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-four years of data on G10 currencies we unveil a distinct *'W'* intraday pattern of returns to the dollar portfolio. We show that positive average returns for going long foreign currencies are almost entirely generated during U.S. main trading hours, whereas currencies collectively depreciate against the U.S. dollar overnight. Moreover, we document that 75% of the HML portfolio returns from a standard carry trade strategy and almost 80% of dollar carry returns are generated during the U.S. trading day. Finally, we show that our main result may be exploitable by investors that are able to benefit from lower than average transaction costs.

Keywords: foreign-exchange, carry trade, high-frequency data, intraday and overnight returns, 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, it appears natural to study the exchange rate dynamics over the whole trading day and, thus, developing this theme, we document the following facts:

1. FX returns vary systematically over the course of a 24-hour period and the turning points coincide with market opening hours in Australia/New Zealand, Asia, Europe and 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 (with the sole exception of the British pound in the first and the Japanese yen in the second window).

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 over the whole 24-hour period.

4. Exploring the implications of these findings we show that from the perspective of a U.S investor: (*i*) carry and (*ii*) dollar carry factor returns are generated almost entirely during U.S. trading hours, while 'expectation hypothesis' type models of risk premia hold during the overnight period in the U.S.

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

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

(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 2017 during which these pairs cover approximately 67% of the total daily turnover in the foreign exchange market (see BIS (2016)).

Equipped with intra-day 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'.

The details of our findings are as follows:

First, 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.

Second, we revisit the canonical expectations hypothesis thesis of Fama (1984) that has been overwhelmingly rejected in the data using close-to-close returns. Building on the work by Lyons and Rose (1995) and Chaboud and Wright (2005), we split daily returns into different intraday components and show that the hypothesis that the slope coefficient β is equal to one cannot be rejected for any currency pair in our sample when only the overnight period is considered (although the intercept α is often significant). Using intraday data, however, the slope coefficient is significantly different from one for all but two currencies. Further, the intercept estimates appear to systematically take the opposite sign in the day than during the night. The results indicate that differences between forward rates and expected spot rates largely emerge during the day.

Third, 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. Overnight, all portfolios depreciate against the dollar and there is no significant spread. Hence, approximately 75% of carry returns are exclusively earned during the main U.S. trading hours. In addition, we document the intraday evolution of carry portfolio returns and show how high- and low- interest rate currencies contribute to the high-minus-low carry portfolio returns during different hours of the trading day.

Fourth, the unconditional dollar portfolio, a strategy that goes long a basket of foreign currencies on average has a non-significant return, appreciates significantly during the day and reverses during the night, reflecting the general pattern of the individual currencies. The dollar carry strategy, where the average forward discount serves as a signal to either go long or short the dollar portfolio, does not reverse overnight but actually yields a small (and insignificant) positive return, leading to a positive return overall. Approximately 20% of the conventional return of a dollar carry strategy can be attributed to overnight dynamics, while almost 80% of the dollar carry returns are generated between 8:00 a.m. and 5:00 p.m. (EST). Further, we find that foreign currency returns evolve very similar in the overnight period irrelevant of the average forward discount, and that portfolio returns only diverge from each other in the intraday period.

Fifth, we document intraday behaviour of the unconditional dollar portfolio which is in stark contrast to the dollar carry strategy. In fact, we provide evidence for a distinct intraday-overnight split of the dollar portfolio, which generates significantly negative returns over night and positive returns during the day. While Fourel, Rime, Sarno, Schmeling, and Verdelhan (2018) show that the dollar portfolio is a strong predictor of currency returns during the day and across different sampling frequencies, we highlight its diverging return patterns during the day and overnight, and document how it differs from the pattern of conditional dollar trading.

Summarising, 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, we also 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.

As intraday return dynamics appear to be robust and systematic, we next explore various risk factors that could be considered as the underlying source of the prevalent return pattern. Specifically, we assess the evolution of the dollar factor in different periods of the day Verdelhan (2018), decompose daily volatility into different intraday components, analyse the occurrence of intraday and daily jumps (Lee and Wang (2017)), and compare liquidity dynamics during the day and over the night (Mancini, Ranaldo, and Wrampelmeyer (2013), Karnaukh, Ranaldo, and Söderlind (2015)). For none of these factors dynamics appear to be significantly different between the intraday and overnight period which would allow us to link the return pattern, say as a mean of compensation, to a corresponding intraday pattern of one of these risk factors. Further, using NBER recession periods we show that intraday return divergences are not explained by business cycle dynamics. Positive intraday and negative overnight returns are resilient characteristics in recessions and economic upswings. We also control for returns on FOMC announcement days (Mueller, Tahbaz-Salehi, and Vedolin (2017)) and on a broader set of days related to U.S. macroeconomic news announcement days (Andersen, Bollerslev, Diebold, and Vega (2003)) to exclude the possibility that our inferences are driven by abnormal returns related to news diffusion or unexpected news announcements. Yet, the pattern of the dollar portfolio prevails on announcement as well as on days without macroeconomic announcements in the United States. Overall, we conclude that the intraday pattern of the dollar portfolio is not explained by any of the aforementioned risk factors.

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. Further, if one adjusts the bid-ask spread to the least conservative magnitude that is suggested by the literature and allowing for shorter holding overnight periods that account for the return reversals around opening hours of major trading venues, we document positive net returns for all individual currency pairs. If spreads are decreased to 25% of the reported size, average annualized net returns range between 0.21% (CAD) and 6.19% (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 investors.

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 describes the results with respect to currency risk premia during the intraday versus overnight period. Section IV summarizes an extensive set of robustness checks. Section V discusses intraday market characteristics such as volatility, liquidity, and trading costs which affect return dynamics differently during the course of the trading day 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 2017, covering 24 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 June 1998 to December 2017. To extend the length of our sample period, we supplement the TRTH data for the January 1994 to May 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),

[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.

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 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), 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]

[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.

[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

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 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 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 $d-1$

$$\Delta S_d^{CTC} = \frac{S_d - S_{d-1}}{S_{d-1}}. \tag{1}$$

Our choice of closing time differs from the "London fix" time at 4:00 p.m. GMT normally used 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, 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

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.

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 venues located outside of the U.S. (see, e.g., BIS (2016)). We define three further subperiods: The first period starts with the opening of markets in Sydney and ends when trading Singapore and Hong Kong starts (5:00–9:00 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.). While the majority of our analysis focuses on the diverging patterns between the intraday and overnight period, we also provide insights on return movements related to the three overnight subperiods, related to the start of trading in the respective major trading venue commences.[9]

More formally, following Lou, Polk, and Skouras (2017), we define intraday (ID) and overnight (ON) components in the following way:

$$\Delta S_d^{ID} = \frac{S_d^{5:00p.m.} - S_d^{8:00a.m.}}{S_d^{8:00a.m.}} \qquad \Delta S_d^{ON} = \frac{1 + \Delta S_d^{CTC}}{1 + \Delta S_d^{ID}} - 1$$

This ensures that our intraday and overnight return measures add up exactly to the close-to-close returns. Having the intraday versus overnight split we then aggregate all daily (normal) returns within every month ($d \in t$) to a monthly frequency as follows:

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

[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.

$$\Delta S_t^{CTC} = \prod_{d \in t}(1 + \Delta S_d^{CTC}) \qquad \Delta S_t^{ID} = \prod_{d \in t}(1 + \Delta S_d^{ID}) \qquad \Delta S_t^{ON} = \prod_{d \in t}(1 + \Delta S_d^{ON})$$

For the full sample we thus obtain 288 monthly observations for CTC, ID and ON returns. Lastly, we log-transform returns ($\ln \Delta S_t = \Delta s_t$) such that $\Delta s_t^{CTC} = \Delta s_t^{ID} + \Delta s_t^{ON}$.[10] Equipped with these return series we proceed to examine different dynamics of intraday and overnight currency 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 2017. Starting at 5:00 p.m. New York time the white area refers to the overnight period (5:00 p.m. – 8:00 a.m.) and the grey-shaded area (8:00 a.m. to 5:00 p.m.) depicts the main trading hours in New York (intraday period). 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 13 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. In addition, we also plot the hourly average log returns over the sample period using grey-shaded boxes for the intraday

[10] Alternatively, returns can directly be expressed in logs and aggregation then happens on the daily level. Again, the approach ensures that intraday and overnight returns add up to daily CTC (log) returns.

and blue-shaded boxes for the overnight period. 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. The dollar portfolio that does not include the Japanese yen exhibits larger swings in the second half of the day, as the yen moves largely counter-cyclically to the other G10 currencies during the day.

[INSERT FIGURE 2 HERE]

Table I summarizes Figures 13 and 2 more formally as it contains the average FX log returns (i.e., exchange rate changes) for the various subperiods 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. (and, consequently, CTC returns are the sum of either columns one, two, three and five or just four and five).

[INSERT TABLE I HERE]

As is evident already from Figure 13, all foreign currencies depreciate against the U.S. dollar after trading in New York ceases. The Australian and New Zealand dollar (-6.48% and -8.62%, 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 -0.07% (GBP) and 6.34% (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 (-6.83%), the EUR (-7.52%), the GBP (-8.69%), followed by the Scandinavian currencies, the SEK (-5.78%) and the NOK (-3.98%). 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 8.61% for the CHF and 1.17% for the CAD. In summary, all returns are positive during the intraday period and negative over night with the exception of the Japanese yen, that shows an opposite pattern, appreciating during the night and depreciating over night by 1.6% 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 2017 for a position that is held for the whole period (CTC, blue) or only during overnight or intraday trading hours (ON, yellow 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 pounds during the intraday period at the end of January 1994, she would have obtained a return to this investment equal to 6.70 USD in December 2017. In contrast, the same trading approach with an overnight position would have led to a portfolio value of approximately 0.11 USD at the end of the sample period. Holding the position for the full 24 years would have resulted in a value of roughly 1.18 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 6.79 USD and 0.17 USD, respectively.

C. Futures Returns

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 line of figure 2 repeats the analysis above by cumulating 5-minute returns on the most liquid futures contracts for each pair, which is almost always the front month contract except in expiration months around settlement Wednesdays. The *'W'* shaped return pattern in the unconditional dollar portfolio is clearly visible. We note that this pattern is computed for a different sample period that the black line computed from TRTH mid-quotes (2005-20017 versus 1994-2017), and accounting for variation in interest rate differentials does not materially affect our main result.

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

D. Robustness

To confirm the robustness of our findings, we conduct an extensive set of tests. Here, we provide a brief summary of the findings and we defer the details of the robustness checks to the appendix.

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. Second, we re-calculate carry and dollar carry returns while excluding the Japanese yen from the cross-section as this is the only currency in the sample that seems to behave considerably different from the other currencies. 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. Third, we check if the systemic intraday pattern is also prevalent for currencies pegged against the U.S. dollar. 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. We find that the exact same intraday return pattern is resembled by the HKD portfolio, and it closely tracks the cycle of appreciations and depreciation of the U.S. dollar portfolio. Finally, we analyse portfolio dynamics for different time periods over the full sample window since 1994. We find that the return patterns are persistent across trading days of the week, months of the year, and, broadly, across different years.

III. Dissecting Currency Risk Premia

Having established that currency returns exhibit a distinct pattern over the a 24-hour period, we next investigate the implications of these findings for well-established facts in the FX literature that are generally based on an analysis of close-to-close returns. We begin our analysis by re-visiting the expectation hypothesis regressions of Fama (1984) using our monthly series based on close-to-close, intraday and overnight returns, respectively. Similarly, we also examine to what extent returns to carry trade (Lustig, Roussanov, and Verdelhan (2011)) or dollar carry trade strategies (Lustig, Roussanov, and Verdelhan (2014)) are driven by intraday and overnight exchange rate dynamics.

