WM/ Reuters commonly used in the literature. Yet, for the sample period after 1998 we can also obtain high-frequency 1-month currency swap points from TRTH to construct 1-month forward rates at

[2] We obtain information on spot quotes from both data sources for a long overlapping period that covers all months between June 1996 and December 2014 and we confirm that returns are very highly correlated, even at high intraday frequencies. Consequently, results do not depend on the data source.

[3] As WM/Reuters data is only available from January 1997 onwards, we use Barclays BBI spot and forward rates for the period from January 1994 to December 1996.

arbitrary times in the day.[4] This additional information allows to get forward discounts in line with the daily spot rates we use in the empirical analysis. However, for our benchmark results we stick with the WM/Reuters forward discounts but we verify for the common sample period that the results remain qualitatively and quantitatively the same if we use the forward discounts sampled at 5:00 p.m. New York time.[5]

Following a vast literature (see, e.g., Menkhoff, Sarno, Schmeling, and Schrimpf (2012), and Mueller, Tahbaz-Salehi, and Vedolin (2017)), the monthly foreign currency excess return (rx_{t+1}) from a strategy that buys a currency at the forward rate in period t (f_t) and sells it at the spot rate in period $t+1$ (s_{t+1}) is defined as $rx_{t+1} = f_t - s_{t+1}$. To be able to account for return dynamics in distinct intraday periods, we construct excess returns in terms of the difference of the forward discount and the future change in the spot rate $rx_{t+1} = f_t - s_t - \Delta s_{t+1}$. This means we combine the forward discount from *Datastream* ($f_t - s_t$) with intraday return dynamics constructed using the high-frequency data (Δs_{t+1}). We assume that the interest rate differential is earned linearly over the period that the currency position is held as we do not have high frequency interest rates.[6] As the excess return is defined for a long position in the foreign currency vis-à-vis the U.S. dollar we use the negative of exchange rate changes ($-\Delta s_{t+1}$) to keep a consistent interpretation between currency changes and currency excess returns (note that the $-\Delta s_{t+1}$ also appears in the expression for the currency excess return).[7]

II. Dissecting Currency Returns

In this section we discuss the definition of close-to-close returns and the dissection into different intraday components. Subsequently, we provide a comparison of these return series, illustrate their developments over the sample period, and describe discrepancies and commonalities between

[4] In order to obtain the outright forward rate, the quoted swap points are simply added to the spot rate quote.

[5] Unlike it is the case for the spot rates, the swap points barely move during the day. This means that any significant intraday patterns in the dynamics of the forward rates are due movements in the underlying spot rates and not the forward discount. As the existing literature almost exclusively uses the WM/Reuters data and results do not depend on the sampling time we decide to not introduce novel data for the forward rates. We report the results using the forward rates sampled at 5:00 p.m. New York time in the Online Appendix as a robustness check.

[6] Furthermore, we explicitly assume that covered interest parity (CIP) holds and that the nominal interest rate differential between foreign (i^*) and domestic country (i) equals the forward discount: $i_t^* - i_t = f_t - s_t$. As shown by Akram, Rime, and Sarno (2008), at lower frequencies CIP tends to hold for major currency pairs.

[7] We use the terms "currency spot changes" and "currency returns" interchangeably and these are not the same as "currency excess returns" that take the interest rate differential into account.

returns that are generated during certain times of the day.

A. Intraday Return Dynamics

Equipped with equally-spaced 5-min spot rates for some of the most important currency pairs in the FX market, we define daily close-to-close log spot returns (Δs_d^{CTC}) as the percent change in the mid-price between 5:00 p.m. on day d and 5:00 p.m. (EST) on day $d-1$

$$\Delta s_d^{CTC} = s_d^{5:00p.m.} - s_{d-1}^{5:00p.m.}. \tag{1}$$

Our choice of closing time differs from the "London fix" time at 4:00 p.m. GMT normally employed in studies using FX data. However, we show as a robustness check that results for daily close-to-close currency returns are virtually identical if the standard data available from Datastream is used.

Next, we dissect daily currency returns into an intraday and an overnight component. While trading in currency markets takes place around the clock on almost every day of the week, we take the perspective of a U.S. investor that is based in New York and we define the beginning and ending of the intraday period as 8:00 a.m. and 5:00 p.m. (EST), respectively. In line with previous studies (e.g., Gargano, Riddiough, and Sarno (2017)) we assume that these hours capture the most active trading period in the spot market for New York based market participants. Further, these trading hours overlap to a large extent with the opening hours of the Chicago Mercantile Exchange, on which various currency derivatives are actively traded. Our definition of the intraday period of the spot market, therefore, also includes the start and end of trading activity of FX forwards, futures and options which have an impact on the price discovery process of currencies vis-a-vis the U.S. dollar in the spot market (Rosenberg and Traub (2009)).[8] In robustness tests we employ alternative intraday and overnight specifications, based on quote currencies' domestic trading hour as in Breedon and Ranaldo (2013) and we find that results are qualitatively unchanged.

While the intraday period captures the main spot trading activity in New York, the overnight window is defined as the remaining period between 5:00 p.m. on day d and 8:00 a.m. on day $d+1$. This window comprises all opening times and some of the closing times of the major FX trading

[8] An overview of currency futures trading hours can be found at `http://www.cmegroup.com/trading-hours.html#fx`.

venues located outside of the U.S. (see, e.g., BIS (2016)). We define three further sub periods: The first period starts with the opening of markets in Sydney and ends when trading Singapore and Hong Kong starts (5:00 p.m.–9:00 p.m., EST). The second period then includes the early trading hours in Southeast and East Asia (including Tokyo) and ends before trading in Europe commences (9:00 p.m.–3:00 a.m., EST). The final subperiod then includes the early European trading hours and ends before markets in the U.S. open again (1:00–8:00 a.m., EST). While the majority of our analysis focuses on the diverging patterns between the intraday and overnight period, we also provide insights on return movements associated with these three overnight subperiods that are related to the start of trading in the respective major trading venue commences.[9] More formally, we define intraday (ID) and overnight (ON) returns in the following way:

$$\Delta s_d^{ID} = s_d^{5:00p.m.} - s_d^{8:00a.m.} \qquad \Delta s_d^{ON} = s_d^{8:00a.m.} - s_{d-1}^{5:00p.m.}$$

where $\Delta s_{d,i} = s_{d,i} - s_{d,i-1}$ refers to the five-minute log spot return on day d between the five minute interval i and $i-1$. Having the intraday versus overnight split we then aggregate all daily (log) returns within every month ($d \in t$) to a monthly frequency as follows:

$$\Delta s_t^{CTC} = \sum_{d \in t} \Delta s_d^{CTC} \qquad \Delta s_t^{ID} = \sum_{d \in t} \Delta s_d^{ID} \qquad \Delta s_t^{ON} = \sum_{d \in t} \Delta s_d^{ON}$$

where Δs_t^j, with $j = CTC, ID, ON$, denotes the log returns in month $t$that is the sum of all daily (d) log returns (Δs_d^j) within the month. It is worth noting that our approach ensures that the sum of the intraday and overnight return components on a daily level equal exactly to the close-to-close return (i.e. $\Delta s_d^{ID} + \Delta s_d^{ON} = \Delta s_d^{CTC}$). By construction, this also holds at the monthly frequency. Thus, we obtain 288 intraday, overnight, and close-to-close returns series for all months over the 25 years between period between 1994 to 2018. In line with previous literature on FX returns (see, e.g. Verdelhan (2018)), we will primarily use these monthly series to analyse return dynamics that occur over different hours over the course of the trading day.[10]

[9] According to BIS (2016), most of the daily turnover in the global FX market is generated in the United Kingdom and the United States, followed by Singapore, Hong Kong, and Japan.

[10] As in Lou, Polk, and Skouras (2017), price changes could be alternatively expressed in simple daily returns, compounded within each month, and then transformed to monthly log returns. Both approaches lead to the same monthly series of log returns.

B. *Intraday Versus Overnight Returns*

We start our analysis by plotting the annualized average cumulative 5-minute log returns over a 24 hour period currency by currency for the full sample window from 1994 to 2018. Starting at 5:00 p.m. New York time and lasting until 8:00 a.m. in the morning of the next day marks the overnight period (5:00 p.m.–8:00 a.m., EST). The dashed black lines at 9:00 p.m., 3:00 a.m., and 8:00 a.m. respectively mark intraday return reversal of currency returns which largely coincide with the opening hours of FX trading venues in Sydney, southeast Asia, and Europe. The remaining hours of the day encompass the intraday period (8:00 a.m. and 5:00 p.m.), which refers to the main trading hours in New York.

As shown, all foreign currencies tend to depreciate after trading in New York ceased, and cumulative returns reach a local minimum around the opening hours of Singapore and Hong Kong. Subsequently, foreign currencies start to reverse and appreciate against the U.S. dollar roughly until trading in Europe commences (around 1:00 a.m. EST), before declining again until markets in the U.S. open. During the intraday period all currencies (except the JPY) appreciate against the U.S. dollar on average. In particular, the most liquid pairs—the EUR, the GBP, and the CHF—strongly increase in value against the U.S. dollar between 8:00 a.m. and 5:00 p.m. Most of the other pairs exhibit a temporary drop between 11:00 a.m. and 12:00 p.m., which coincides with the London fixing time. After U.S. markets close all foreign currencies depreciate again with the AUD, the NZD and the JPY experiencing the largest drops.

[INSERT FIGURE 1 HERE]

In Figure 2 we show the average cumulative returns over a 24 hour period of an unconditional dollar portfolio that goes long all foreign currencies in equal weights. Aggregating across currencies, the distinct depreciation of foreign currencies after local markets open combined with the distinct depreciation of the U.S. dollar during the intraday period when U.S. markets are open leads to a very clear *'W'*-shaped intraday pattern with the basket of foreign currencies depreciating after 5:00 p.m. EST before reversing with a local peak in the middle of the night. Thereafter, the foreign currencies drop again in value on average until the U.S. markets open. Overall, there is a significant appreciation of the U.S. dollar during the overnight period of around 4% per year followed by a reversal during the day of the same magnitude.

[INSERT FIGURE 2 HERE]

Table 1 summarizes Figures 1 and 2 more formally as it contains the average FX log returns (i.e., exchange rate changes) for the various sub-periods we consider. The first column ($-\Delta s^{SYD}$) refers to returns during the early Australian trading hours (5:00 p.m. to 9:00 p.m.), followed by Southeast Asian trading (9:00 p.m. to 3:00 a.m., denoted by $-\Delta s^{SEA}$), and the first hours of European trading (3:00 a.m. to 8:00 a.m., denoted $-\Delta s^{EU}$). Taking together, these three subperiods constitute the overnight period, denoted by $-\Delta s^{ON}$ (5:00 p.m. to 8:00 a.m.) and given that we show average log returns, columns one through three add up to column four. Intraday returns (denoted $-\Delta s^{ID}$, from 8:00 a.m. to 5:00 p.m.) refer to the main trading hours in the U.S., while average close-to-close returns are summarized in the last columns, and calculated using by daily exchange rate changes at 5:00 p.m. accumulated within each month (and, consequently, CTC returns are the sum of either columns one, two, three and five or just four and five).

[INSERT TABLE 1 HERE]

As is evident already from Figure 1, all foreign currencies depreciate against the U.S. dollar after trading in New York ceases. The Australian and New Zealand dollar (-6.50% and -7.85%, respectively) show the most negative average returns, while the Scandinavian currencies depreciate the least compared to other currency pairs. It is worth highlighting that irrespective of the magnitude of the returns, average annualized returns of all G10 currencies are different from zero at the 5% or 1% level of significance. The next two columns also display a clear return pattern in the cross-section with most currencies appreciating significantly during the second subinterval before dropping significantly before U.S. markets open. Overall, the fact that individual currencies depreciate during the first few hours after local markets open seems to be very robust for the G-10 currencies in our sample. After trading in Southeast Asia commences, all foreign currencies (except the GBP) appreciate significantly against the U.S. dollar ($-\Delta s^{SEA}$). During these times of the day, average returns range between -0.24% (GBP) and 5.95% (NZD). The next reversal occurs in parallel to the start of trading in Europe and most foreign currencies start to depreciate vis-‘a-vis the U.S. dollar. While this is also true for the Australian and New Zealand dollar, they do not depreciate as much as during the first few hours after markets in Australia open and they depreciate not nearly as much as the European currencies during the same period. Taken together, the entire average overnight returns ($-\Delta s^{ON}$) are negative for all currencies except the JPY. The returns are particularly negative for the most liquid European currencies such as the CHF (-6.06%), the EUR (-6.42%), the GBP (-7.73%), followed by the Scandinavian currencies, the SEK (-6.08%) and the NOK (-3.29%). In turn, all currencies (again with the exception of the JPY) appreciate against the U.S. dollar during the main trading hours in New York, ranging between 8.14% for the CHF and 1.00% for the CAD. In summary, all returns are positive during the intraday period and negative overnight with the exception of the Japanese yen, that shows an opposite pattern, appreciating during the night and depreciating over night by 1.62% in each direction. Finally, the CTC column indicates that most of the currencies do not appreciate or depreciate much against the U.S. dollar on average and, in particular, the average return on the dollar portfolio is very close to zero.

[INSERT FIGURE 3 HERE]

Figure 3 illustrates the economic magnitude of the differences between intraday and overnight returns if transaction costs are ignored. The graph shows the hypothetical total return indices for the individual currencies starting in January 1994 with a value of one and ending in December 2018 for a position that is held for the whole period (CTC, blue) or only during overnight or intraday trading hours (ON, green or ID, red, respectively). Not very surprisingly, the diverging pattern over the day between overnight and intraday returns translates into diverging trends in the long-run. For example, if an investor could have invested one dollar in British pound during the intraday period at the end of January 1994, she would have obtained a return to this investment equal to 7.21 USD in December 2018. In contrast, the same trading approach with an overnight position would have led to a portfolio value of approximately 0.14 USD at the end of the sample period. Holding the position for the full 25 years would have resulted in a value of roughly 1.21 USD. The biggest spread between overnight and intraday returns is generated for the Swiss franc where the values of the respective positions in December 2017 are 7.66 USD and 0.22 USD, respectively.

III. Statistical Robustness

In an initial attempt to explain these findings we conduct an extensive investigation of the statistical properties of the W-shaped dollar portfolio return pattern documented in section II.

A. Alternative Cross-Sections

First, we change the cross-section of currencies by excluding one currency at a time from the dollar portfolio and confirm that our main results are not driven by a specific currency. For every combination of currencies used to form the dollar portfolio, we find that the basket of currencies appreciates during the day and depreciates overnight. As expected, returns to the strategies are lower due to the importance of the yen as a funding currency, but the general intraday pattern remains unchanged. Moreover, broadly speaking, Figure 4 displays a 'W' return pattern over the full trading day which implies a strong common factor structure in intraday returns for the developed market dollar basket.

[INSERT FIGURE 4 HERE]

Second, we check if the systemic intraday pattern is special to the U.S or special to the geographical location of the U.S. To this end, we use 5-minute intraday data of the Hong Kong dollar (HKD) vis-á-vis the U.S. dollar to construct an unconditional HKD portfolio against the set of G10 currencies (see Figure 5). We find that intraday patter of the HKD portfolio mirrors the pattern of the U.S. dollar portfolio, and it closely tracks the cycle of appreciation and depreciation of the U.S. dollar portfolio.

[INSERT FIGURE 5 HERE]

B. Calendar Effects

B.1. Day of the Week Effects

Figure 6 plots cumulative 5-minute returns sampled for each trading day of the week. In terms of close-to-close returns, returns on Thursday are the most positive, which is primarily driven by a cumulative return that peaks later in European trading hours than the remaining days of the week. Tuesday and Wednesday close-to-close returns are close to zero while Monday and Tuesday returns are negative. Aside from differences in magnitudes, each day of the week displays the same W-shaped intraday return pattern where the sequence of reversals is clearly visible around the opening times of the major trading venues we consider. Also, we note the large positive returns to holding foreign currencies before close of trade in the U.S on Fridays. Table 2 tests the statistical significance of our intraday split using a regression dummy framework. Close-to-close returns are statistically different than zero on Mondays and Thursdays but not different than zero on other days. Remarkably, almost all of the SYD, SEA and EUR returns are significant at conventional levels. The exception to this rule being returns in Europe on Tuesday and Thursdays. However, the U.S intraday pattern is consistently positive but only statistically significant on Thursdays and Fridays. In summary, the W-shaped dollar portfolio return pattern systematically present in each day of the week and shows up with high levels of statistical significance.

[INSERT FIGURE 6 AND TABLE 2 HERE]

B.2. Month of the Year Effects

Figure 7 plots cumulative 5-minute returns for each month of the year, averaged across all trading days. As expected, returns for a given my display larger variation in their intraday patterns. Specific monthly characteristics worth highlighting are (*i*) large negative CTC returns in January, May, August and November; and (*ii*) large positive CTC returns in April, June, September, and December. Moreover, we note the unusually large positive drift in during SEA trading hours in December. Taking a step back and considering the broader patterns a W-shaped return pattern is clearly visible in each month of the year. Table 3 estimates the statistical significance of this visual inspection using daily returns of our intraday sub sample split using a regression dummy framework. Point estimates for each month almost always go in the direction of a W-shaped pattern, although the statistical significance of individual returns is lower, as expected, due to the smaller sample size and thus lower test power. In summary, the intraday dollar portfolio return pattern documented above is a pervasive feature throughout the calendar year.

[INSERT FIGURE 7 AND TABLE 3]

C. Sub-sample Analysis

Figure 8 examines the economic and statistical stability of our intraday return dissection over time by computing daily return averages for each sub period return, year by year. Consider first the intraday returns, depicted by the green bars, which show that foreign currencies consistently appreciate during U.S trading hours in almost every year of our sample. Moreover, when returns are negative, they are relatively small in magnitude with one exception: the 2008 financial crisis year. The purple bars depict overnight return averages, and show that foreign currencies consistently systematically depreciate in almost every year of the sample. Within the overnight period, we see that overnight foreign currency depreciation is consistently associated with negative returns during both SYD (blue bars) and EUR (pink) trading hours, while SEA trading hours (black bars) are consistently positive. The remarkable finding shows that the sequence of reversals that generate the W-shaped pattern highlighted above are not driven by particular sub samples or the financial crisis and subsequent period of unconventional monetary policy expansion. In fact, we see the same pattern in each year of the sample which highlights the statistical advantages of working with high frequency datasets with a large time dimension.

The bottom panel of figure 8 reports the p-value is a t-test of the statistical difference of SYD / SEA / EUR / ON / ID return averages versus the null of zero. The dotted line reported the 10% significance level and shows that in the 24 year sample we see statistically significant sub period returns at the 10% level in 12-years for SYD, 14-years for SEA, 8-years for EUR, 6-years for ID, and 7-years for ID returns. Finally, figure 9 shows the intraday cumulative spot return of the dollar portfolio for each individual year in our sample. As shown, the systematic pattern is broadly present across all years between 1994 and 2018, and foreign currencies in the night and appreciate during the day. We note the only exceptions appear to be years during financial crises and recession periods (e.g. LTCM/ Russian financial crisis (1998/1999) and global financial crisis (2008/2009).

[INSERT FIGURE 8 AND FIGURE 9 HERE]

D. Futures Returns and High Frequency Interest Rate Differentials

The CME has offered currency futures since the breakdown of the post WWII Bretton Woods agreement in 1972 that imposed fixed exchange rates between the world's currencies. The development of currency futures was initiated by Chicago Mercantile Exchange Chairman Leo Melamed working in connection with the Nobel Prize winning economist Milton Friedman.[11]. In September 1993 CME introduced the GLOBEX electronic trading platform which facilitated global trade for (almost) 24-hours a day 5-days a week so that currency futures trade concurrent to the OTC spot market. With respect to OTC indicative spot quotes, futures prices have two attractive properties: (*i*) quotes are real-time executable; and (*ii*) futures prices incorporate the cost of carry which in the currency is an implied interest rate differential. Thus, studying intraday futures returns answers two question: (*i*) are the findings above an artefact of our dataset; and (*ii*) are the FX return patterns we observe offset by high frequency fluctuation in the cost of carry (interest rate differential).

The blue bars in Figure 10 show the average hour-by-hour returns on the most liquid futures contracts for each pair.[12] The *'W'* shaped return pattern in the unconditional dollar portfolio is clearly visible both for the average (red line) and median (green line). We note that this pattern is computed for a different sample period compared to the dollar portfolio shown in Figure 2 (2005 to 2017 versus 1994 to 2017). Furthermore, accounting for variations in (expected) interest rate differentials does not materially affect our main result.

[INSERT FIGURE 10 HERE]

IV. Dissecting Currency Risk Premia

Having established that currency returns exhibit a distinct pattern within the 24-hour trading day, we next investigate the implications of this finding for well-established facts in the FX literature that are generally based on an analysis of close-to-close returns. In particular, the forward premium puzzle goes back to Fama (1984) and is one of the major stylised facts reflecting the failure of

[11] `www.cmegroup.com/education/files/understanding-fx-futures.pdf`

[12] The most liquid contract currency by currency is almost always the front month contract except in expiration months around settlement Wednesdays.

uncovered interest rate parity (UIP). Another well studied failure of UIP is the carry trade anomaly that has take centre stage in the literature for more than two decades (for a recent study, see (Lustig, Roussanov, and Verdelhan (2011))). While the forward premium puzzle is a fact about a regression coefficient, the carry trade is about a profitable trading strategy based on portfolio sorts.

With a few exceptions, the extant literature studies UIP failures based on monthly data for a variety of currency cross-sections. Given the results we document for the high-frequency behaviour of the major currency pairs, it is natural to ask how this affects the widely studied currency strategies or anomalies around the clock. In section II we document a persistent pattern that is consistent for a large cross-section of currencies from developed countries. In particular, the W-shaped pattern we document applies to currencies that are used either as funding or investment currencies in the carry trade. Hence, it is not obvious how the currency-by-currency or dollar portfolio results carry over to more complicated currency trading strategies.

A. Currency Anomalies as Trading Strategies

Hassan and Mano (2018) propose a framework that recasts both the forward premium puzzle as well as the carry strategy in the context of trading strategies that can be implemented using the forward discount (and expectations thereof) at the portfolio formation stage. In particular, they provide a mapping between the forward premium, carry trade and dollar carry anomalies by decomposing the unconditional covariance of currency returns with forward premia, i.e., currency risk premia, into a (i) cross-currency; (ii) a between-time-and-currency, and (iii) a cross-time component. First, they recast the forward premium puzzle as a trading strategy that they call the forward premium trade (or fpt).[13] Trading on the correlation in the data that drives the forward premium puzzle implies buying currencies that have a higher forward premium (i.e., interest rate differential to the U.S. dollar) than they usually do. Second, equipped with the fpt, they decompose currency risk premia into a static trade, a dynamic trade, a dollar trade (plus a constant). The static trade reflects cross-currency variation, the dynamic trade between-time-

[13]Fama (1984) regresses the forward discount on the currency excess return: $rx_{i,t} = \alpha_i + \beta_i^{fpp}(f_{i,t} - s_{i,t}) + \varepsilon_{i,t+1}$, where $rx_{i,t} = f_{i,t} - s_{i,t+1}$. In the data β_i^{fpp} is generally larger than zero and often larger than one, suggesting the high-interest rate currencies appreciate.

and-currency variation, and the dollar trade cross-time variation in forward premia:

$$\underbrace{cov\left(rx_{i,t+1}\left(fp_{i,t}-\overline{fp_i}\right)\right)}_{\text{Currency Risk Premia}} = \underbrace{E\left[rx_{i,t+1}\left(\widehat{fp_i}-\widehat{fp}\right)\right]}_{\text{static trade}}$$

$$+\underbrace{E\left[rx_{i,t+1}\left(fp_{i,t}-\widehat{fp_t}-\left(\widehat{fp_i}-\widehat{fp}\right)\right)\right]}_{\text{dynamic trade}} \tag{2}$$

$$+\underbrace{E\left[rx_{i,t+1}\left(\overline{fp_t}-\overline{fp}\right)\right]}_{\text{dollar trade}} + \text{constant} \tag{3}$$

where $fp_{i,t}$ is country i's forward discount at time t, $\widehat{fp_t}$ is cross-sectional average forward discount at time t, $\widehat{fp_i}$ is the time-series average of country i's forward discount, $\widehat{fp}$ is the time-series average of the cross-sectional average forward discount.