A. Forward Premium Regressions

We start by running the same regressions as in Fama (1984) to test the expectations hypothesis and re-examine the forward premium puzzle. To this end, we estimate the following regression:

$$\Delta s_{t+1} = \alpha + \beta(f_t - s_t) + \epsilon_{t+1} \tag{2}$$

where $\Delta s_{t+1} = s_{t+1} - s_t$ refers to the monthly log exchange rate change, f_t denotes the 1-month log forward rate and s_t is the log spot rate in period t. Unlike in the original specification we estimate three separate versions of equation (2) by using our monthly close-to-close, intraday, or overnight return time series as the dependent variable on the left-hand side, respectively. The forward discount on the right-hand side of the regression is constructed using monthly forward and spot rates obtained from WM/Reuters via *Datastream*. As widely discussed in the literature, under the expectations hypothesis the intercept is expected to be zero ($H_0 : \alpha = 0$) and the slope coefficient to be equal to one ($H_1 : \beta = 1$).[12] The hypothesis implies that the forward rate is an unbiased estimate of the future spot exchange rate. As rational agents drive the value of the forward rate to the price of the expected future exchange rate, speculation in the forward market is not profitable. In contrast, if the forward rate is higher (lower) than the expected spot rate, market participants earn a premium from buying (selling) a currency in the forward market. Deviations of the slope coefficient from unity are also consistent with the existence of a time-varying risk premium (Fama (1984)). Table II summarizes the regression results.

[INSERT TABLE II HERE]

Using close-to-close returns we largely confirm the existing evidence in Panel A of Table II: The estimate of the intercept is close to zero and not significant. At the same time, the point estimate for the slope coefficient is negative apart from the NZD and significantly different from one for a third of the currencies (AUD, EUR, and SEK). Once we split up the close-to-close return series into an intraday and an overnight component, the results become much more unambiguous. For the intraday regressions (Panel B in Table II), the point estimate for the intercept term is now always negative and significantly different from zero for six out of nine currencies. At the same time, the

[12]For an extensive survey, see for example Engel (1996).

slope coefficient is negative again for all currencies except the NZD, ranging between -2.52 (EUR) and 1.09 (NZD). Moreover, the estimate is significantly different for seven out of nine currencies; we are not able to reject the null hypothesis $H_0 : \beta = 1$ only for the Norwegian krone (NOK) and the New Zealand dollar (NZD). The results are consistent with significant non-zero risk premia during the intraday period. Interestingly, we find that the regression results are largely reversed during the overnight period (Panel C in Table II). First, all coefficient estimates for the intercept (with the exception of the JPY) are positive ranging between -0.02 (JPY) and 0.68 (GBP). In addition, the intercept term is significantly different from zero for all European currencies (CHF, EUR, GBP, NOK, SEK). Second, while almost all slope coefficients are negative during the day, there is no clear pattern for the sign of the coefficient during the night. The estimates range from -0.67 (NZD) to 1.13 (CAD), and none of them is significant. Moreover, we cannot reject the null hypothesis $H_0 : \beta = 1$ for any of the nine currencies we consider.

In summary, our findings suggest that deviations from the expectation hypothesis are largely driven by return dynamics observed during U.S. trading hours. As we cannot reject the null hypothesis that the slope coefficient is equal to one during the overnight period the results point towards the existence of a risk premium that is only statistically different from zero during certain hours of the trading day. The results are also consistent with the view that rational agents' expectations about the future path of the spot exchange rate are in line with the forward rate during overnight hours, but then deviate when trading in New York commences. The differences in expected and realized future spot rates generate room for a risk premium which seems to be earned mainly during the day (in the U.S.).

B. Carry Trade Revisited

As the previous results suggest that risk premia occur largely during the day, we next examine what diverging FX return dynamics imply for other well-known FX strategies. To this end, we follow Lustig and Verdelhan (2007) and Lustig, Roussanov, and Verdelhan (2011) and sort currencies' excess returns into portfolios based on their forward discount $f_t - s_t$. At the beginning of each month, we allocate currencies into three portfolios, whereby portfolio 3 (P3) contains the three currencies with the largest forward discount or, equivalently, the highest interest rates, while the three currencies with the lowest forward discount are assigned to portfolio 1 (P1).

Monthly portfolio returns are calculated as the equally-weighted average of currency excess returns contained in the portfolio. Following Lustig, Roussanov, and Verdelhan (2011) we also construct a high-minus-low portfolio from the difference between high (P3) and low interest rate portfolios (P1). Finally, we also report the returns from the unconditional dollar portfolio (dol) that captures returns earned from going long all nine foreign currencies. Portfolios are rebalanced every month based on the forward discount at the end of the month and we form three sets of portfolios using the close-to-close, intraday and overnight return series, respectively. Note that for all three sets the portfolio composition is the same as we use on sorting criterion, the forward discount at the time of portfolio formation. Table III summarizes annualized average excess returns and associated t-statistics for the three sets of carry trade portfolios.

[INSERT TABLE III HERE]

As before, we start by verifying the well-known finding that portfolio excess returns are monotonically increasing in the interest rate differential from −1.44% for P1 with low interest rate currencies to 2.89% for the high interest rate currency portfolio (P3) (see top of Panel A in Table III). The high-minus-low (HML) portfolio generates an excess return of 4.33% per year and is highly statistically significant.[13] The excess return to the unconditional dollar portfolio is a measly 0.67% per year and not statistically significant. Decomposing the carry trade returns into an intraday and overnight component again reveals some striking results (see bottom of Panel A in Table III). First, for all three portfolios we find that there is a significant intraday vs. overnight reversal in average excess returns, mirroring the results from Section B for individual currencies and the overall portfolio. For the high interest rate currency portfolios, the returns range between 6% for the intraday and −3.05% for the overnight period, whereas the spread is slightly smaller for the low interest rate currency portfolios with 2.74% and −4.17, respectively. Second, for both the intraday and the overnight period, the excess returns to the high interest rate currency portfolio are higher than excess returns to the low interest rate currency portfolio, leading to positive excess returns for the HML portfolio for both periods. However, the returns are only monotonically increasing during the intraday period and the difference is only statistically significant during the day. Third, this implies that the return to the carry portfolio is predominantly earned during the

[13] As a comparison, in Lustig, Roussanov, and Verdelhan (2011) the average annualized return for the high-minus-low portfolio for developed countries is 5.88% per annum during the period from November 1983 to December 2009.

U.S. trading hours. For our sample, 75% of the total carry return or 3.25% per year are earned during the intraday period. The remaining 25% or 1.12% per year are earned during the overnight period although the return by itself is not statistically significant.

It is worth noting that the results based on forward discount sorts are in line with the time series regressions presented earlier. Overall, the carry trade strategy is more profitable during the intraday period, when expectations of the future spot rate and forward rate diverge from each other. During the overnight period when the expectations hypothesis cannot be rejected statistically, the carry trade strategy also appears less profitable.

We further examine the evolution of the spot return component of carry trade portfolios over the course of the full 24-hour period (note that we assume that the interest rate component is earned linearly over the trading day so any high-frequency variation must come from spot exchange rate changes). Thus, we calculate average portfolio returns (i.e., average log exchange rate changes, not average excess returns!) for every five-minute interval and for all the portfolios. The resulting cumulative returns over the day are shown in in Figure 4 for the high-minus-low portfolio (HML, black line), as well as the high and low interest rate currency portfolios, respectively (P3, blue line and P1, green line).

[INSERT FIGURE 4 HERE]

First, it is important to note the that the graphs in Figure 4 only reflect spot rate changes and not interest rate differentials. As is evident from the figure, the average return for the HML portfolio is slightly negative over the course of the 24-hour day. This means that on average over our sample period, high interest rate currencies slightly depreciate versus the low interest rate currencies in line with the predictions of uncovered interest rate parity. However, the depreciation is not strong enough to offset the positive interest rate differential that is earned by going long high interest rate currencies while shorting low interest rate currencies. Thus, overall, the returns to the carry trade over our sample period are mainly due to the interest rate differential that is not fully offset with the corresponding depreciation of high interest rate currencies.[14] Second, the graphs illustrate roughly how all portfolios appreciate during the day but lose value during the overnight period. However, there are distinct differences in the dynamics of the high and low

[14]For earlier sample periods, the carry trade was profitable on both legs. Instead of depreciating, high interest rate currencies even appreciated against funding currencies.

interest rate currency portfolios, respectively, that ultimately determine the pattern of the HML portfolio over the day. Initially, portfolio P3 drops quicker and more severely than P1, leading to a drop in the HML portfolio. The reversal after 9:00 p.m. New York time is roughly the same for both portfolios, leading to a roughly flat evolution of the HML portfolio until about 5:00 a.m. New York time. At this point the currencies in portfolio P1 depreciate much more strongly compared to currencies in portfolio P3, leading to a steep increase in the HML portfolio until markets in NY open. During the day, the HML portfolio fluctuates around but overall, there is not a significant change in value during U.S. trading hours.

In Panels B and C in Table III we consider trading strategies that exploit the reversal in returns when moving from the intraday to the overnight period. The portfolios in Panel B all go long the foreign currencies during the day and short during the overnight period. The resulting returns are very high and statistically significant for all three portfolios, irrespective of the interest rate differential. In fact, once the intraday-overnight reversal is exploited, the difference between high and low interest rate currency portfolios is no longer statistically significant. Quite naturally, the excess return to a signed dollar portfolio is now also large and statistically significant, given the strong reversal pattern that is common to all currencies with the exception of the Japanese yen. The most profitable of the hypothetical trading strategies (given that we abstract from transaction costs at this point) is a strategy that goes long the high interest rate currencies during the day and short the low interest rate currencies during the night (Panel C in Table III). The average annualized return for such an approach is 10.16% (t-stat: 6.04). The return from the alternative reversal strategy ($P1^{Intra} - P3^{Over}$) is comparably smaller, but still of a larger magnitude compared to returns from a conventional HML carry trade strategy (5.80% versus 4.33% per annum).

Overall, it appears that the results from the forward premium regressions are mirrored in a cross-sectional currency portfolio exercise. We find carry trade returns are almost entirely generated during the day, while overnight speculation in the forward market does not appear to be profitable. Moreover, during our sample period, the main source of profitability of the carry trade is the interest rate differential whereas the exchange rate component of the HML portfolio exhibits slightly negative returns on overage. Over that day, the HML portfolio is rather volatile with a distinct period between around 6:30 a.m. and 8:30 a.m. during which it strongly appreciates driven by a sharp drop in low interest rate currencies in the hours before U.S. markets open.

C. Dollar Carry Decomposition

The unconditional dollar portfolio in Table III already points towards potential profits that can be earned from buying and holding U.S. dollar during certain times of the day, unconditional of the movements of the forward discount. As a next step, we further examine potential trading profits that can be exploited by conditioning the direction of the trade on the average implied interest rate, or equivalently, average forward discount (AFD). Following Lustig, Roussanov, and Verdelhan (2014), we construct dollar carry trade portfolios, which are based on the sign of the AFD defined as

$$\bar{f}_t - \bar{s}_t = \frac{1}{N}\sum_{i=1}^{N} f_t^i - s_t^i \tag{3}$$

where $\bar{f}_t - \bar{s}_t$ is the average monthly forward discount, and f_t^i and s_t^i are the one-month forward rate and spot rate for country i in month t, respectively. We use the AFD as an end-of-month signal to allocate the nine currency excess returns into different portfolios. We follow a trading strategy where we invest in foreign currencies if the AFD takes positive values, and we sell the quote currencies otherwise. Again, we analyse the dynamics for monthly close-to-close, intraday, and overnight returns. The results are shown in Table IV. The column "ADF ≤ 0" refers to months in which we short the foreign currencies following a negative signal, but do not trade otherwise. The column "ADF > 0" applies the alternate strategy, whereby we invest in foreign currencies following a positive ADF, but do not trade in the remaining months. We obtain a signal to invest in foreign currencies in 160 months, and to short foreign currencies in the remaining 128 months. The column "dollar-carry" refers to returns from a dynamic trading strategy during which we buy and sell foreign currencies in every month, depending on the signal that we obtain from the ADF. As a comparison, we report the return of "ADF ≤ 0 (excl. 0)" and "ADF > 0 (excl. 0)' if we exclude the months, in which no trade is conducted, and returns of the unconditional dollar portfolio.

[INSERT TABLE IV HERE]

In contrast to the unconditional dollar portfolio constructed in the previous section, the dollar carry portfolio based on close-to-close returns generates a significant and positive return of 3.65%

(t-stat: 2.27).[15] Further, we note that dollar carry returns are largely generated during New York trading hours. Table IV shows that intraday dollar carry trade return is 2.86% (t-stat: 2.42). This is equivalent to almost 80% of the dollar carry trade strategy based on close-to-close returns. A large fraction of these profits is attributed to long positions of foreign currencies during U.S. trading dollar (3.79%), as the dollar tends to depreciate during these times. Holding short positions of foreign currencies during the day only generates 0.93%. We find opposite dynamics for the overnight period during which returns from shorting and buying foreign currencies are both negative. Yet, the overnight dollar carry strategy generates positive, even though not significant, returns of 0.85%. It is worth noting that these low but positive returns are driven from shorting the U.S. dollar when the AFD $\leq$ (-2.43%). Hence, while the dollar-carry strategy is positive during the day and overnight, the unconditional dollar portfolio is always negative over night.

In Panel B and C, we examine overnight minus intraday returns, as well as different reversal strategies that exploit the diverging return trends between these two periods. In Panel B, almost all strategies generate positive returns that are statistically different from zero at the 5% level or higher. Returns from this simple trading approach are in the range of 2.06% (Dollar Carry) and 9.72% (AFD $>$ 0). Furthermore, we find that the AFD can be used as a signal to build reversal trading strategies (Panel C). A trading approach that shortens foreign currencies over night and buys them during the day ($AFD^{Intra} > 0 - AFD^{Over} \leq 0$) generates a return of 6.22% with a t-statistic of 5.83. These results suggest that returns from a conventional dollar carry trading strategy can be enhanced by exploiting intraday return movements.

The dynamics of the intraday spot component of the dollar carry portfolios are shown in Figure 5. The figure shows the cumulative spot returns over the course of the trading day for the dollar carry portfolio (black line), for portfolio returns in months where investors go long foreign currencies (blue line, AFD $>$ 0), and portfolio returns where investors short foreign currencies (green line, AFD $\leq$ 0).

[INSERT FIGURE 5 HERE]

As displayed in Figure 5, dollar carry returns decline between the end of trading in New York and the start of the trading day in Southeast Asia. Subsequently, foreign currencies appreciate

[15] As a comparison, Lustig, Roussanov, and Verdelhan (2014) report an average annualized raw return of 5.60% for the dollar carry strategy for developed countries for the period November 1983 to June 2010

between 9:00 p.m. and 3:00 a.m. which results into positive cumulative dollar carry returns. This positive development even continues in the following few hours but it is then largely driven by the steady depreciation of foreign currencies in months when the average forward discount is negative. At the beginning of the intraday period, we note that the dollar carry return is already positive, and then continues to increase until 5:00 p.m. in the afternoon. In contrast to HML carry returns, the dollar carry portfolio does not exhibit a drop in the run-up to the London 4:00 p.m. fix, but instead indicates a strong appreciation of foreign currencies around the end of European trading hours. A further difference compared to Figure 4 is that differences between the intraday and overnight period are less distinct. While the majority of the dollar strategy's return is also generated during trading hours in New York, returns are negative only for a short period of time during the first few hours of the overnight period and lower in magnitude. Lastly, it is worth noting that portfolio returns of AFD > 0 and AFD ≤ 0 share the same dynamics for most part of the overnight period, and that these portfolio returns only start to diverge from each other once trading in Europe and New York commences. It is this diverging return spread which makes the dollar carry strategy profitable.

IV. Risk Based Explanations

As the previous section indicates that our findings are robust to different return specifications and alternative definition of intraday periods, we next explore possible explanations for the diverging pattern between intraday and overnight returns. In particular, we compare the dollar exposure across currencies during the day and overnight (Verdelhan (2018)) and we analyse the role of intraday volatility, currency jumps, and liquidity dynamics. Also, we contrast returns in crises periods and on announcements days - FOMC and general macroeconomic announcements - with dynamics of the average day, to investigate if the found intraday patttern in recessions and on announcements days are potentially driving our findings.

A. Dollar Risk Factors

In line with Verdelhan (2018), we assess the exposure of each bilateral exchange rate versus the U.S. dollar portfolio in a simple regression framework of the form

$$\Delta s_t^i = \alpha + \beta^i Dol_t + \varepsilon$$

where Δs_t^i refers to the change in the spot rate in period t and $Dol_t = \frac{1}{N}\sum \Delta s_t^j$, where $j \neq i$, refers to the unconditional dollar portfolio that excludes the currency pair on the left-hand side of the regression. We estimate the regression for close-to-close (Verdelhan (2018)), intraday (Fourel, Rime, Sarno, Schmeling, and Verdelhan (2018)), and overnight monthly return series in order to obtain a complete decomposition of currencies' time-varying exposure to the dollar factor (β^i) over the day.[16]. Comparing the dollar exposure between the intraday and overnight period, we note the following observations. First, the coefficient associated with the dollar portfolio is significant and positive for all currencies in the intraday and overnight period. Intraday it ranges between 0.30 (JPY), and 1.44 (SEK), and 0.31 (JPY) and 1.34 (NZD) overnight. Second, while differences are small, intraday coefficients are almost always larger than overnight. Notable exceptions are the Australian dollar (AUD) and New Zealand dollar (NZD), where the dollar factor is larger in magnitude during the night. Third, the explanatory power of the dollar factor is slightly larger for all currencies during the intraday period. Intraday (overnight) the lowest adjusted $\bar{R}^2$ is 0.08 (0.04) and it increases to up 0.74 (0.62) for the euro. Overall, there are no systematic differences between overnight and intraday dollar factors; thus we conclude it is unlikely that the exposure to the U.S. dollar is the explanation for the findings we document above.

B. Volatility

A possible explanation for the diverging return patterns during the intraday and overnight periods could be that investors demand a higher compensation for buying or selling a foreign currency if the volatility in one period is higher relative to the remaining time of the day. To control for this explanation, we conduct a simple variance decomposition of close-to-close returns in Table V. For all currency pairs and different specifications of the dollar portfolio, the table shows the

[16]The complete regression results are shown in the Online Appendix.

variance, which can be attributed to the intraday and overnight period, and the associated scaled covariance term. Numbers in squared brackets denote the fraction that each intraday component contributes to the overall total daily variance.

[INSERT TABLE V HERE]

For most currency pairs, the intraday and overnight variances contribute roughly the same share to the total daily return variance. Exceptions to this observation are Asian-Pacific currencies (AUD, JPY, NZD), for which the overnight variance is slightly larger to the intraday values. As the opposite is true for most European currencies and the Canadian dollar, the higher level of volatility is likely to be related to the increasing trading activity of these currencies during their local trading hours. The only exception to this pattern is the British pound where the overnight variance is slightly higher compared to the intraday period. For the dollar portfolio, we note that differences between overnight and intraday volatility are almost the same. Due to the small differences between overnight and intraday volatility, as share of close-to-close volatility (0.45), we suppose it is unlikely that return volatility is the main driver of the diverging intraday and overnight pattern.

To shed further light onto the intraday volatility pattern, we exhibit the average absolute percentage change at each five minute time-stamp over the trading day in Figure 6.

[INSERT FIGURE 6 HERE]

For all currency pairs we observe a spike of the intraday volatility at the end of the trading hours in New York, before volatility decreases significantly in the subsequent hours. Most currencies, in particular the Japanese yen, show an increase in the volatility pattern before trading commences in Singapore and Hong Kong, and it decreases subsequently until approximately 1:00 a.m. At this point of the trading day, which coincides with the opening hours of trading venues in Europe, a distinct increase in volatility can be observed for all currency pairs. Again, volatility largely declines afterwards until it shows the largest spike when New York trading commences. Further, currencies remain volatile for the next three hours (approximately until 11:00 a.m. or 12:00 a.m. Eastern time which is the time of the London fix), then drops over most of the intraday period, and then spikes one last time when New York trading ceased.

C. Currency Jumps

While the relative contribution of overnight and intraday volatility to total daily volatility appears to be very similar across currencies, we next analyse if currencies are prone to exhibit sudden crashes or return jumps at certain times of the day. For example, Lee and Wang (2016) argue that jumps in the spot market are more likely to occur around the opening and closing hours of large FX trading venues across the globe and that they occur in clusters. Further, Lee and Wang (2017) split the day in a 'Jump period', around Tokyo closing time, and 'No Jump period' and propose a modified carry trade strategy that accounts for currencies' sensitivity for negative jumps. As the jump sensitivity of funding currencies is larger than for investing currencies, the modified carry trade strategy that unwinds positions at certain times of the day outperforms the conventional carry trade approach.

To detect currency return jumps, we employ the jump test proposed by Lee and Mykland (2008) and account for return intra-week periodicity as in Boudt, Croux, and Laurent (2011). Figure 8 displays the relative number of times that jumps occur at each 5-minute time stamp. We explicitly distinguish between positive return jumps that imply a sudden appreciation of the foreign currency vis-a-vis the U.S. dollar (blue) and return crashes, which capture for a sudden depreciation of the foreign currency (yellow).

[INSERT FIGURE 8 HERE]

As illustrated, most currencies tend to exhibit more jumps and crashes after trading in New York ceases. This pattern is particular prevalent for European currencies and the Canadian dollar, while jumps of the Australian dollar, New Zealand dollar, and Japanese yen are less common. This observation points toward the close link between the occurrence of jumps and liquidity dynamics, as latter currencies are likely to be more actively traded during the early hours of the new trading day. Therefore, they are less likely to exhibit jumps compared to European currency pairs whose main trading venues open at a later time of the day. Interestingly, it appears that the number of currency jumps and crashes are almost the same over the entire trading day such that it is unlikely that diverging intraday return patterns are explained by jump risk that is biased in one . To investigate this observation more explicitly, Table VI shows the absolute and relative number of jumps for each intraday subperiod.

[INSERT TABLE VI HERE]

For all currency pairs, we find that jumps are relatively more likely to occur during the overnight period. For example, for the Australian dollar 64% of all jumps occur overnight, while only 36% of jumps occur between 8:30 a.m. and 5:00 p.m. (intraday period). As indicated earlier, this pattern is even stronger for European currencies, for which up to 80% (CHF) of all jumps occur during the overnight period. This is to some extent unsurprising, however, as the overnight period encompasses 16 hours, while there are only 8 intraday hours. Important to note with respect to the return pattern, however, is that the occurrence of currency jumps and crashes is almost uniformly distributed in each sub-period and, therefore, over the entire trading day. As shown in the last three columns of Table VI positive ($J > 0$) and negative ($J < 0$) jumps occur almost with the same likelihood. Yet, if the W-shaped intraday return pattern of currencies could be explained by currency crash risk, we would expect that the occurrences of currency crashes and jumps differ during the intraday and overnight period. This would provide additional incentive to short and invest certain currency pairs at certain hours of the day.

D. Liquidity

Next, we examine FX market liquidity as a possible driver that impacts returns differently during the night and over the day. Following earlier literature, we measure market liquidity by the quoted bid-ask spread. An increase in the spread implies an increase in the cost of a transaction and possibly exacerbates or delays the execution of a trade (Brunnermeier, Nagel, and Pedersen (2009)). Hence, the market is considered to be more illiquid. In contrast, lower bid-ask spreads imply a higher degree of liquidity. In Table VII we compare the average bid-ask spreads at close-to-close time, and during intraday and overnight periods. In the bottom part of the panel we present the t-statistic of conventional t-tests, assessing if liquidity conditions are significantly different from each other across sub-periods.