The carry trade turns out to be the sum of static and dynamic trades, while the forward premium trade is the sum of the dynamic and dollar trades. This means that the carry trade and the forward premium trade share the the dynamic trade which can be thought of as the updating component of both strategies. In addition, the dollar trade is also a component of the forward premium trade, whereas the dollar and the carry are orthogonal by construction. Based on this observation Hassan and Mano (2018) argue that the extent to which researchers should search for a *common* theoretical explanation for carry and forward premium anomalies depends on the relative contribution of their shared dynamic component. In summary, we focus on two trading strategies:

$$\text{Carry trade P\&L:} \quad \textstyle\sum_{i,t}\left[rx_{i,t+1}\left(fp_{i,t}-\widehat{fp_t}\right)\right] \tag{4}$$

$$\text{Forward premium trade P\&L:} \quad \textstyle\sum_{i,t}\left[rx_{i,t+1}\left(fp_{i,t}-\widehat{fp_i}\right)\right] \tag{5}$$

where $\sum_{i,t} x_{i,t} = (\sum_i^N \sum_t^T x_{i,t})$ over some investment period $t = 1, ..., T$. Following Hassan and Mano (2018) we compute the expectations above by implementing a set of trading strategies using linear portfolio weights as indicated in parenthesis in equation 4. The carry portfolio is both zero cost (the portfolio weights sum up to zero) and neutral with respect to the dollar. However, the linear portfolio weights differ slightly from the standard approach in the literature that sorts currencies into equally weighted portfolios based on the forward discount and then analyses the return differential between the high and low interest rate portfolio.[14] In order to make the magnitudes of the returns comparable to the results based on portfolio sorts, we also re-scale the linear weights such that the weights for long and the short leg of the portfolio sum up to one every period, respectively. Obviously, the same scaling factor has to be applied to every component of the decomposition in equation 2. Note that unlike for the carry strategy, the weights for the other strategies do not necessarily sum up to zero.

[INSERT TABLE 4 AND FIGURE 11 HERE]

Table 4 shows the annualised returns for the trading strategies above split into the same intraday periods considered in Table 1. Different than the results in Table 1, we also include the interest rate differential (or the forward premium) in the analysis. While we have exchange rates sampled at the five minute frequency, the rebalancing frequency of the portfolios is monthly and, hence, we use the monthly forward premia. Consequently, we assume that the interest rate differential is earned linearly over the month although we report the return decompositions with and without the interest rate differential in the top and bottom panels, respectively.

Over our sample period, both the carry trade as well as the forward premium trade are profitable on average with 4.20% and 6.44% per year, respectively. However, almost all of the carry return and over half of the forward premium trade return is due to the interest rate differential that is earned by going long high interest rate currencies. This means that over our sample period the returns to the carry trade are due to the high interest rate currencies not depreciating enough for uncovered interest rate parity to hold.

Consistent with the low frequency findings of Hassan and Mano (2018), table 4 shows that for all intervals of the trading day the dynamic trade contribution to currency risk premia is small. Consequently, carry and the static trade as well as the forward premium and the dollar trade are almost identical as can clearly be seen in figures 11a and 11b. Based on this evidence one could conjecture that the carry trade and forward premium puzzles are driven by distinct economic forces.

Figures 11c to 11f soundly reject this conjecture: the individual legs of each of the trading strategies considered above inherit versions of the W-shaped return pattern. However, it is striking

[14] See, e.g., Lustig, Roussanov, and Verdelhan (2011).

that, when taken together the strategies look distinctly different. The bulk of the spot carry return is earned during the day while the exact opposite is true for the forward premium return. Since the dynamic contribution of carry and forward premium trades is small, this also implies that returns to the static trade and the dollar carry trade are also earned during the day and overnight, respectively, as can be seen in table 4. In numerical terms, we find that $\sim 80\%$ of realised carry trade returns returns are earned ID, while in contrast $\sim 70\%$ of realised dollar trade returns are earned ON.

Examining more closely the respective legs of the strategies reveals that the positive performance during the day for the static carry trade is driven by the fact that the appreciation of the high interest currencies (that are long in portfolio) exceeds the appreciation of the low interest currencies (that are short in the portfolio) during the day while they move almost in tandem overnight. Furthermore, the low interest rate currencies depreciate much more than the high interest currencies during the EU time window before US markets open. A different pattern is observed for the dollar carry trade. Until the European markets open the returns to both strategies are flat. Thereafter, returns to the long leg continue to remain close to zero whereas the short leg depreciates sharply during European trading hours until about noon New York time, with the biggest drop happening before New York markets open (in line with the short leg in the carry trade).

Overall, we show in this section how the W-shape pattern that we document affects the returns of well-known trading strategies. Taken the interest rate differential into account, all strategies generate positive returns both during the day and overnight. This is in stark contrast to the dollar portfolio that exhibits a strong reversal pattern over the 24 hour period. While the intraday movements do not affect the close-to-close returns that are earned by investing the strategies over a long period of time, the decompositions imply that different sets of currencies are held long and short in the portfolio at any given point in time. As a result, returns to the various strategies are not earned evenly over the day but can be attributed to distinct windows. Both Carry returns are mainly earned during the hours after European markets open and before the US starts trading as well as during the US trading hours. At least part of the pattern is driven by the fact the low interest rate currencies such as the CHF or the EUR depreciate sharply during European hours before the US opens.

V. Intraday Profitability and Transaction Costs

The analysis so far is based reported high-frequency mid-quotes and, hence, doesn't account for transaction costs. In this section we examine whether the trading strategies implied by the return patterns are still profitable if transaction costs are explicitly taken into account. The return decompositions in Table 1 suggest that a trader would have to shift positions up to four times over the course of a 24-hour period to exploit all the exchange rate movements we document.

The main purpose of this section is to establish whether there are some strategies that can be profitably exploited or whether transaction costs positive returns for the various sub-periods we consider. As discussed in section D, the most transparent and straightforward way to trade in FX on an exchange is to use the CME futures. Since the CME quotes are executable, we start our analysis of trading profits using the bid and ask prices of FX futures over the 2005 to 2017 sample. Using the return patterns documented in Table 5 we pick the best time period from our subperiods over the day to take a long or short position in a particular currency, respectively. We then calculate the average annualised returns taking the bid and ask spreads into account and calculate the Sharpe ratio for each short and long position. The results are summarized in Table 6 and they are not very encouraging as all of the strategies lead to significantly negative annualized Sharpe ratios over the sample period we consider. This means that the return pattern that we document for currency returns over the course of the day cannot be systematically exploited by trading in FX futures.

[INSERT TABLE 5 AND TABLE 6 HERE]

This may seem surprising at first as futures are generally considered very liquid. However, this is not necessarily the case in the FX market where a large fraction of the overall daily volumes is still traded in the over-the-counter market and not on an exchange. In fact, the most liquid FX futures, the EUR-USD contract, has spreads that are magnitudes larger than those of the most liquid contracts on CME, the e-mini and the 10-year Treasury futures. Moreover, depending on the intraday period the executable spreads in the futures are also often larger than the indicative quotes we have through TRTH and Olsen. In fact, during the overnight period we find that bid-ask spread of futures exceed the those in spot, on average, by 60%, while the costs of intraday trading are only slightly lower on CME. Further, we note that bid-ask spreads tend do spike more drastically in futures markets around New York closing time (5:00 p.m., EST) than in spot markets, affecting the profit of the proposed strategies significantly as long and short positions are opened and closed at this point in time of the day.

Hence, we extend our analysis to the spot data based on indicative quotes. To calculate returns net of transaction costs for the over-the-counter spot data we follow the existing literature (see, e.g., Della Corte, Ramadorai, and Sarno (2016), Menkhoff, Sarno, Schmeling, and Schrimpf (2012), Lustig, Roussanov, and Verdelhan (2011)) and use the quoted bid-ask spreads as a proxy for the effective spread. However, Gilmore and Hayashi (2011) for example argue that the spreads reported to the databases tend to be substantially wider compared to the effective spreads based on firm quotes and executed trades. This leads to measures of net returns that are too conservative compared to what professional traders that move large volumes can possibly achieve. Gargano, Riddiough, and Sarno (2017) compare the bid-ask spreads from *Datastream* with quoted prices from other data providers in the years after the financial crisis period and suggest decreasing indicative spreads by up to 75% in order to obtain a more realistic proxy of the transaction costs that big traders in the over-the-counter FX market face.

When considering the profitability of the trading strategies based on the over-the-counter rates, we take an agnostic approach and report results for different spread adjustments ranging from zero to 75% in line with the existing literature.[15] Moreover, we again pick the best sub-period over the 24-hour day to be long and short a particular currency in our sample and report the results in Table 7. The left and the right panels denote the returns to entering into a short and a long position for a given sub-period and currency.[16]

[INSERT TABLE 7 HERE]

Not very surprisingly, continuous buying and selling of currencies during particular times of the

[15] We follow the approach in Gargano, Riddiough, and Sarno (2017) and verify that the daily bid-ask spreads from the TRTH database closely resemble those from the publicly available indicative quotes from *Datastream* and they are roughly comparable in size over the full sample period. This means that arguments with regards to reducing the spreads to obtain more realistic results are broadly applicable in our context as well. More details on the comparison of bid-ask spreads are provided in the Online Appendix.

[16] "ON" and "ID" denotes the entire overnight and intraday period, respectively. "SYD" is the first period during the night after markets in the U.S. close, followed by the "SEA" and "EU" period, during which the Asian and European markets open, respectively.

day has a substantial impact on the profitability of intraday trading strategies. First, it is noteworthy that the previously reported positive returns in both intraday periods vanish across almost all currency pairs (except GBP intraday) when the entire reported bid-ask spread is considered as a proxy of trading costs ($-\Delta s_{100\%}$). Second, decreasing the bid-ask spread to more representative levels of the effective spread, we find that selling and buying the most liquid currency pairs (CHF, EUR, GBP) during the entire overnight and intraday period leads to positive net returns. For example, if we consider 50% of the originally reported spread as the costs of trading ($-\Delta s_{50\%}$), an equally-weighted portfolio of the three currency pairs generates 3.50% and 2.41% during the intraday and overnight period, respectively. For the euro (EUR) and British pound (GBP) these returns are significant at least at the 5% level, while returns for the Swiss franc (CHF) are only weakly significant (10%) during the day. Third, if we even allow to hold long and short positions of individual currency pairs for sub-overnight periods, we obtain positive returns for all individual currency pairs. If the spreads are decreased to 25% of the reported size ($-\Delta s_{25\%}$), net returns range between 0.21% if a short position of the Canadian dollar (CAD) is held during the main south-east Asian trading hours, and 6.19% if a short position of the British pound (GBP) is held during the entire overnight period. Further, the profitability of holding short or long positions only during certain sub-periods of the day is confirmed by Sharpe ratios (Table 8) for which volatility dynamics in each sub-period are taken into account. The risk-free rate is measured by the 4-weeks U.S. Treasury Bill.

[INSERT TABLE 8 HERE]

As shown, Sharpe ratios are positive for long and short positions that were associated with significant and positive intraday net returns in the previous table. Depending on the size of the transaction costs, positive Sharpe ratios range between 0.12 (CHF^{ID}) and 0.42 (GBP^{ID}) for $-\Delta s_{50\%}$ and even increase to 0.77 (GBP^{ID}) for $-\Delta s_{25\%}$. For the least conservative way of estimating transaction costs, four out of nine long positions and short positions generate positive Sharpe ratios. For the majority of these cases, the highest ratios are obtained from holding positions for the entire overnight or intraday period, while shorter trading intervals are only preferable for the Australian dollar and Japanese yen. Overall, the analysis exemplifies that investors can exploit the systematic price trends between return reversals that occur around opening hours of major

FX trading venues and it shows that intraday trading in the FX spot market is profitable.

VI. Conclusion

In this paper we study currency risk premia around the clock for the G10 currencies. We find that most currencies (with the exception of the Japanese yen) appreciate against the U.S. dollar during New York trading hours (i.e., the intraday period) and depreciate during the rest of the 24 hour day (i.e., the overnight period). This finding implies that currency returns have distinct dynamics depending on the time of day, measured with respect to the U.S. trading day.