[INSERT TABLE VII HERE]

The following observations are worth noting. First, comparing the three periods, market liquidity appears to be the lowest towards the end of New York's main trading hours. At this time of the day, the average bid-ask spread ranges between 3.50 (EUR) and 11.64 basis points (NZD). It is on average higher at this point of the day than during overnight and intraday periods. Second, comparing liquidity conditions between intraday ($B\bar{A}S^{ID}$) and overnight ($B\bar{A}S^{OV}$) Table VII indicates that trading costs are lower during the day for all currency pairs. Third, the absolute difference between intraday and overnight bid-ask spreads ranges between 0.06 basis points (AUD) and 1.06 (NOK). Even though some of the differences are small in magnitude, the t-statistics in the bottom part of the table indicate that we strongly reject the null hypothesis for all currencies that liquidity dynamics across sub-periods are the same. To shed further light on liquidity conditions within each sub-period, we plot the bid-ask spread across all five minute intervals normalized by average daily bid-ask spread.

[INSERT FIGURE 7 HERE]

Starting in the left Panel of Figure 7, we note that liquidity conditions are relatively stable for AUD, NOK, and JPY between 8:00 p.m. and 4:00 p.m. on the following day. While there exists an increase in liquidity once European trading commences, intraday volatility stays reasonably constant over time. These changes, however, during the last part of trading hours in New York. For all three currencies the plots display a significant jump in illiquidity. Similar trends can be observed for the European currencies and the Canadian dollar. Across all currencies, liquidity conditions worsen towards the end of the intraday period and improve with the opening of trading venues in the Asian-Pacific region. The decline in bid-ask spreads for European currencies, however, is less distinct as for the AUD, NOK, and JPY. In fact, intraday liquidity conditions for CHF, EUR, GBO, NOK, SEK, and CAD only significantly improve with increasing trading activity in Europe.

E. Recessions and Crises Periods

While the sub-sample analysis already indicates that the diverging intraday and overnight return pattern is a common characteristic across the entire sample, lastly, we explicitly examine if the intraday return patterns is driven by crises periods. To this end, we use NBER business cycle classifications to identify recession periods and we consider all months between March 2001 and November 2001, and between December 2007 and June 2009, as crises periods. We then re-construct and plot cumulative average 5-min returns over the trading day but explicitly distinguish between the 28 crisis-months and the remaining 228 months of the business cycle. We find that separating the return patterns of crises periods from the sample does not have a significant impact on the general intraday return pattern. Similar to the analysis that is based on the entire sample, we find that foreign currencies tend to depreciate during the beginning of the trading day, appreciate once trading in Singapore and Hong Kong commences, depreciate again during the early trading hours in Europe, and then strongly appreciate during the main trading hours in New York. During recession months, this pattern continues to exist for most of the currencies, but it is less consistent across the sample. In particular the point in time when currencies start to appreciate in the intraday periods appears to have shifted from 8:00 a.m. (EST) to the middle of New York's trading day. Overall, however, we conclude that the drift between overnight and intraday returns is not driven by crisis periods and, in fact, that it is more pronounced in non-crisis periods.

F. FOMC Announcement Days

Fifth, we check to what extent average positive returns during the intraday period are positively skewed by scheduled FOMC announcement days. As documented in Mueller, Tahbaz-Salehi, and Vedolin (2017), foreign currencies tend to systematically appreciate on days, when monetary policy decisions are announced at approximately 2.15 p.m. (EST). To control for these abnormal return dynamics, we first identify all 192 scheduled FOMC announcement days between January 1994 and December 20147, exclude these dates from our sample, and then re-calculate average annualized returns for monthly overnight, intraday, and close-to-close returns. We find that excluding 168 out of 5991 days from the sample virtually does not have any strong effect on average annualized returns and, more importantly, it does not affect the spread between the two intraday sub-periods. For example, overnight returns continue to be negative and range between -8.69% and -0.98 for GBP and CAD, respectively, while they are largely positive during the day (CAD: 1.17%; GBP: 8.32%). Again, the only exception to this trend is the Japanese yen which shows countercyclical return dynamics compared to the rest of the sample. We conclude that the documented return differences between the intraday and overnight period do not arise because of abnormal returns during scheduled FOMC announcement days.

G. Macroeconomic Announcement Days

In similar vein to the FOMC announcement days, we also explicitly account for macroeconomic announcement. As many of them occur at 8:30 a.m., there might concerns that positive intraday returns are driven by abnormal returns on these announcement days. Even though the number of days with macroeconomic announcements is substantially higher than the number of FOMC announcement days (1372 days between September 1996 to August 2016), we find that the split between intraday and overnight returns continue to exist. Overnight returns range between -8.69% and 1.60%, while intraday returns range between -1.60 % and 8.33 % for the British pound and Japanese yen, respectively. We conclude that macroeconomic announcements do not drive the differential between intraday and overnight returns.

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 I 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 C, 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 1996 to 2017 sample. Using the return patterns documented in Table X 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. The results are summarized in Table XI and they are not very encouraging as all of the strategies lead to significantly negative average annualized returns 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.

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.[17] Moreover, we again pick the best sub-period over

[17] 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.

the 24-hour day to be long and short a particular currency in our sample and report the results in Table VIII. 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.[18]

[INSERT TABLE VIII HERE]

Not very surprisingly, continuous buying and selling of currencies during particular times of the 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 IX) 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 IX 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 trans-

[18] "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.

action 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 I. Intraday Returns: By Main Trading Hours

This table reports annualized average returns for different intraday periods. $-\Delta s^{SYD}$ refers to returns after trading in Sydney commenced (5:00 p.m. to 9:00 p.m.); $-\Delta s^{SEA}$ 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.); $-\Delta s^{EU}$ refers to returns during main trading hours in Europe (3:00 a.m. to 8:00 a.m.); $-\Delta s^{ON}$ refers to the overnight returns from an U.S. investors perspective. It equals the sum of the first three columns ($-\Delta s^{AUS} + -\Delta s^{SEA} + -\Delta s^{EU}$). $-\Delta s^{ID}$ refers to the intraday returns during the main trading hours in New York (8:00 a.m. and 5:00 p.m.). $-\Delta s^{CTC}$ refers to daily close-to-close returns between 5:00 p.m. on day t and 5:00 p.m. on day $t+1$ ($-\Delta s^{CTC} = -(\Delta s^{ON} + \Delta s^{ID})$). "dol" refers to the unconditional dollar portfolio that goes long all foreign currencies, and "dol (excl. JPY)" is the unconditional dollar portfolio that invests in all foreign currencies except the Japanese yen. 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 2017, comprising 288 monthly observations.

	$-\Delta s^{SYD}$	$-\Delta s^{SEA}$	$-\Delta s^{EU}$	$-\Delta s^{ON}$	$-\Delta s^{ID}$	$-\Delta s^{CTC}$
AUD	-6.48	4.40	-0.31	-2.40	2.94	0.54
	(-6.50)	(4.52)	(-0.29)	(-1.44)	(1.94)	(0.22)
CAD	-2.51	3.05	-1.52	-0.98	1.17	0.18
	(-5.38)	(5.87)	(-1.94)	(-0.92)	(0.83)	(0.11)
CHF	-2.48	0.47	-4.82	-6.83	8.61	1.78
	(-3.36)	(0.61)	(-4.10)	(-4.82)	(5.55)	(0.83)
EUR	-4.51	4.02	-7.03	-7.52	7.80	0.28
	(-6.74)	(5.92)	(-7.60)	(-6.02)	(5.26)	(0.14)
GBP	-5.55	-0.07	-3.06	-8.69	8.33	-0.36
	(-9.54)	(-0.12)	(-3.22)	(-6.96)	(6.86)	(-0.21)
JPY	-2.07	5.06	-1.39	1.60	-1.60	0.00
	(-2.24)	(5.34)	(-1.25)	(0.97)	(-1.24)	(-0.00)
NOK	-2.34	3.80	-5.45	-3.98	3.63	-0.35
	(-2.96)	(4.08)	(-4.61)	(-2.65)	(2.06)	(-0.16)
NZD	-8.62	6.34	-0.94	-3.21	4.17	0.96
	(-7.60)	(5.46)	(-0.83)	(-1.59)	(2.81)	(0.38)
SEK	-2.22	3.26	-6.82	-5.78	5.87	0.09
	(-2.66)	(3.26)	(-5.96)	(-3.63)	(3.01)	(0.04)
dol	-4.13	3.19	-3.05	-3.99	4.03	0.05
	(-7.84)	(8.12)	(-3.66)	(-3.76)	(3.70)	(0.03)
dol	-4.37	3.13	-3.39	-4.63	4.76	0.14
(excl. JPY)	(-7.79)	(7.32)	(-3.78)	(-4.08)	(4.10)	(0.08)

Table II. Forward Premium Puzzle: Intraday vs. Overnight

This table reports results from estimating the following regression with ordinary least squares

$$s_{t+h} - s_t = \alpha + \beta(f_{t,h} - s_t) + \epsilon$$

where $s_{t+h} - s_t$ refers to the monthly close-to-close, intraday, or overnight return in period $t+h$, $f_{t,h}$ denotes the end-of-month log forward rate with maturity h, and s_t is the end-of-month log spot rate. Returns are multiplied by the factor 100, such that all variables are expressed in percent per month. The maturity of the forward rate is 1 month ($h = 1$). The forward discount is calculated using Datastream forward rates and spot rates. Numbers in parentheses refer to standard t-statistics if the estimated co-efficient is equal to zero. The row $\beta = 1$ reports the t-statistic of a simple t-test with the null hypotheses that $\beta = 1$. The sample period is January 1994 to December 2017, comprising 288 monthly observations. ***,**, and * denote statistical significance at the 10%, 5% and 1% level, respectively. Numbers in parentheses display Newey-West standard errors.

Panel A: Close-to-close

	AUD	CAD	CHF	EUR	GBP	JPY	NOK	NZD	SEK
$\hat{\alpha}$	0.26	-0.01	-0.33	-0.13	0.11	-0.04	0.05	-0.17	0.02
	(1.07)	(-0.10)	(-1.15)	(-0.73)	(0.56)	(-0.13)	(0.28)	(-0.38)	(0.08)
$\hat{\beta}$	-1.76	-1.28	-1.18	-2.93	-1.28	-0.22	-0.26	0.42	-1.14
	(-1.24)	(-0.79)	(-0.79)	(-2.06)	(-0.83)	(-0.20)	(-0.19)	(0.19)	(-1.07)
$\beta = 1$	(-1.94)	(-1.40)	(-1.47)	(-2.76)	(-1.47)	(-1.12)	(-0.94)	(-0.27)	(-2.01)
$\bar{R}^2$	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00

Panel B: Intraday

	AUD	CAD	CHF	EUR	GBP	JPY	NOK	NZD	SEK
$\hat{\alpha}$	-0.04	-0.10	-0.94	-0.74	-0.57	-0.02	-0.29	-0.59	-0.48
	(-0.29)	(-0.73)	(-4.11)	(-5.74)	(-4.63)	(-0.12)	(-1.92)	(-2.65)	(-2.56)
$\hat{\beta}$	-1.25	-2.41	-1.42	-2.52	-2.05	-0.72	-0.08	1.09	-1.63
	(-1.53)	(-1.43)	(-1.26)	(-2.38)	(-2.11)	(-1.17)	(-0.09)	(1.17)	(-1.37)
$\beta = 1$	(-2.76)	(-2.03)	(-2.15)	(-3.33)	(-3.14)	(-2.81)	(-1.15)	(0.10)	(-2.21)
$\bar{R}^2$	0.00	0.01	0.00	0.01	0.01	0.00	0.00	0.00	0.01

Panel C: Overnight

	AUD	CAD	CHF	EUR	GBP	JPY	NOK	NZD	SEK
$\hat{\alpha}$	0.30	0.08	0.61	0.61	0.68	-0.01	0.34	0.42	0.49
	(1.41)	(0.83)	(3.00)	(5.29)	(4.58)	(-0.07)	(2.46)	(1.01)	(3.58)
$\hat{\beta}$	-0.51	1.13	0.25	-0.41	0.77	0.50	-0.17	-0.67	0.49
	(-0.48)	(0.91)	(0.24)	(-0.41)	(0.66)	(0.67)	(-0.22)	(-0.36)	(0.47)
$\beta = 1$	(-1.40)	(0.10)	(-0.73)	(-1.41)	(-0.20)	(-0.66)	(-1.46)	(-0.90)	(-0.49)
$\bar{R}^2$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table III. Carry Trade: Intraday vs. Overnight

This table reports the average annualized portfolio returns from a conventional carry trade strategy (Panel A). At the beginning of each month, currencies are sorted according to their forward discount in the previous month. The forward discount is defined as $fp = f_t - s_t$, where f_t refers to the log forward rate with one-month maturity and s_t is the log spot rate. Currencies with a low (high) forward discount are assigned to portfolio P1 (P3). Currencies are held for one month and then re-allocated to a new portfolio. The column "P3-P1" refers to a high-minus-low strategy that goes long currencies in P3 and short currencies that are allocated to P1. "dol" refers to the unconditional dollar portfolio that invests equally in all foreign currencies. In Panel B, Intraday-Overnight refers to the return obtain from a strategy that goes long all portfolios during the day, and that shorts portfolios over night. In Panel C, Reversal strategies are based on a strategy that goes long the best (worse) performing portfolio intraday and that sells the worst (best) performing portfolio during overnight periods. Returns are annualized by multiplying log-returns by 12, and then by the factor 100 to express numbers in percent. Further, for intraday and overnight returns, we assume that the forward premium is earned equally during the overnight and intraday period. For these two daily sub-periods, excess returns are constructed as: $(rx_{t+1}^{Over/Intra} = \frac{f_t - s_t}{2} - \Delta s_{t+1})$. The sample period is January 1994 to December 2017, comprising 288 monthly observations.

Panel A: Carry Trade

	P1	P2	P3	P3-P1	dol
Close-to-close					
$\bar{rx}^{CTC}$	-1.44	0.18	2.89	4.33	0.62
t-stat	(-0.88)	(0.10)	(1.41)	(2.63)	(0.39)
Intraday					
$\bar{rx}^{ID}$	2.74	5.32	6.00	3.25	4.72
t-stat	(2.31)	(4.13)	(4.44)	(3.30)	(4.07)
Overnight					
$\bar{rx}^{ON}$	-4.17	-5.09	-3.05	1.12	-4.05
t-stat	(-3.89)	(-4.82)	(-2.17)	(0.85)	(-4.05)

Panel B: Intraday-Overnight Trading

	P1	P2	P3	P3-P1	dol
$\bar{rx}^{ID-ON}$	6.91	10.41	9.05	2.13	8.78
t-stat	(4.46)	(6.47)	(4.92)	(1.31)	(6.10)

Panel C: Reversal Strategies

	$P3^{Intra} - P1^{Over}$	$P1^{Intra} - P3^{Over}$
Ann. Avg.	10.16	5.80
t-stat	(6.04)	(3.36)

Table IV. Dollar Carry Trade: Intraday vs. Overnight

This table reports the average annualized return of a dollar carry trading strategy, where portfolios are sorted according to the average forward discount $\bar{f}_t - \bar{s}_t = \frac{1}{N}\sum_{i=1}^{N} f_t^i - s_t^i$, where $\bar{f}_t - \bar{s}_t$ is the average monthly forward discount, and f_t^i and s_t^i are the one-month log forward rate and log spot rate for country i, respectively. The column "AFD ≤ 0" refers to the average return from a strategy where investors sell foreign currencies at the beginning of a month (128 months) if the lagged average foreign interest rate in the previous month is below the U.S. interest rate (and no trade is executed otherwise). The column "AFD > 0" refers to a strategy where investors go long foreign currencies (160) at the beginning of the month if the average forward discount in the previous month is positive (and no trade is executed otherwise). "Dollar-Carry" refers to the strategy where investors buy foreign currencies at the beginning of a month, when the average foreign discount in the previous month is positive, and foreign currencies are shorted otherwise. "dol" is the return from an unconditional dollar portfolio where investors go long all foreign currencies if the AFD in the previous month is positive. "AFD < 0 (excl. 0)" and "AFD > 0 (excl. 0)" refer to the average annualized returns if we only consider months, in which a trade was conducted. In Panel B, Intraday-Overnight refers to the returns obtain from a strategy that going long currencies during the day, and selling currencies overnight. In Panel C, Reversal strategies are based on a strategy that goes long the best (worse) performing portfolio intraday and that sells the worst (best) performing portfolio during overnight periods. The sample period is January 1994 to December 2017, comprising 288 monthly observations.

Panel A: Dollar Carry

	AFD ≤ 0	AFD > 0	Dollar-Carry	dol	AFD ≤ 0 (excl. 0)	AFD > 0 (excl. 0)
Close-to-close						
$\bar{rx}^{CTC}$	-1.51	2.14	3.65	0.62	-3.42	3.83
t-stat	(-1.57)	(1.65)	(2.27)	(0.39)	(-1.58)	(1.66)
Obs	288	288	288	288	128	160
Intraday						
$\bar{rx}^{ID}$	0.93	3.79	2.86	4.72	2.11	6.80
t-stat	(1.31)	(4.09)	(2.42)	(4.07)	(1.31)	(4.18)
Overnight						
$\bar{rx}^{ON}$	-2.43	-1.63	0.80	-4.05	-5.48	-2.92
t-stat	(-4.15)	(-1.96)	(0.78)	(-4.05)	(-4.31)	(-1.97)

Panel B: Intraday-Overnight Trading

	AFD ≤ 0	AFD > 0	Dollar-Carry	dol	AFD ≤ 0 (excl. 0)	AFD > 0 (excl. 0)
$\bar{rx}^{ID-ON}$	3.36	5.42	2.06	8.78	7.59	9.72
t-stat	(3.83)	(4.54)	(1.35)	(6.10)	(3.95)	(4.66)

Panel C: Reversal Strategies

	$AFD > 0^{Intra}$ - $AFD \leq 0^{Over}$	$AFD \leq 0^{Intra}$ - $AFD > 0^{Over}$
Ann. Avg.	6.22	2.56
t-stat	(5.83)	(2.35)

Table V. Intraday Returns: Variance Decomposition

This table reports the variance decomposition based on monthly intraday return series. σ^2_{ID} refers to the monthly return variance during main trading hours in New York (8:00 a.m. to 5:00 p.m., EST), while σ^2_{ON} is the monthly return variance over night (5:00 p.m. to 8:00 a.m., EST). $2 \times cov_{(IN,ON)}$ refers to the covariance of these two series, σ^2_{CTC} denotes the monthly return variance of close-to-close returns, sampled at 5:00 p.m. (EST). "dol" refers to the unconditional dollar portfolio that goes long all foreign currencies, and "dol (excl. JPY)" is the unconditional dollar portfolio that invests in all foreign currencies except the Japanese yen. Numbers in parentheses refer to the weight that each intraday return variance contributes to the monthly variance of close-to-close returns. The sum of the intraday variances and the covariance term (first three columns) equals to the monthly variance in the last column (σ^2_{CTC}). The sample period is January 1994 to December 2017, comprising 288 monthly observations.

	σ^2_{ID}	σ^2_{ON}	$2 \times cov_{(IN,ON)}$	σ^2_{CTC}
AUD	4.59	5.55	1.46	11.60
	[0.40]	[0.48]	[0.13]	[1.00]
CAD	3.92	2.28	-0.27	5.92
	[0.66]	[0.38]	[-0.05]	[1.00]
CHF	4.81	4.01	0.44	9.25
	[0.52]	[0.43]	[0.05]	[1.00]
EUR	4.40	3.12	0.69	8.21
	[0.54]	[0.38]	[0.08]	[1.00]
GBP	2.95	3.12	-0.26	5.81
	[0.51]	[0.54]	[-0.04]	[1.00]
JPY	3.36	5.44	1.04	9.84
	[0.34]	[0.55]	[0.11]	[1.00]
NOK	6.22	4.51	-1.07	9.66
	[0.64]	[0.47]	[-0.11]	[1.00]
NZD	4.43	8.13	-0.02	12.53
	[0.35]	[0.65]	[-0.00]	[1.00]
SEK	7.63	5.08	-2.71	10.00
	[0.76]	[0.51]	[-0.27]	[1.00]
dol	2.37	2.25	0.55	5.18
	[0.46]	[0.44]	[0.11]	[1.00]
dol	2.69	2.57	0.63	5.89
(excl. JPY	[0.46]	[0.44]	[0.11]	[1.00]

Table VI. Intraday Jump Risk: Intraday Versus Overnight

This table reports the absolute and relative number of jumps for each currency pair for the overnight and intraday period, and for the entire day. Jumps are detected using the Lee and Mykland (2008) jump test statistic, where intraweek periodicity is taken into account following the procedure in Boudt, Croux, and Laurent (2011). The level of significance for the jump statistic is 5%. The test is based on 5-minute return data. $J > 0$ refers to the number of positive jumps (appreciation of foreign currency), $J < 0$ denotes the number of negative jumps (depreciation of foreign currency), and J is the total number of jumps. Numbers in brackets refer to the relative number of jumps in the sub-period, in percent, compared to the total number of jumps. $-\Delta s^{ON}$ refers to the overnight period (5:00 p.m. to 8:00 a.m. EST), $-\Delta s^{ID}$ denotes the intraday period (8:00 a.m. to 5:00 p.m.), and $-\Delta s^{CTC}$ refers to close-to-close, capturing the dynamics of the entire trading day. The sample period is January 1994 to December 2017.

	$-\Delta s^{ON}$			$-\Delta s^{IN}$			$-\Delta s^{CTC}$		
	$J > 0$	$J < 0$	J	$J > 0$	$J < 0$	J	$J > 0$	$J < 0$	J
AUD	5,698	6,353	12,051	3,479	3,692	7,171	9,177	10,045	19,222
	[30]	[33]	[63]	[18]	[19]	[37]	[48]	[52]	[100]
CAD	11,777	11,409	23,186	2,837	2,539	5,376	14,614	13,948	28,562
	[41]	[40]	[81]	[10]	[9]	[19]	[51]	[49]	[100]
CHF	8,406	8,239	16,645	3,229	2,939	6,168	11,635	11,178	22,813
	[37]	[36]	[73]	[14]	[13]	[27]	[51]	[49]	[100]
EUR	5,652	5,774	11,426	3,050	2,955	6,005	8,702	8,729	17,431
	[32]	[33]	[66]	[17]	[17]	[34]	[50]	[50]	[100]
GBP	7,618	7,980	15,598	3,394	3,224	6,618	11,012	11,204	22,216
	[34]	[36]	[70]	[15]	[15]	[30]	[50]	[50]	[100]
JPY	5,659	5,098	10,757	3,261	2,958	6,219	8,920	8,056	16,976
	[33]	[30]	[63]	[19]	[17]	[37]	[53]	[47]	[100]
NOK	13,747	13,842	27,589	3,765	3,602	7,367	17,512	17,444	34,956
	[39]	[40]	[79]	[11]	[10]	[21]	[50]	[50]	[100]
NZD	7,233	7,492	14,725	4,365	4,437	8,802	11,598	11,929	23,527
	[31]	[32]	[63]	[19]	[19]	[37]	[49]	[51]	[100]
SEK	13,367	13,235	26,602	3,974	3,918	7,892	17,341	17,153	34,494

Table VII. Liquidity Dynamics: Average Bid-Ask Spread

This table reports the average bid-ask spread ($\frac{ask-bid}{mid}$) expressed in basis points, for close-to-close ($B\bar{A}S^{CTC}$), intraday ($B\bar{A}S^{ID}$, 8:00 a.m. to 5:00 p.m., EST), and overnight ($B\bar{A}S^{ON}$, 5:00 p.m. to 8:00 a.m., EST) periods. Bid-ask spreads are measured in basis points. The bottom part shows t-statistics of a t-test with the null hypothesis $H_0 : B\bar{A}S^i = B\bar{A}S^j$ where $i \neq j$ and $i, j = CTC, ID, ON$. The sample period is January 1994 to December 2017, comprising 288 monthly observations.