We revisit well-known results in the foreign exchange literature and find the following: (i) Running Fama (1984) regressions to test the expectations hypothesis we cannot reject that the β coefficient is equal to one for all currencies in the sample during the overnight period; (ii) carry returns and dollar carry returns are almost entirely earned during the intraday period; (iii) the dollar portfolio earns a significant positive return intraday but reverses equally strongly during the night.

In summary, we present novel stylised facts with respect to the most important global currencies. The results suggest that the distinction between intraday and overnight periods is not only important in the equity markets as documented by Lou, Polk, and Skouras (2017) but also in the global foreign exchange market. These facts are intuitively appealing given the global nature currency markets which trade globally in distinct geographical regions as the second hand of the clock rotates. However, studying a number of risk-based alternatives we fail to explain the basic '*W*' shaped intraday return pattern of the dollar portfolio. We leave this as a puzzle to solve in future research.

VII. Appendix: Tables

Table 1. Intraday Returns: Geographical Dissection

This table reports annualized average returns for different intraday periods. "SYD" refers to returns after trading in Sydney commenced (5:00 p.m. to 9:00 p.m.); "SEA" refers to returns subsequent to the opening of the main trading venues in Southeast Asia (Singapore and Hong Kong, 9:00 p.m. to 3:00 a.m.); "EU" refers to returns during main trading hours in Europe (3:00 a.m. to 8:00 a.m.); "ON" refers to the overnight returns from an U.S. investors perspective. It equals the sum of the first three columns (SYD + SEA + EU. "ID" refers to the intraday returns during the main trading hours in New York (8:00 a.m. and 5:00 p.m.). "CTC" refers to daily close-to-close returns between 5:00 p.m. on day t and 5:00 p.m. on day $t+1$ (CTC = ON + ID). "DOL" refers to the unconditional dollar portfolio that goes long all foreign currencies.
Positive values imply the foreign currency appreciates versus the U.S. dollar. All times are measured in Eastern Standard Time, taking into account daylight saving changes in New York. The sample period is January 1994 to December 2018 (300 monthly observations).

	SYD	SEA	EU	CTO	OTC	CTC
AUD	-6.50	4.14	-0.39	-2.76	2.81	0.05
	(-6.88)	(4.39)	(-0.37)	(-1.63)	(1.94)	(0.02)
CAD	-2.37	2.78	-1.61	-1.19	1.00	-0.19
	(-5.53)	(5.53)	(-2.16)	(-1.17)	(0.75)	(-0.12)
CHF	-1.64	0.29	-4.71	-6.06	8.14	2.08
	(-2.64)	(0.39)	(-4.03)	(-4.54)	(5.34)	(1.02)
EUR	-3.09	3.62	-6.94	-6.42	7.18	0.76
	(-5.04)	(5.48)	(-7.72)	(-5.54)	(4.99)	(0.39)
GBP	-4.38	-0.24	-3.12	-7.73	7.90	0.17
	(-8.31)	(-0.40)	(-3.31)	(-6.50)	(6.61)	(0.10)
JPY	-1.31	4.50	-1.44	1.75	-1.64	0.11
	(-1.69)	(4.86)	(-1.36)	(1.12)	(-1.28)	(0.05)
NOK	-1.90	3.56	-4.96	-3.29	2.85	-0.44
	(-2.63)	(4.02)	(-4.30)	(-2.37)	(1.66)	(-0.21)
NZD	-7.85	5.95	-0.77	-2.68	3.89	1.21
	(-7.14)	(5.25)	(-0.69)	(-1.34)	(2.75)	(0.49)
SEK	-2.29	2.88	-6.67	-6.08	5.28	-0.80
	(-3.04)	(2.99)	(-5.88)	(-4.01)	(2.84)	(-0.37)
DOL	-3.45	3.09	-3.32	-3.68	4.25	0.57
	(-7.12)	(5.73)	(-5.01)	(-3.91)	(3.84)	(0.37)

Table 2. Day of the Week Effects

This table reports annualized average returns for different intraday periods for the dollar portfolio (DOL) which goes unconditional long all foreign currencies. Table details are reported in the caption of Table 1. For each intraday sub-period, we regress daily returns on a set of day of the week dummies. t-statistics reported in parenthesis are corrected for autocorrelation and heteroskedacity. The sample period is January 1994 to December 2018 (300 monthly observations).

	SYD	SEA	EUR	ON	ID	CTC
β_{mon}	-5.44	3.15	-7.56	-9.85	2.91	-6.94
	(-3.20)	(2.37)	(-4.32)	(-3.58)	(1.34)	(-2.01)
β_{tue}	-5.20	3.59	-1.56	-3.16	3.71	0.55
	(-4.66)	(2.59)	(-0.91)	(-1.25)	(1.46)	(0.15)
β_{wed}	-2.20	3.62	-3.31	-1.89	4.19	2.31
	(-2.46)	(2.86)	(-1.96)	(-0.84)	(1.52)	(0.64)
β_{thu}	-1.30	4.11	-1.48	1.33	6.36	7.69
	(-1.28)	(3.03)	(-0.77)	(0.54)	(2.31)	(2.14)
β_{fri}	-6.63	2.49	-3.91	-8.05	5.76	-2.29
	(-6.82)	(1.82)	(-2.36)	(-3.39)	(1.98)	(-0.62)

Table 3. Month of the Year Effects

This table reports annualized average returns for different intraday periods for the dollar portfolio (DOL) which goes unconditional long all foreign currencies. Table details are reported in the caption of Table 1. For each intraday sub-period, we regress daily returns on a set of month of the year dummies. t-statistics reported in parenthesis are corrected for autocorrelation and heteroskedacity. The sample period is January 1994 to December 2018, (300 monthly observations).

	SYD	SEA	EUR	ON	ID	CTC
β_{jan}	-4.43	1.37	-4.90	-7.96	0.82	-7.14
	(-1.95)	(0.69)	(-1.63)	(-1.86)	(0.20)	(-1.22)
β_{feb}	-1.98	2.30	-5.72	-5.40	6.08	0.68
	(-1.22)	(1.21)	(-2.29)	(-1.55)	(1.53)	(0.13)
β_{mar}	-3.58	1.41	-4.42	-6.59	8.88	2.29
	(-2.09)	(0.74)	(-1.62)	(-1.73)	(2.13)	(0.41)
β_{apr}	-2.64	3.53	-4.72	-3.83	14.29	10.46
	(-1.30)	(1.68)	(-1.80)	(-1.05)	(4.01)	(1.00)
β_{may}	-5.57	2.98	-3.76	-6.35	-0.61	-6.96
	(-3.55)	(1.40)	(-1.40)	(-1.73)	(-0.15)	(-1.23)
β_{jun}	-4.36	4.89	-5.15	-4.62	9.59	4.97
	(-2.78)	(2.07)	(-1.86)	(-1.18)	(2.30)	(0.88)
β_{jul}	-7.79	3.57	-2.69	-6.90	8.73	1.83
	(-5.47)	(1.85)	(-1.13)	(-2.01)	(2.30)	(0.35)
β_{aug}	-5.37	-0.26	-1.57	-7.21	2.06	-5.15
	(-4.05)	(-0.14)	(-0.63)	(-2.11)	(0.54)	(-1.02)
β_{sep}	-6.79	3.67	-0.15	-3.26	9.21	5.94
	(-3.71)	(1.75)	(-0.05)	(-0.83)	(2.20)	(1.04)
β_{oct}	-3.04	5.15	-2.05	0.06	0.06	0.12
	(-1.71)	(2.16)	(-0.74)	(0.01)	(0.01)	(0.02)
β_{nov}	-2.85	4.18	-4.15	-2.82	-5.85	-8.67
	(-1.25)	(2.00)	(-1.36)	(-0.67)	(-1.34)	(-1.46)
β_{dec}	-0.64	8.58	-3.11	4.83	1.63	6.46
	(-0.30)	(4.24)	(-1.15)	(1.20)	(0.37)	(1.10)

Table 4. FX Trading Strategies: Intraday Return Decomposition
This table reports annualized average returns for the carry, forward premium, static, dynamic, dollar trade (dot), and unconditional dollar portfolio (DOL) for different intraday periods. The overnight period "ON" ranges from 5:00 p.m. to 8:00 a.m. the next day and comprises the period "SYD" after trading in Sydney commences (5:00 p.m. to 9:00 p.m.); 'SEA", the subsequent period when the main trading venues in Southeast Asia open (Singapore and Hong Kong, 9:00 p.m. to 3:00 a.m.); and "EU", the early trading hours in Europe (3:00 a.m. to 8:00 a.m.). Panel A refers to returns that include the forward premium (interest rate differential), while Panel B displays the returns solely based on the change of the spot rate. Positive values imply the foreign currency appreciates versus the U.S. dollar. All times are measured in Eastern Standard Time, taking into account daylight saving changes in New York. The sample period is January 1994 to December 2018 (300 monthly observations).

	SYD	SEA	EU	ON	ID	CTC
			Panel A: Excess Returns			
Dynamic	-0.33	-0.53	0.74	-0.12	1.17	1.04
	(-0.91)	(-1.18)	(1.41)	(-0.16)	(1.80)	(1.11)
Static	-3.13	2.19	1.89	0.95	2.21	3.16
	(-4.83)	(2.71)	(2.31)	(0.78)	(2.24)	(1.97)
Carry	-3.46	1.66	2.62	0.83	3.37	4.20
	(-4.85)	(2.05)	(2.92)	(0.59)	(3.34)	(2.39)
Fwd Prem	-1.55	0.09	5.03	3.58	2.86	6.44
	(-1.84)	(0.09)	(3.40)	(1.83)	(1.38)	(2.32)
Dollar Carry	-1.22	0.63	4.29	3.70	1.69	5.39
	(-1.65)	(0.66)	(3.30)	(2.20)	(0.89)	(2.16)
			Panel B: Change in spot rate			
Dynamic	-0.56	-0.89	0.44	-1.01	0.64	-0.37
	(-1.56)	(-1.96)	(0.84)	(-1.29)	(0.99)	(-0.39)
Static	-3.65	1.42	1.24	-0.99	1.04	0.05
	(-5.62)	(1.75)	(1.52)	(-0.81)	(1.06)	(0.03)
Carry	-4.21	0.53	1.68	-1.00	1.68	-0.32
	(-5.91)	(0.66)	(1.87)	(-1.41)	(1.67)	(-0.18)
Fwd Prem	-2.12	-0.77	4.31	1.41	1.56	2.97
	(-2.53)	(-0.70)	(2.92)	(0.72)	(0.75)	(1.07)
Dollar Carry	-1.56	0.11	3.86	2.42	0.92	3.34
	(-2.12)	(0.12)	(2.98)	(1.44)	(0.49)	(1.34)

Table 5. CME Futures Intraday Returns: By Main Trading Hours

This table reports average annualized returns for short and long positions of FX futures traded on the Chicago Mercantile Exchange (CME) for different sub-periods of the trading day associated with the main trading hour of the largest FX trading venues: Sydney ("SYD", 5:00 p.m. to 9:00 p.m.), south-east Asia ("SEA", 9:00 p.m. to 3:00 a.m.), Europe ("EU", 3:00 a.m. to 8:00 a.m.), overnight ("ON", 5:00 p.m. to 8:00 a.m.) and intraday ("ID", 8:00 a.m. to 5:00 p.m.). The sample period is January 1996 to December 2017, comprising 264 monthly observations.