	AUD	CAD	CHF	EUR	GBP	JPY	NOK	NZD	SEK
$B\bar{A}S^{CTC}$	6.55	4.41	5.12	3.50	3.53	4.47	7.68	11.64	9.31
$B\bar{A}S^{ID}$	6.19	4.17	4.62	3.13	3.20	4.10	6.62	9.76	8.26
$B\bar{A}S^{ON}$	6.14	4.52	4.82	3.31	3.28	4.18	7.75	10.23	8.96
$B\bar{A}S^{CTC} = B\bar{A}S^{ID}$	8.26	11.06	16.25	14.25	14.16	11.76	21.84	28.91	16.66
$B\bar{A}S^{CTC} = B\bar{A}S^{ON}$	10.61	-4.78	9.64	6.75	11.54	9.50	-1.14	21.98	5.71
$B\bar{A}S^{ON} = B\bar{A}S^{ID}$	10.22	-128.41	-52.94	-56.28	-26.35	-21.65	-157.69	-59.41	-81.53

Table VIII. 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. – 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. 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 IX. 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

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

This table reports average annualized net 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. – 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.). 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 long and short positions. For each currency pair we report the most profitable short and long positions. Numbers in parentheses refer to t-statistics. For the majority of FX futures, the sample period is January 1996 to December 2017, comprising 264 monthly observations. Due to data availability, the sample starts in January 1999 for EUR and in 2005 for NOK, NZD, and SEK.

	$-\Delta s^{SYD}$	$-\Delta s^{SEA}$	$-\Delta s^{EU}$	$-\Delta s^{ON}$	$-\Delta s^{ID}$	$-\Delta s^{CTC}$
AUD	-5.19	1.16	0.82	-3.20	3.34	0.14
	(-4.75)	(1.10)	(0.70)	(-1.68)	(2.09)	(0.06)
CAD	-2.92	3.21	-0.84	-0.55	0.88	0.33
	(-3.87)	(5.40)	(-1.00)	(-0.40)	(0.60)	(0.18)
CHF	-3.50	1.81	-3.48	-5.17	5.96	0.79
	(-4.44)	(2.12)	(-2.78)	(-3.34)	(3.88)	(0.36)
EUR	-5.23	4.55	-5.66	-6.36	6.62	0.26
	(-7.05)	(5.75)	(-5.26)	(-4.21)	(3.93)	(0.11)
GBP	-3.02	-0.92	-2.43	-6.37	5.74	-0.63
	(-3.94)	(-1.30)	(-2.47)	(-4.60)	(4.38)	(-0.36)
JPY	-3.98	6.56	-1.36	1.22	-1.59	-0.37
	(-4.37)	(6.29)	(-1.26)	(0.72)	(-1.15)	(-0.17)
NOK	-4.22	-0.54	0.34	-4.47	2.41	-2.06
	(-1.02)	(-0.34)	(0.18)	(-0.96)	(0.50)	(-0.70)
NZD	-9.14	2.69	0.94	-5.48	5.53	0.05
	(-4.15)	(1.59)	(0.56)	(-1.70)	(2.33)	(0.01)
SEK	-15.39	3.46	0.10	-11.84	10.57	-1.26
	(-1.90)	(2.55)	(0.02)	(-2.10)	(2.00)	(-0.41)
dol	-5.63	2.20	-0.61	-4.04	4.03	-0.23
	(-4.50)	(3.68)	(-0.50)	(-2.52)	(2.55)	(-0.10)
dol	-6.22	1.71	-0.28	-4.79	4.77	-0.26
(excl. JPY)	(-4.48)	(2.62)	(-0.21)	(-2.72)	(2.76)	(-0.11)

Table XI. Net Returns: Long and Short Positions of CME Futures

This table reports average annualized net spot returns for short and long positions of 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. – 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.). 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 ease of reading, positive returns are highlighted in red. Numbers in parentheses refer to t-statistics. For the majority of FX futures, the sample period is January 1996 to December 2017, comprising 264 monthly observations. Due to data availability, the sample starts in January 1999 for EUR and in 2005 for NOK, NZD, and SEK.

Panel A: Short Positions

AUD^{EU}	CAD^{EU}	CHF^{EU}	EUR^{EU}	GBP^{EU}	JPY^{EU}	NOK^{EU}	NZD^{EU}	SEK^{EU}
-32.12	-11.56	-10.94	-2.25	-9.42	-9.29	-92.29	-14.97	-190.29
(-10.71)	(-10.82)	(-5.95)	(-1.68)	(-6.80)	(-6.32)	(-8.33)	(-7.86)	(-2.06)

Panel B: Long Positions

AUD^{SEA}	CAD^{SEA}	CHF^{SEA}	EUR^{SEA}	GBP^{SEA}	JPY^{SEA}	NOK^{SEA}	NZD^{SEA}	SEK^{SEA}
-28.07	-9.98	-13.19	-3.77	-13.21	-4.82	-97.08	-14.86	-138.66
(-10.77)	(-11.12)	(-9.47)	(-3.51)	(-11.20)	(-4.39)	(-8.99)	(-6.93)	(-2.83)

VIII. Appendix: Figures

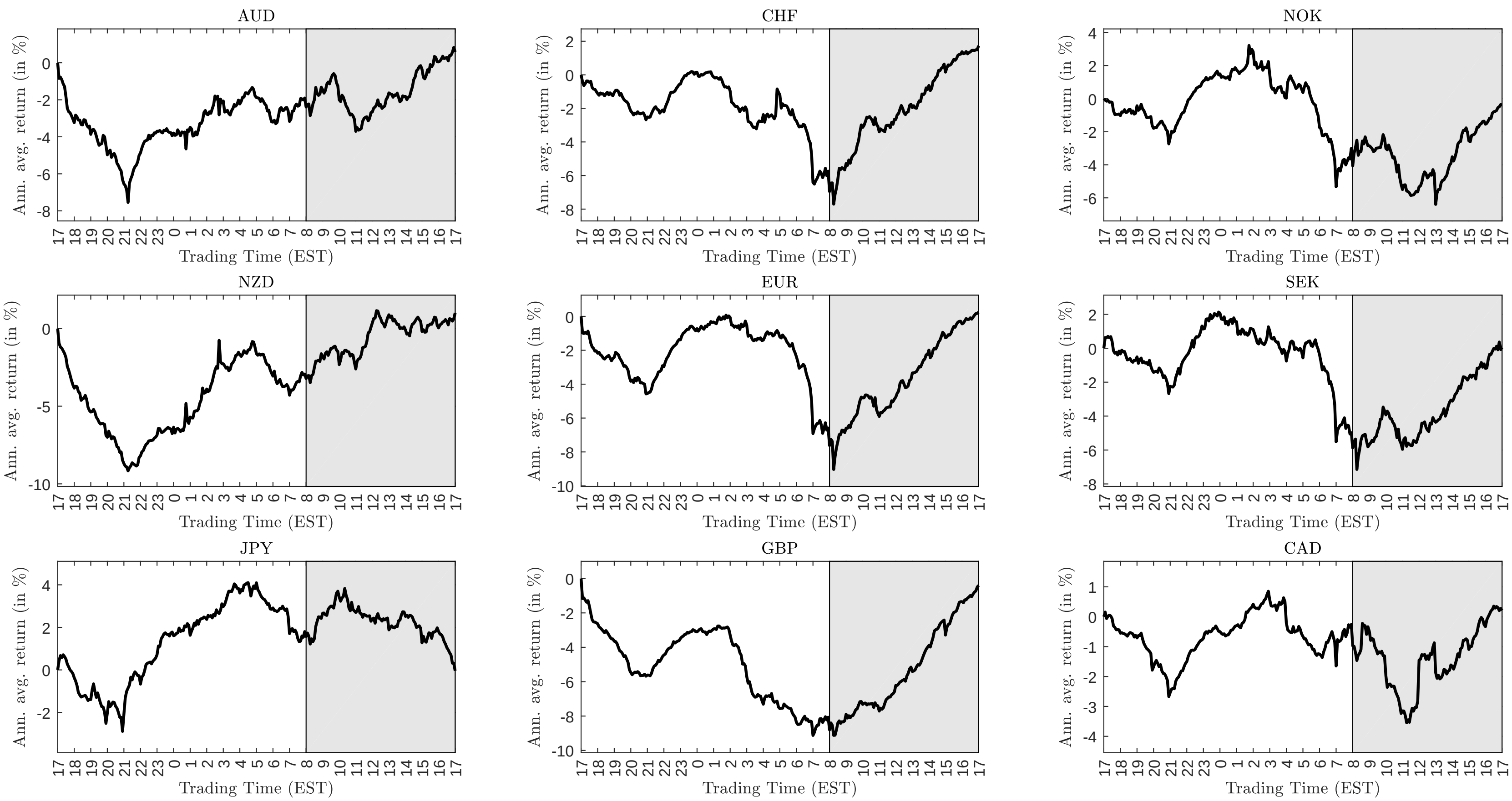

Figure 1. Cumulative 5-min Returns of Individual Currencies
This figure displays cumulative average annualized 5-min returns ($-\Delta s$) over the course of a trading day. The grey-shaded area marks the main trading hours in New York (8:00 a.m. to 5:00 p.m. EST). Hours (x-axis) refer to Eastern Standard Time (EST). The sample period comprises all months between January 1994 to December 2017.