	SYD	SEA	EU	ON	ID	CTC
AUD	-3.42	0.52	1.76	-1.15	1.29	0.15
	(-3.92)	(0.54)	(1.86)	(-0.71)	(0.81)	(0.06)
CAD	-1.80	1.61	-0.84	-1.03	1.40	0.37
	(-3.48)	(3.06)	(-1.21)	(-0.99)	(1.18)	(0.24)
CHF	-2.86	0.67	-2.20	-4.39	5.15	0.76
	(-4.31)	(0.89)	(-1.95)	(-3.07)	(3.82)	(0.39)
EUR	-3.79	2.94	-3.54	-4.39	4.56	0.18
	(-6.41)	(3.34)	(-3.72)	(-3.08)	(2.89)	(0.09)
GBP	-2.42	-0.47	-1.14	-4.03	3.49	-0.54
	(-3.75)	(-0.72)	(-1.34)	(-3.24)	(2.96)	(-0.34)
JPY	-2.34	3.24	-0.70	0.23	-0.52	-0.29
	(-3.18)	(3.28)	(-0.69)	(0.15)	(-0.44)	(-0.14)
NOK	-3.31	0.10	-1.91	-5.13	3.05	-2.07
	(-2.72)	(0.09)	(-1.38)	(-2.27)	(1.45)	(-0.78)
NZD	-6.83	1.93	0.77	-4.03	4.02	-0.01
	(-3.08)	(1.31)	(0.59)	(-1.36)	(1.57)	(-0.00)
SEK	-3.06	1.90	-1.78	-2.94	1.60	-1.34
	(-1.34)	(1.55)	(-1.33)	(-0.99)	(0.59)	(-0.44)
dol	-3.19	1.36	-0.92	-2.74	2.41	-0.38
	(-5.01)	(2.11)	(-1.33)	(-2.17)	(1.75)	(-0.19)

Table 6. Sharpe Ratios: Long and Short Positions in CME Futures

This table reports annualized Sharpe ratios for short and long positions in FX futures traded on the Chicago Mercantile Exchange (CME), across different sub-periods of the trading day associated with the main trading hour of the largest FX trading venues: Sydney ("SYD", 5:00 p.m. to 9:00 p.m.), south-east Asia ("SEA", 9:00 p.m. to 3:00 a.m.), Europe ("EU", 3:00 a.m. to 8:00 a.m.), overnight ("ON", 5:00 p.m. to 8:00 a.m.) and intraday ("ID", 8:00 a.m. to 5:00 p.m.). For long (short) overnight positions foreign currencies are bought (sold) at the ask (bid) price at the start of the trading period, and sold (bought) at the bid (ask) price at the end of the trading period. We only report the most profitable long and short positions across the trading day. For the majority of FX futures, the sample period is January 1996 to December 2017, comprising 264 monthly observations.

Panel A: Short Positions

AUD^{SYD}	CAD^{SYD}	CHF^{ON}	EUR^{ON}	GBP^{ON}	JPY^{SYD}	NOK^{ON}	NZD^{SYD}	SEK^{SYD}
-3.86	-3.34	-2.99	-1.57	-2.17	-3.21	-2.52	-4.90	-1.23

Panel B: Long Positions

AUD^{SEA}	CAD^{SEA}	CHF^{ID}	EUR^{ID}	GBP^{ID}	JPY^{SEA}	NOK^{ID}	NZD^{ID}	SEK^{SEA}
-2.74	-2.97	-2.90	-1.36	-2.27	-1.78	-2.45	-4.26	-1.24

Table 7. Net Returns: Long and Short Positions of Foreign Currencies

This table reports average annualized net spot returns for short and long positions of foreign currencies across different sub-periods of the trading day associated with the main trading hour of the largest FX trading venues: Sydney ("SYD", 5:00 p.m. to 9:00 p.m.), south-east Asia ("SEA", 9:00 p.m. to 3:00 a.m.), Europe ("EU", 3:00 a.m. to 8:00 a.m.), overnight ("ON", 5:00 p.m. to 8:00 a.m.) and intraday ("ID", 8:00 a.m. to 5:00 p.m.). $-\Delta s_{i\%}$ refers to the spot returns net of the bid-ask spread, where i = 100%, 75%, 50%, and 25% denote the proportion of the original bid-ask spread, which is used to proxy transaction costs. For long (short) overnight positions foreign currencies are bought (sold) at the ask (bid) price at the start of the trading period, and sold (bought) at the bid (ask) price at the end of the trading period. We only report the most profitable long and short positions. For the ease of reading, positive returns are highlighted in red. Numbers in parentheses refer to t-statistics. The sample period is January 1994 to December 2017, comprising 288 monthly observations. '

	Short Positions					Long Positions			
	$-\Delta s_{100\%}$	$-\Delta s_{75\%}$	$-\Delta s_{50\%}$	$-\Delta s_{25\%}$		$-\Delta s_{100\%}$	$-\Delta s_{75\%}$	$-\Delta s_{50\%}$	$-\Delta s_{25\%}$
AUD^{SYD}	-9.56	-5.61	-1.66	2.30	AUD^{SEA}	-10.96	-7.12	-3.28	0.56
	(-9.50)	(-5.65)	(-1.68)	(2.34)		(-10.85)	(-7.19)	(-3.35)	(0.57)
CAD^{SYD}	-8.99	-6.13	-3.27	-0.40	CAD^{SEA}	-8.30	-5.47	-2.63	0.21
	(-17.58)	(-12.34)	(-6.74)	(-0.85)		(-15.42)	(-10.31)	(-5.02)	(0.40)
CHF^{ON}	-5.92	-2.90	0.12	3.14	CHF^{ID}	-3.47	-0.45	2.57	5.59
	(-4.03)	(-1.98)	(0.09)	(2.17)		(-2.20)	(-0.29)	(1.65)	(3.60)
EUR^{ON}	-1.07	0.96	2.99	5.03	EUR^{ID}	-0.33	1.70	3.74	5.77
	(-0.85)	(0.77)	(2.40)	(4.03)		(-0.22)	(1.15)	(2.52)	(3.90)
GBP^{ON}	0.00	2.06	4.13	6.19	GBP^{ID}	0.07	2.14	4.20	6.26
	(0.00)	(1.67)	(3.35)	(5.03)		(0.06)	(1.76)	(3.46)	(5.16)
JPY^{SYD}	-8.98	-6.26	-3.55	-0.83	JPY^{SEA}	-5.44	-2.82	-0.19	2.43
	(-9.71)	(-6.83)	(-3.89)	(-0.91)		(-5.61)	(-2.93)	(-0.20)	(2.57)
NOK^{EU}	-11.16	-7.11	-3.07	0.97	NOK^{ID}	-13.63	-9.31	-5.00	-0.68
	(-9.28)	(-5.97)	(-2.59)	(0.83)		(-7.48)	(-5.16)	(-2.80)	(-0.38)
NZD^{SYD}	-19.91	-12.84	-5.78	1.28	NZD^{SEA}	-19.17	-12.79	-6.41	-0.04
	(-16.06)	(-10.77)	(-4.98)	(1.12)		(-15.40)	(-10.64)	(-5.47)	(-0.03)
SEK^{EU}	-13.99	-8.89	-3.79	1.31	SEK^{ID}	-15.73	-10.33	-4.93	0.47
	(-11.56)	(-7.52)	(-3.27)	(1.14)		(-7.90)	(-5.23)	(-2.51)	(0.24)

Table 8. Sharpe Ratios: Long and Short Positions of Foreign Currencies

This table reports average annualized Sharpe ratios ($SR = \frac{\mu - R_f}{\sigma}$) for short and long positions of foreign currencies across different sub-periods of the trading day associated with the main trading hour of the largest FX trading venues: Sydney ("SYD", 5:00 p.m. – 9:00 p.m.), south-east Asia ("SEA", 9:00 p.m. – 3:00 a.m.), Europe ("EU", 3:00 a.m. – 8:00 a.m.), overnight ("ON", 5:00 p.m. – 8:00 a.m.) and intraday ("ID", 8:00 a.m. – 5:00 p.m.). $-\Delta s_{i\%}$ refers to the spot returns net of the bid-ask spread, where $i = 100\%$, 75%, 50%, and 25% denote the proportion of the original bid-ask spread, which is used to proxy transaction costs. For long (short) overnight positions foreign currencies are bought (sold) at the ask (bid) price at the start of the trading period, and sold (bought) at the bid (ask) price at the end of the trading period. We only report the most profitable long and short positions. The risk-free rate refers to the 4-weeks U.S. Treasury Bill. For the ease of reading, positive returns are highlighted in red. Numbers in parentheses refer to t-statistics. The sample period is January 1994 to December 2017, comprising 288 monthly observations. ‘

	Short Positions					Long Positions			
	$-\Delta s_{100\%}$	$-\Delta s_{75\%}$	$-\Delta s_{50\%}$	$-\Delta s_{25\%}$		$-\Delta s_{100\%}$	$-\Delta s_{75\%}$	$-\Delta s_{50\%}$	$-\Delta s_{25\%}$
AUD^{SYD}	-2.23	-1.47	-0.68	0.13	AUD^{SEA}	-2.49	-1.77	-1.01	-0.23
CAD^{ON}	-2.20	-1.70	-1.20	-0.69	CAD^{ID}	-1.63	-1.24	-0.85	-0.46
CHF^{ON}	-1.05	-0.64	-0.21	0.21	CHF^{ID}	-0.66	-0.27	0.12	0.51
EUR^{ON}	-0.44	-0.11	0.22	0.55	EUR^{ID}	-0.27	0.01	0.29	0.56
GBP^{ON}	-0.27	0.07	0.41	0.75	GBP^{ID}	-0.26	0.08	0.43	0.77
JPY^{SYD}	-2.30	-1.73	-1.15	-0.55	JPY^{SEA}	-1.46	-0.93	-0.39	0.17
NOK^{EU}	-2.23	-1.54	-0.83	-0.12	NOK^{ID}	-1.72	-1.25	-0.76	-0.27
NZD^{SYD}	-3.48	-2.44	-1.29	-0.07	NZD^{SEA}	-3.32	-2.39	-1.37	-0.29
SEK^{EU}	-2.63	-1.82	-0.96	-0.06	SEK^{ID}	-1.77	-1.24	-0.68	-0.12

VIII. Appendix: Figures

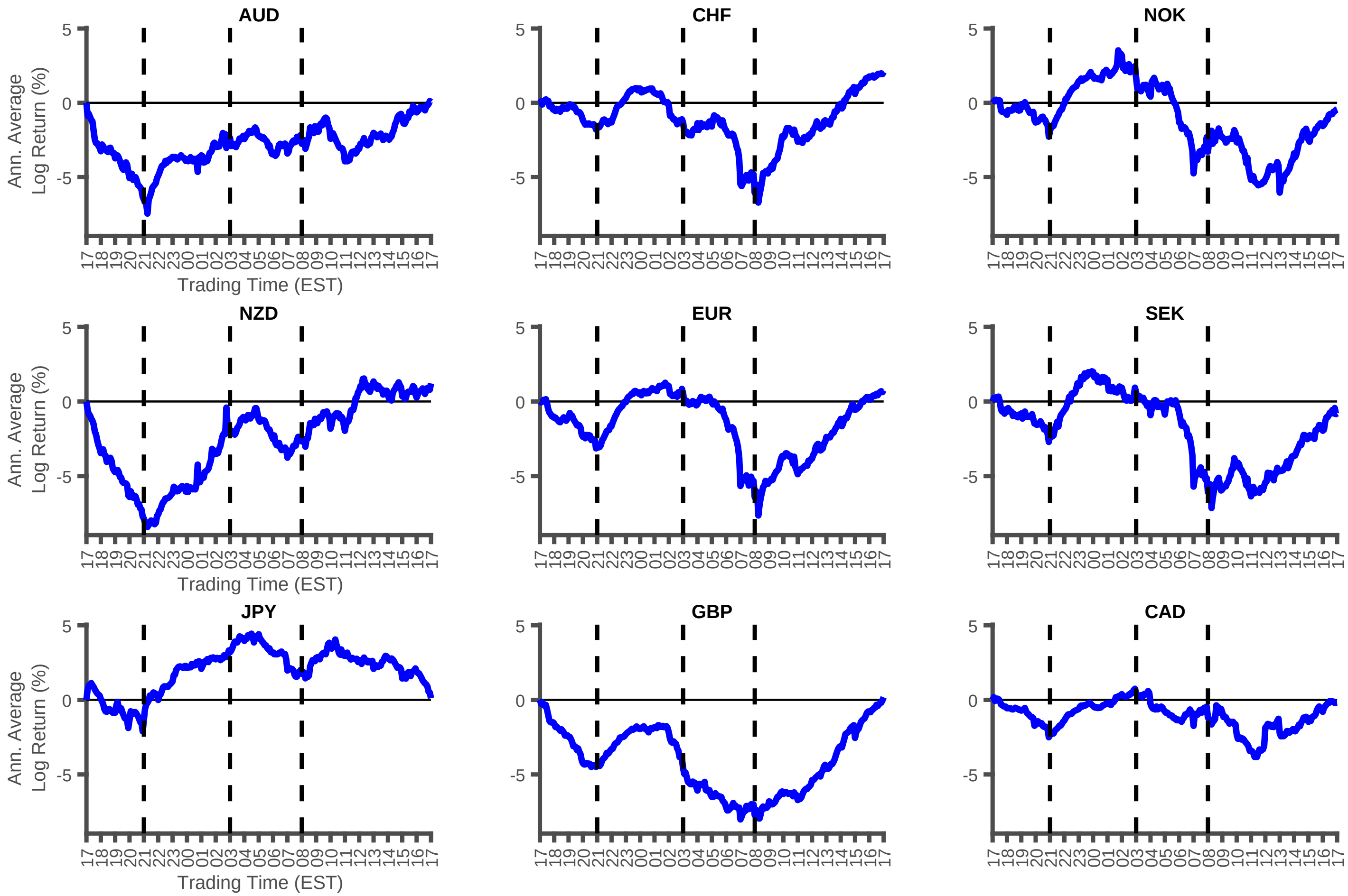


Figure 1. Cumulative 5-min Returns of Individual Currencies
This figure displays cumulative average annualized 5-min returns ($-\Delta s$) over the course of a trading day. An increase means the foreign currency appreciates against the U.S. dollar. The three black dashed lines at 9:00 p.m., 3:00 a.m., and 8:00 a.m. refer to the start of the trading hours in Sydney, south-east Asia, Europe, and New York. Trading hours (x-axis) refer to Eastern Standard Time (EST). The sample period comprises all months between January 1994 to December 2018 (300 monthly observations).

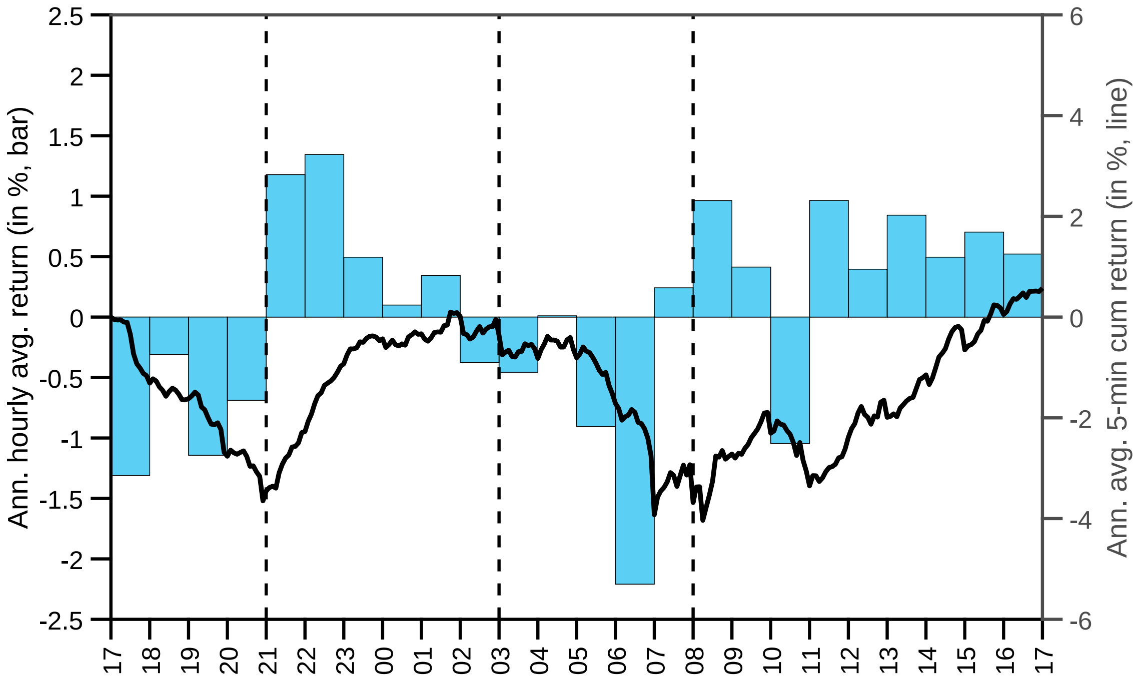


Figure 2. Cumulative 5-min Returns of the Unconditional Dollar Portfolio
This figure displays the cumulative average annualized 5-minute intraday returns ($-\Delta s$) of the unconditional dollar portfolio that goes long in all foreign currencies. An increase of the dollar portfolio implies that foreign currencies appreciate against the U.S. dollar. The three black dashed lines at 9:00 p.m., 3:00 a.m., and 8:00 a.m. refer to the start of the trading hours in Sydney, south-east Asia, Europe, and New York. Trading hours (x-axis) refer to Eastern Standard Time (EST). The sample period comprises all months between January 1994 to December 2018 (300 monthly observations).

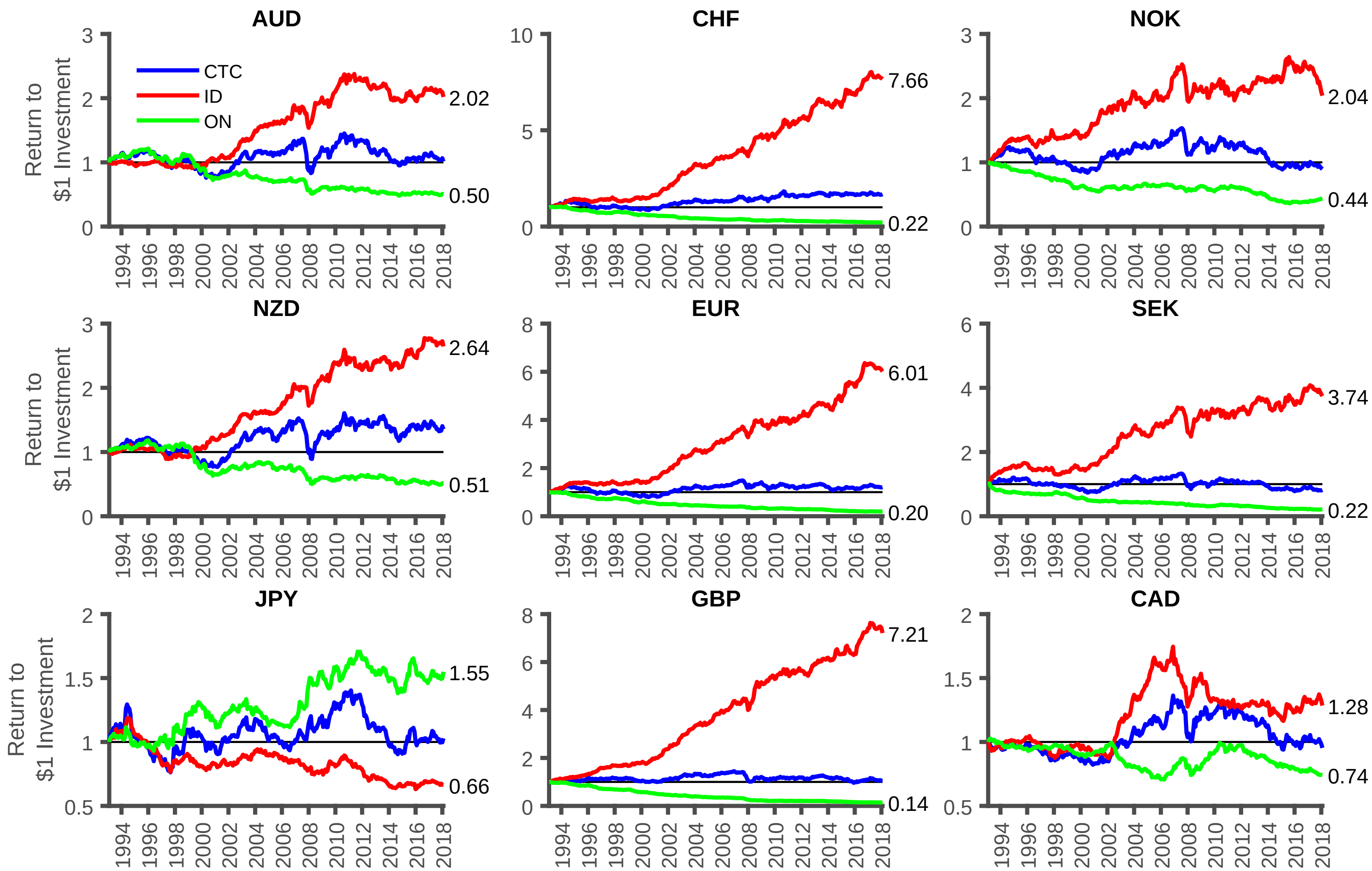


Figure 3. Total Return Indices: ID vs ON

This figure displays the total return indices (compounded simple monthly returns) for close-to-close (CTC), intraday (ID), and overnight (ON) time series starting with an initial investment of $1 in January 1994. The sample period is January 1994 to December 2018 (300 monthly observations).

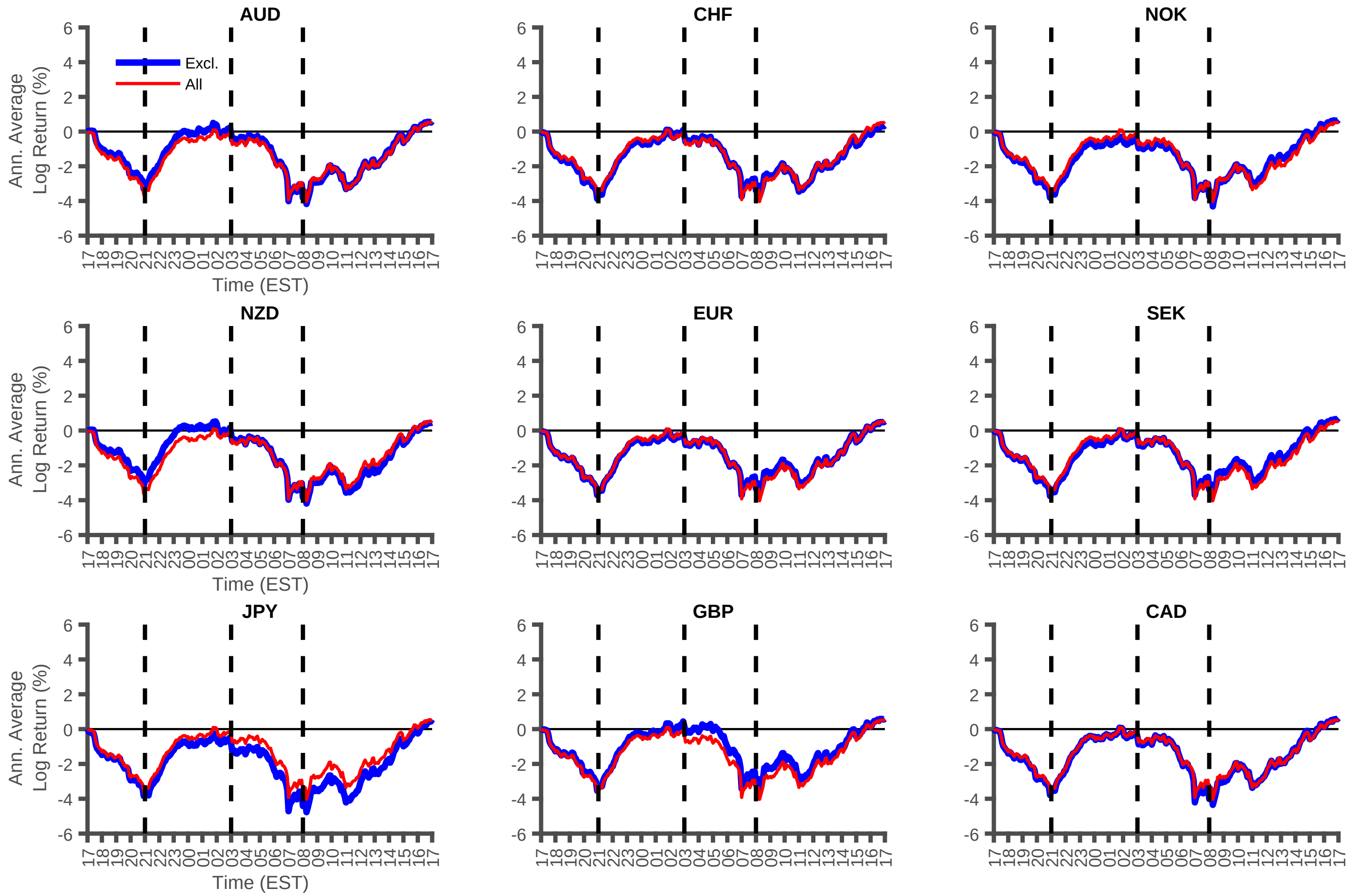


Figure 4. Dollar Portfolio: Alternative Currency Cross-sections

This figure displays the cumulative intraday return pattern of the unconditional dollar portfolio (blue line) for different currency cross-sections, whereby we exclude the currency indicated by the title. The red-line serves as comparison and refers to the dollar portfolio consisting of all ten foreign currencies. The three black dashed lines at 9:00 p.m., 3:00 a.m., and 8:00 a.m. refer to the start of the trading hours in Sydney, south-east Asia, and Europe. Hours (x-axis) refer to Eastern Standard Time (EST). The sample period comprises all months between January 1994 to December 2018 (300 monthly observations).