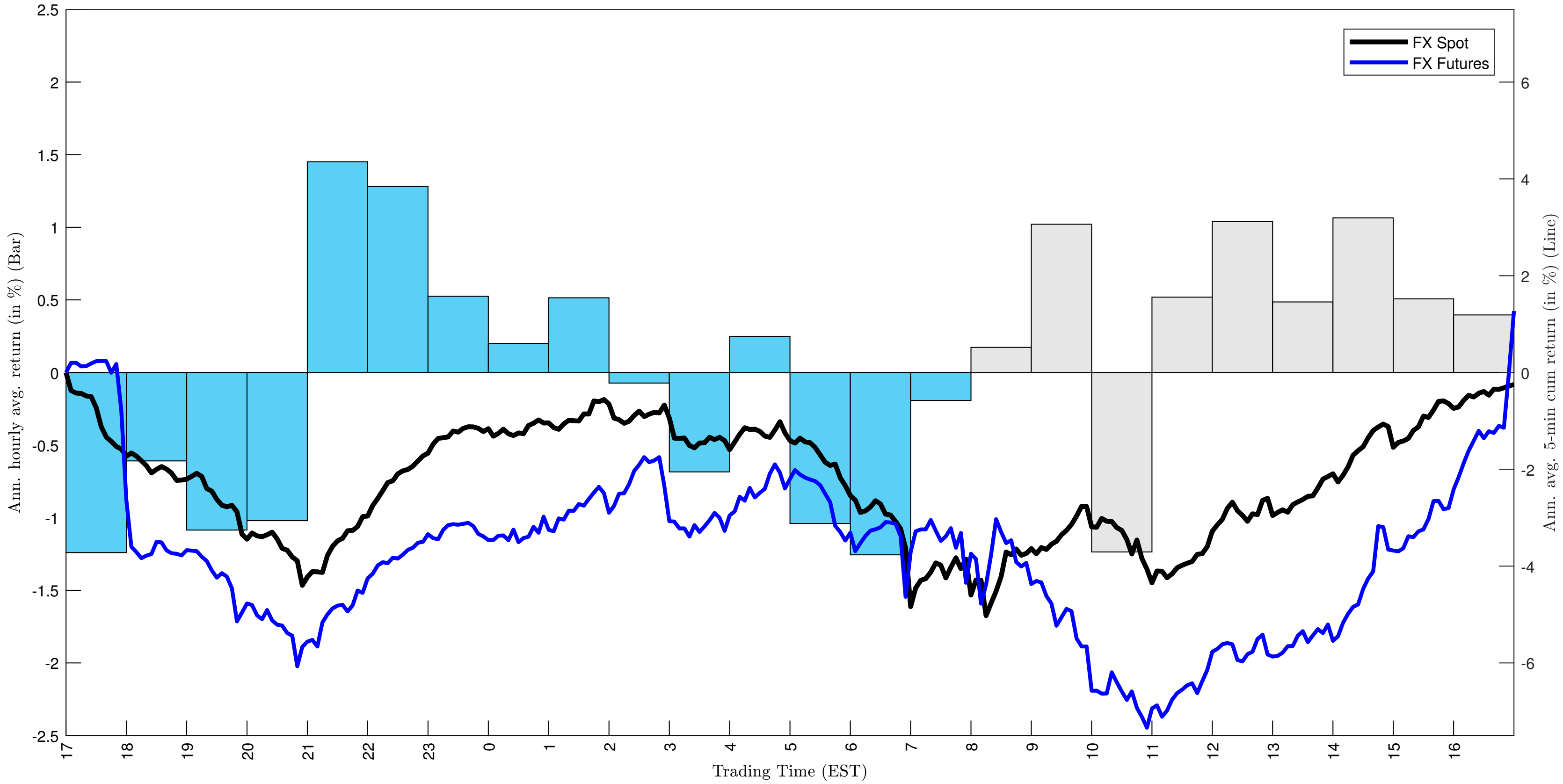

Figure 2. Cumulative 5-min Returns of the Unconditional Dollar Portfolio

This figure displays the development of the unconditional dollar portfolio over the course of the trading day. The bars refer to the average hourly return within each hour. Grey bars mark the main trading hours in New York (8:00 a.m. to 5:00 p.m.) and blue bars refer to the overnight period. The black line shows the cumulative average annualized 5-min returns ($-\Delta s$) of the unconditional dollar portfolio that goes long all foreign currencies. An increase of the dollar portfolio implies that foreign currencies appreciate against the U.S. dollar. Trading hours (x-axis) refer to Eastern Standard Time (EST). The sample period comprises all months between January 1994 to December 2017.

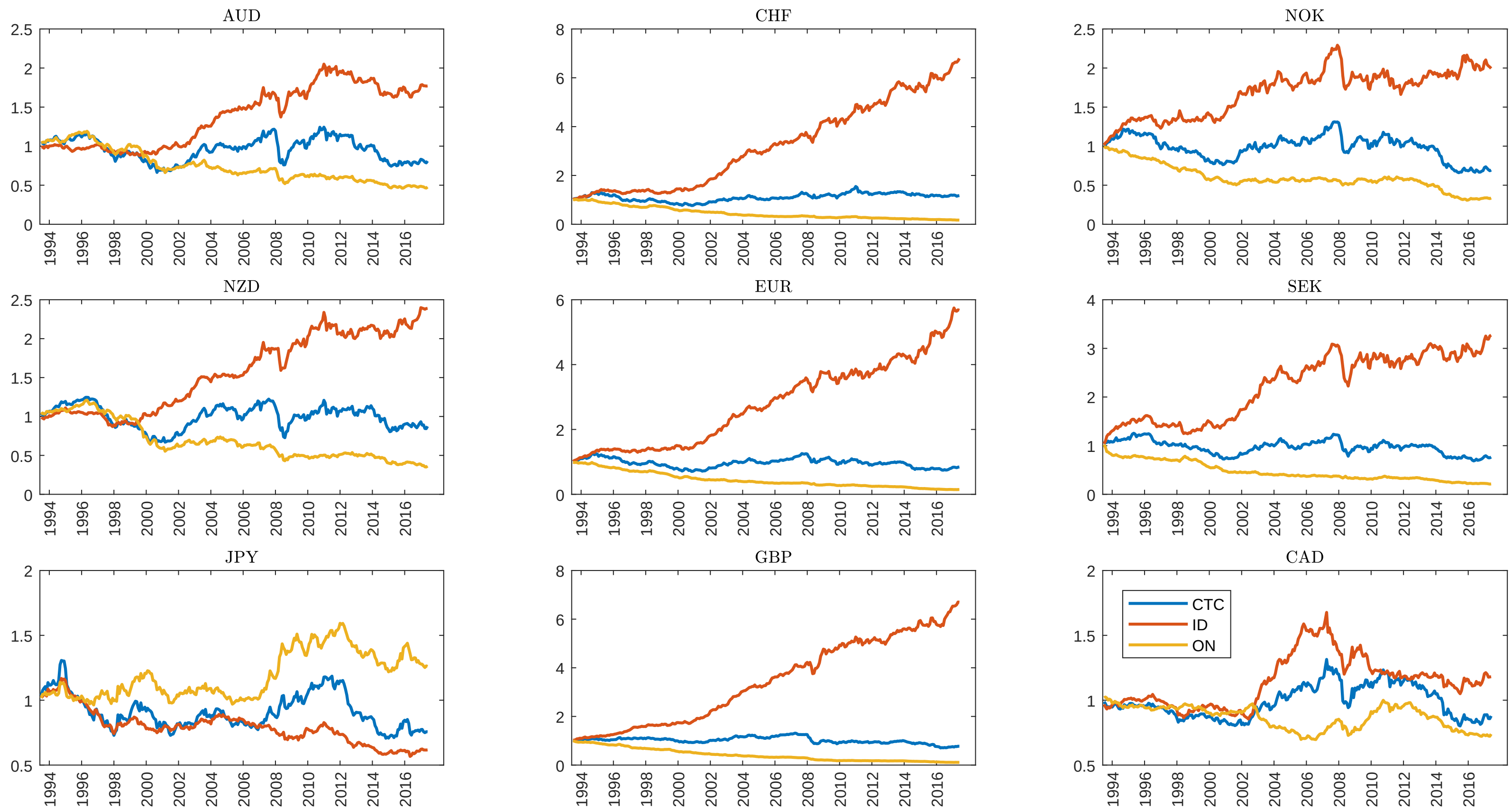

Figure 3. Total Return Index Individual Currencies
This figure displays a total return index for close-to-close (CTC), intraday (ID), and overnight (ON) time series starting with a value of one in 1994. The sample period is January 1994 to December 2017.

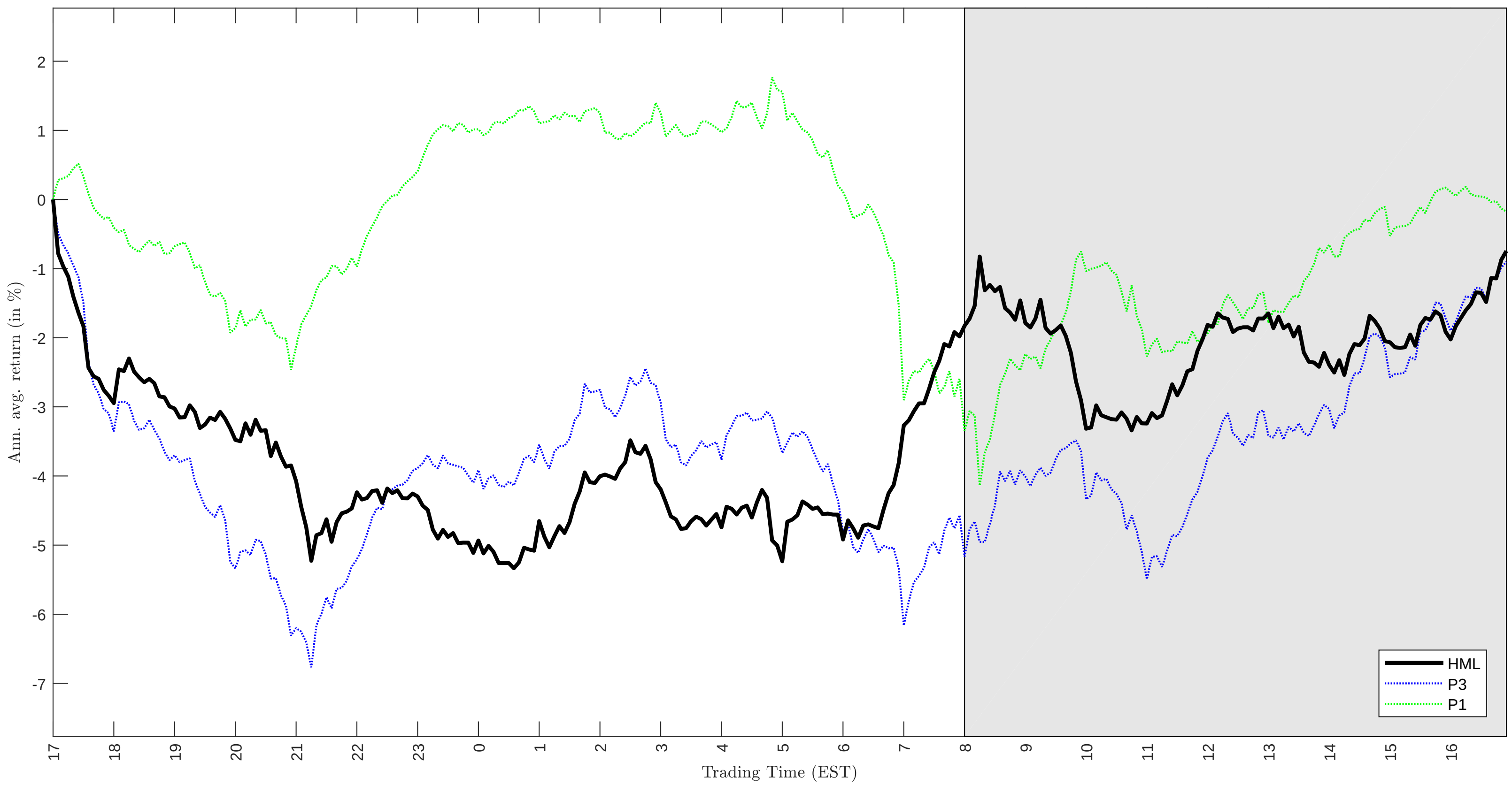

Figure 4. Carry Trade: Cumulative Spot Return Component

This figure displays the average annualized return from the high-minus-low (HML, black line) spot return component of a conventional carry trade strategy, from portfolio 1 (low interest rate currencies, green line) and from portfolio 3 (high interest rate currencies, blue line) over the course of a trading day. The x-axis refers to trading hours measured in Eastern Standard Time (EST). The sample period is January 1994 to December 2017.