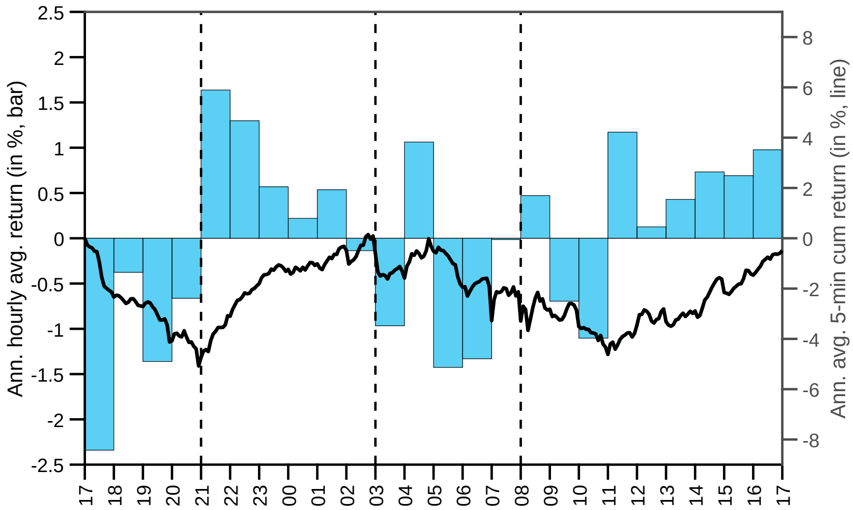


Figure 5. Dollar Portfolio: Hong Kong Dollar

This figure displays the cumulative average annualized 5-minute intraday returns of the unconditional Hong Kong dollar portfolio (red line). The red-shaded area refers to the 10% confidence interval of the cumulative intraday returns. The three black dashed lines at 9:00 p.m., 3:00 a.m., and 8:00 a.m. refer to the start of the trading hours in Sydney, south-east Asia, and Europe. Hours (x-axis) refer to Eastern Standard Time (EST). The sample period comprises all months between January 2005 to December 2017.

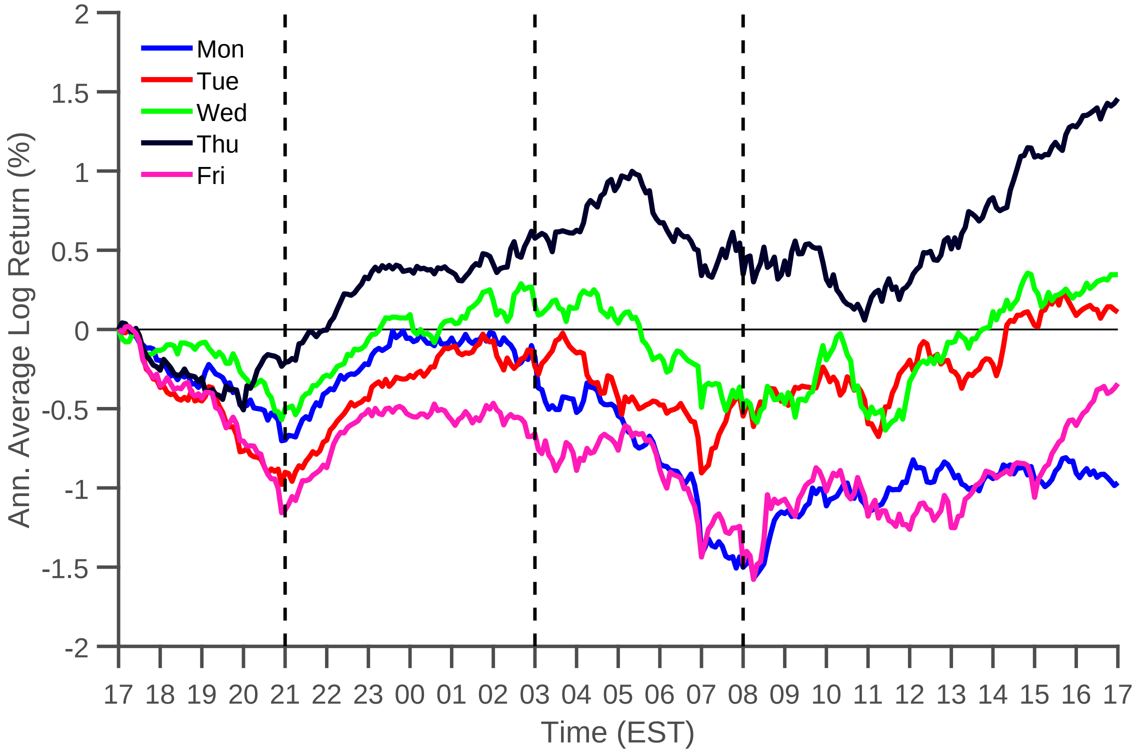


Figure 6. Intraday Cumulative Dollar Portfolio Returns: Day by Day
This figure displays the cumulative average annualized 5-minute intraday returns of the unconditional dollar portfolio, sampled by day of the week. The sample period comprises all months between January 1994 to December 2018 (300 monthly observations).

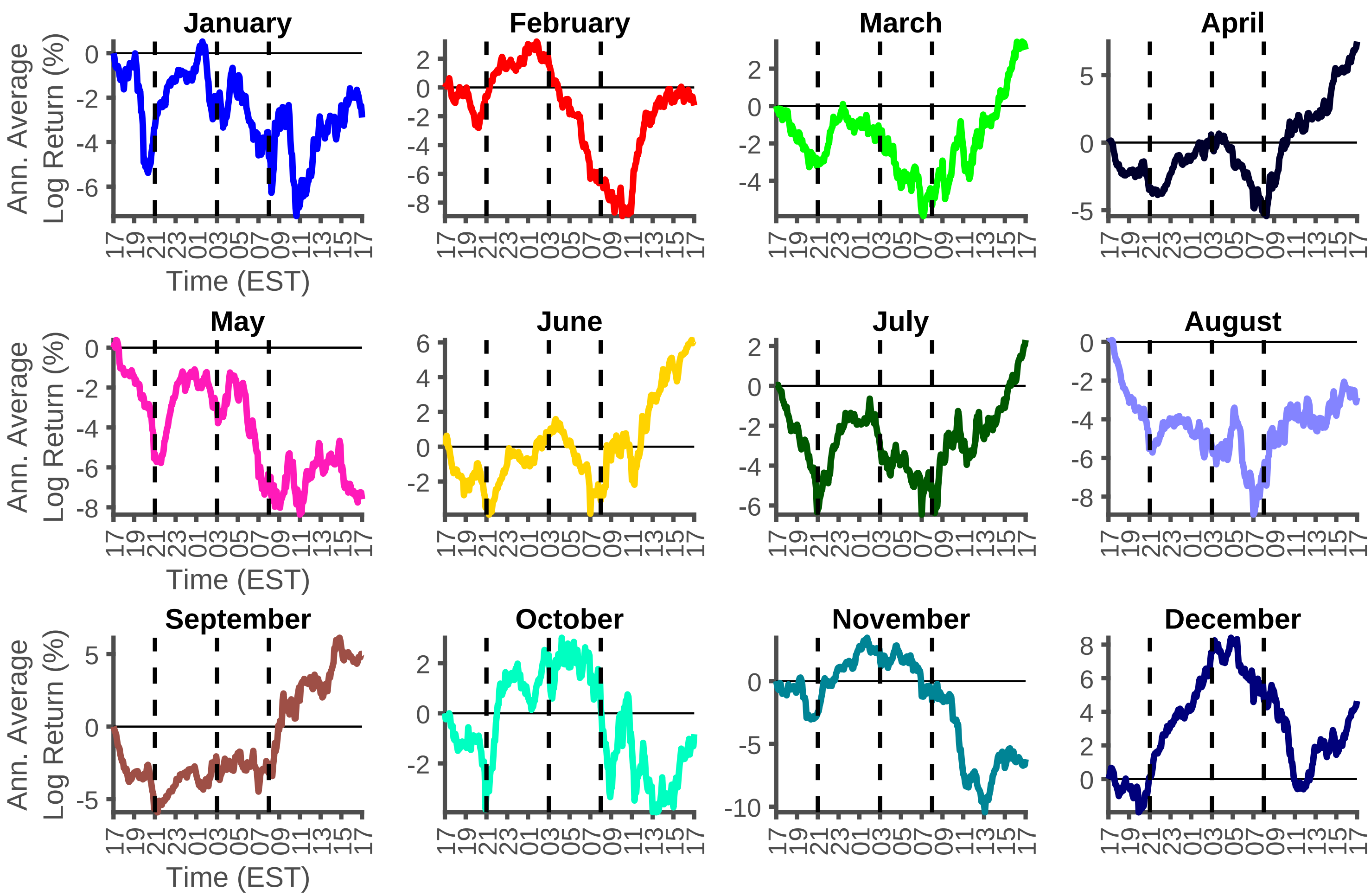


Figure 7. Intraday Cumulative Dollar Portfolio Returns: Month by Month
This figure displays the cumulative average annualized 5-minute intraday returns of the unconditional dollar portfolio, sampled by month of the year. The sample period comprises all months between January 1994 to December 2018 (300 monthly observations).

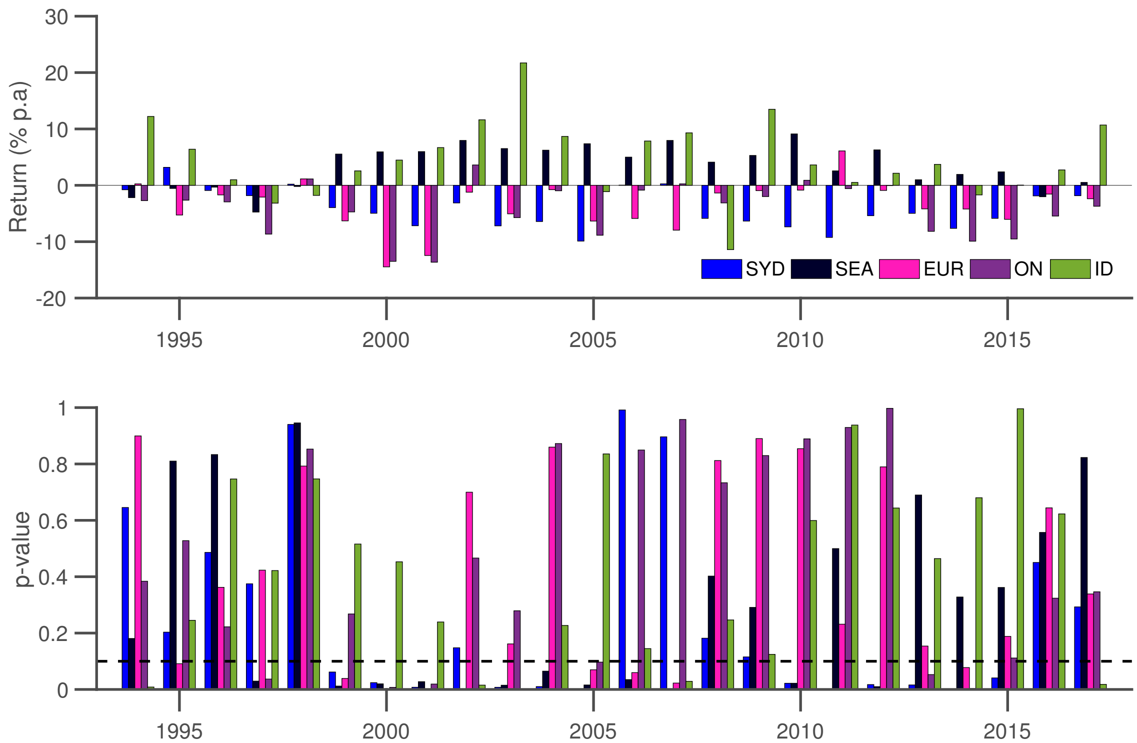


Figure 8. Dollar Portfolio Returns: Year by Year

This figure displays average yearly returns to the dollar portfolio sampled at different intraday sub periods: SYD which refers to returns after trading in Sydney commenced (5:00 p.m. to 9:00 p.m.); SEA which refers to returns subsequent to the opening of the main trading venues in Southeast Asia (Singapore and Hong Kong, 9:00 p.m. to 3:00 a.m.); EUR which refers to returns during main trading hours in Europe (3:00 a.m. to 8:00 a.m.). Time series starting with an initial investment of $1 in 1994. The top panel plots averages within each year. The bottom panel plots p-values from a t-test against the null of zero. The sample period is January 1994 to December 2018 (300 monthly observations).

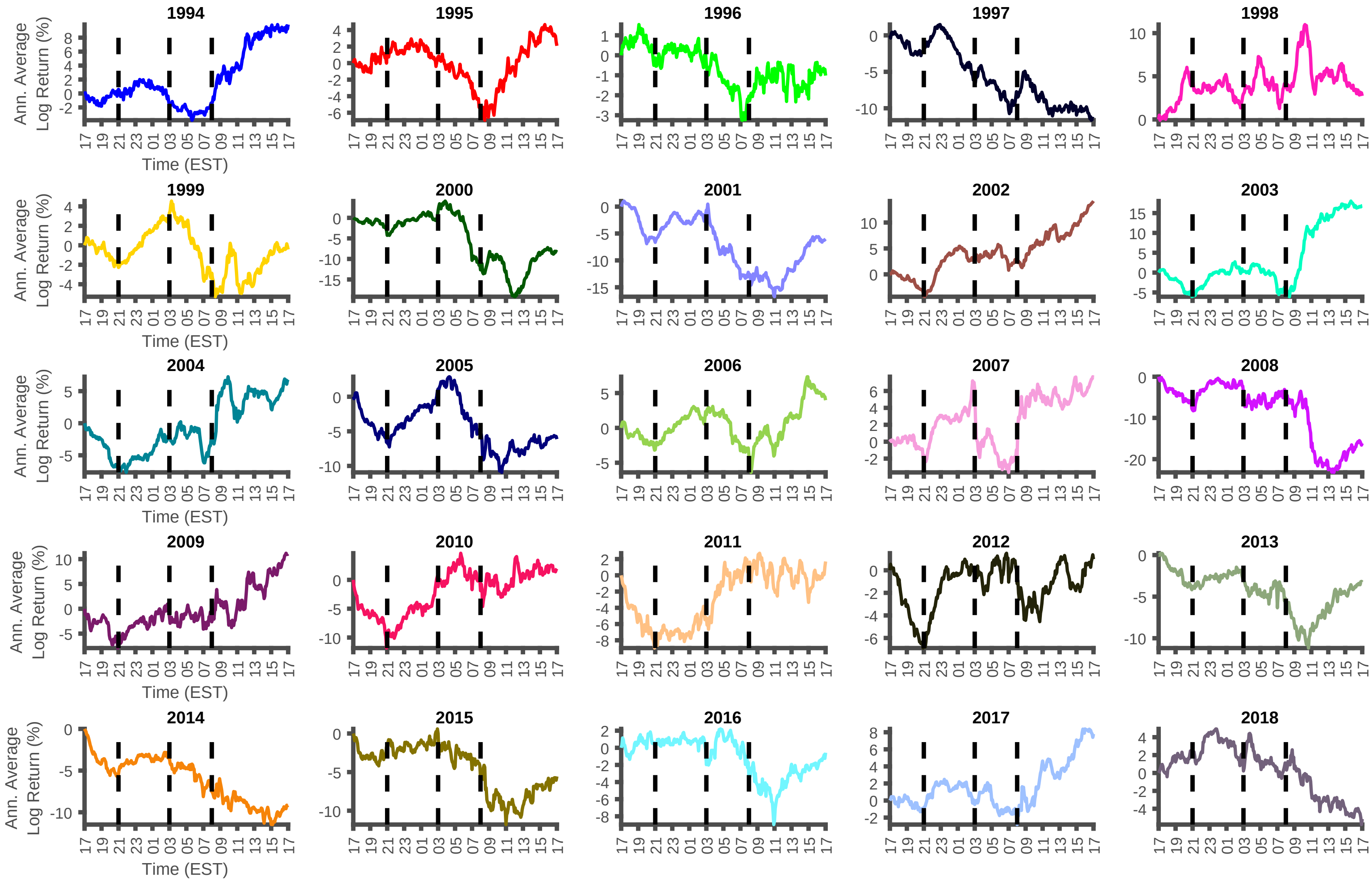


Figure 9. Intraday Cumulative Dollar Portfolio Returns: Year by Year
This figure displays the cumulative average annualized 5-minute intraday returns of the unconditional dollar portfolio, sampled for each year individually. The sample period comprises all months between January 1994 to December 2018 (300 monthly observations).

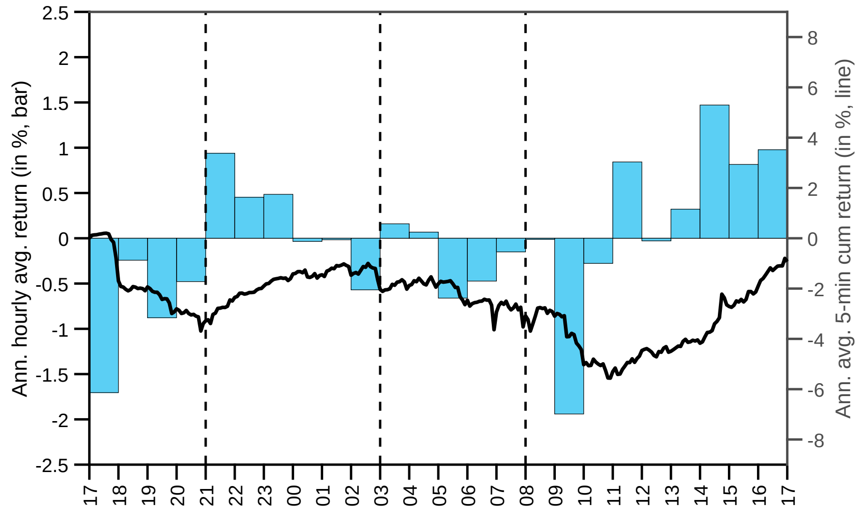
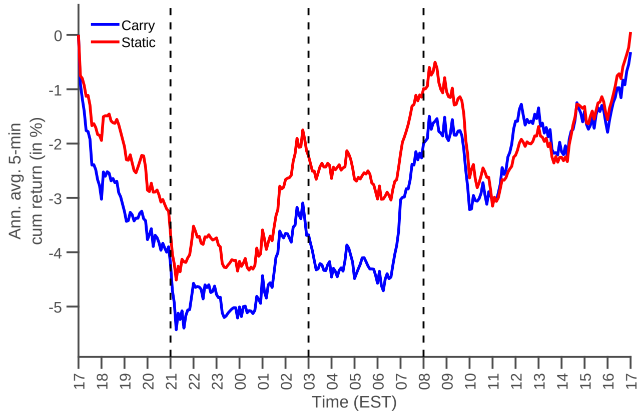
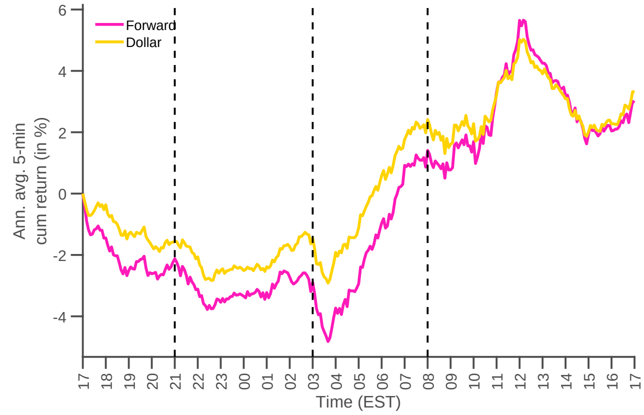


Figure 10. Dollar Portfolio: Currency Futures

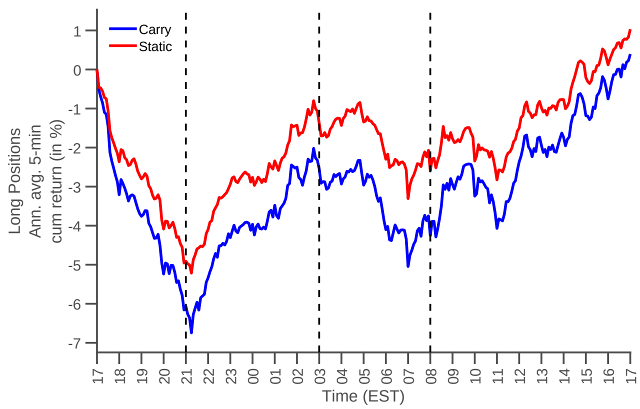
This figure displays the cumulative average annualized 5-minute intraday returns of the unconditional dollar portfolio constructed from FX Futures. The red-shaded area refers to the 10% confidence interval of the cumulative intraday returns. The three black dashed lines at 9:00 p.m., 3:00 a.m., and 8:00 a.m. refer to the start of the trading hours in Sydney, south-east Asia, and Europe. Hours (x-axis) refer to Eastern Standard Time (EST). The sample period comprises all months between January 1996 to December 2017.



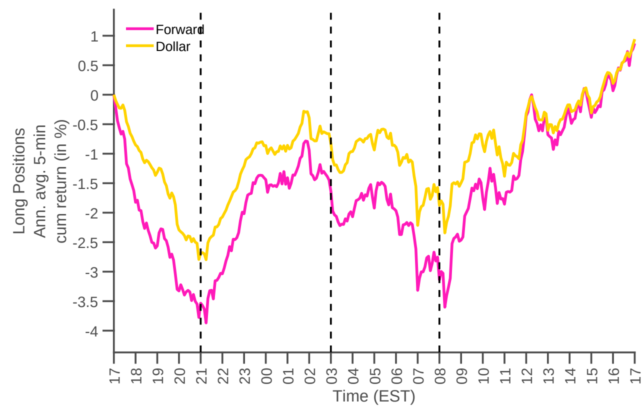
(a) FX Strategies Intraday I



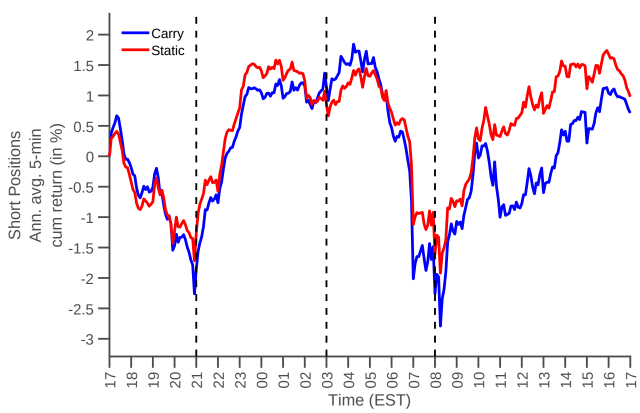
(b) FX Strategies Intraday II



(c) FX Strategies Intraday: Long Positions I



(d) FX Strategies Intraday: Long Positions II



(e) FX Strategies Intraday: Short Positions I

(f) FX Strategies Intraday: Short Positions II

Figure 11. FX Trading Strategies: Intraday Decomposition

These figures show cumulative average annualized 5-min returns over the course of a trading day for the static and conventional carry trade (left column) and the forward premium and dollar trade strategy (right column). The three black dashed lines at 9:00 p.m., 3:00 a.m., and 8:00 a.m. refer to the start of the trading hours in Sydney, south-east Asia, and Europe. Hours (x-axis) refer to Eastern Standard Time (EST). The sample period comprises all months between January 1994 to December 2018 (300 monthly observations).

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