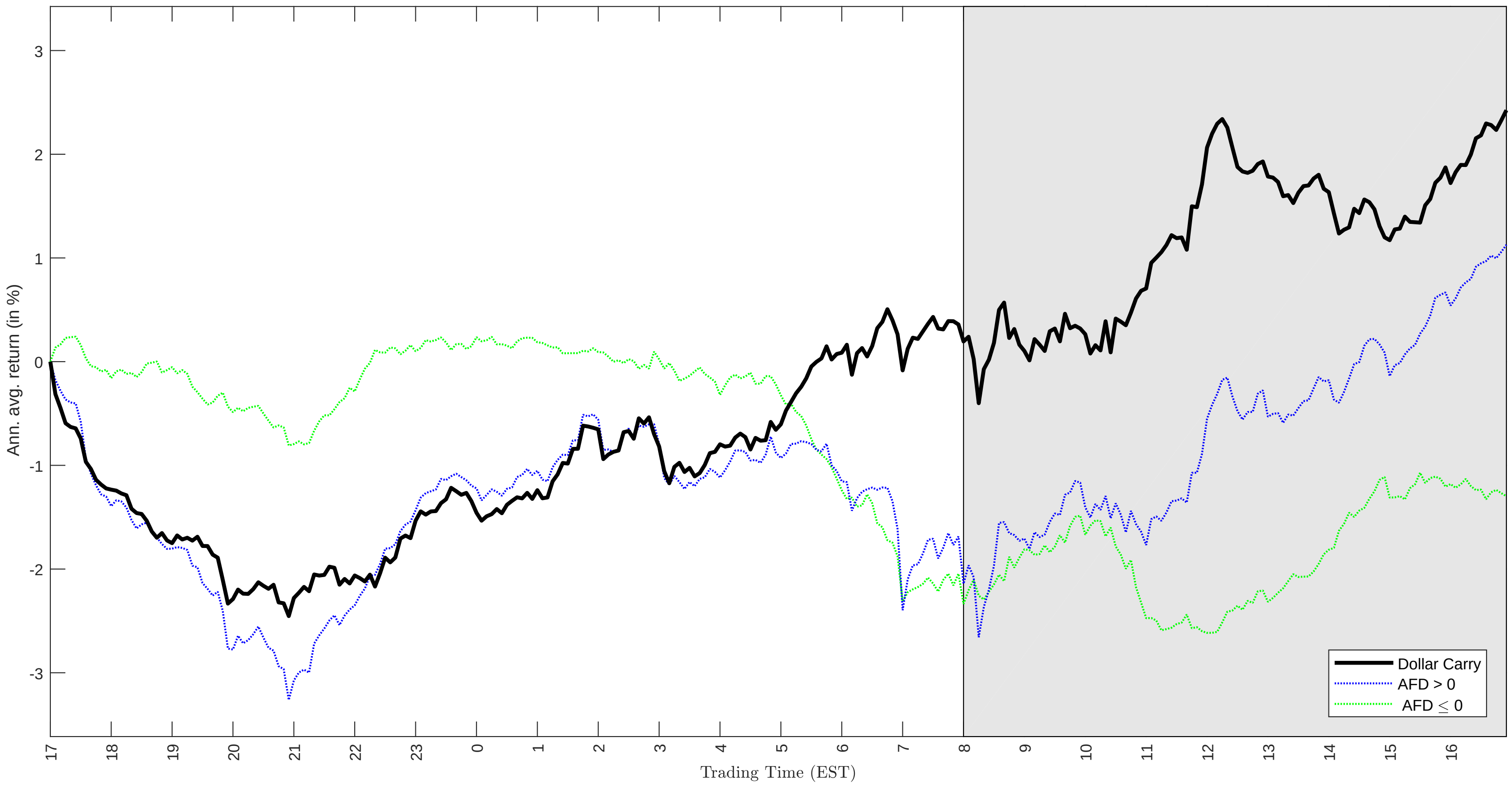

Figure 5. Dollar Carry Trade: Cumulative Spot Return Component

This figure displays the average annualized return of the spot return component from a conventional dollar carry strategy (black line), from a portfolio where investors sell foreign currencies ($AFD \leq 0$, green line), and from a portfolio that buys foreign currencies ($AFD > 0$, blue line) over the course of a trading day. The x-axis refers to trading hours measured at Eastern Standard Time (EST). The sample period is January 1994 to December 2017.

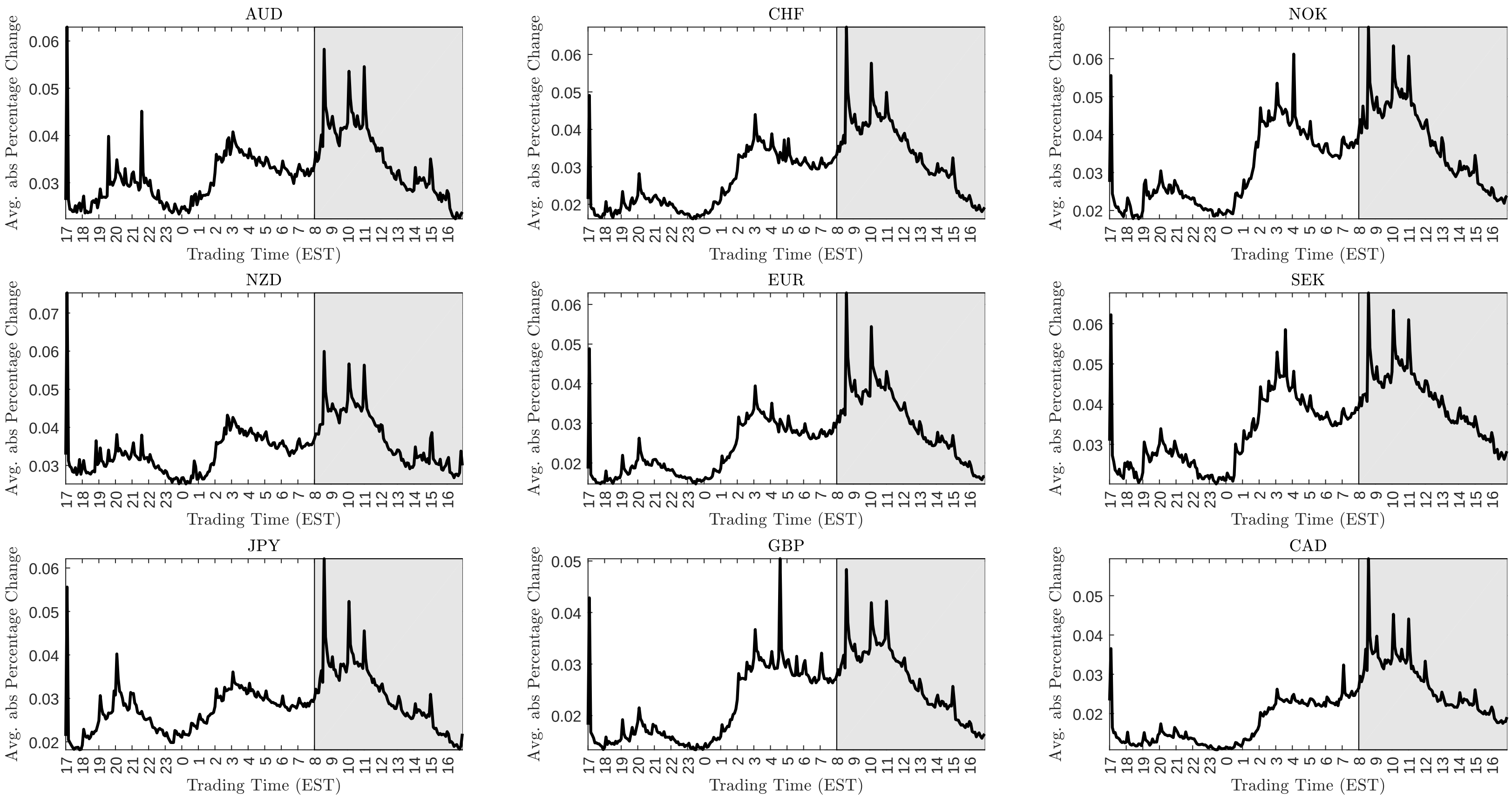

Figure 6. Intraday Volatility: Average Absolute Percentage Change

This figure displays the average absolute percentage change $|\Delta \bar{s}_i| = 1/T \sum_{i=1}^{T} |\Delta s_i|$ as a measure of intraday volatility, where Δs_i refers to the 5-min return at time i, and T refers to the total number of days in the sample. The grey-shaded area marks main trading hours in New York (8:30 a.m. to 5:00 p.m.). Hours (x-axis) refer to Eastern Standard Time.

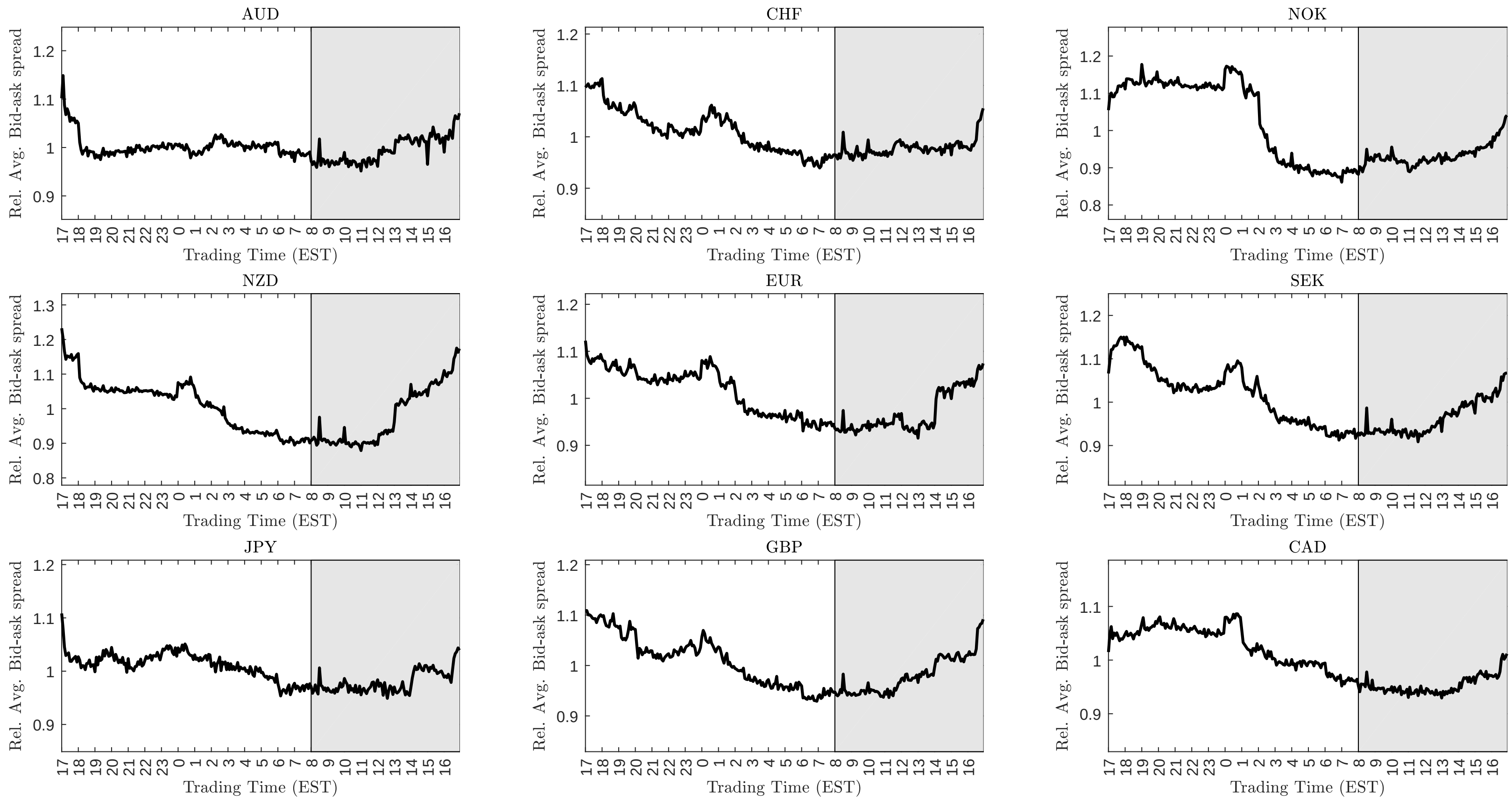

Figure 7. Average Bid-Ask Spread

This figure displays the relative average bid-ask spread at the 5-min frequency. The bid-ask spread is constructed as $(ask_t - bid_t)/mid_t$, where ask_t, bid_t, and mid_t refer to the ask, bid, and mid-price, respectively. Each bid-ask spread is normalized by the average bid-ask spread during the associated day. The grey shaded area marks main trading hours in New York (8:30 a.m. to 5:00 p.m. EST).

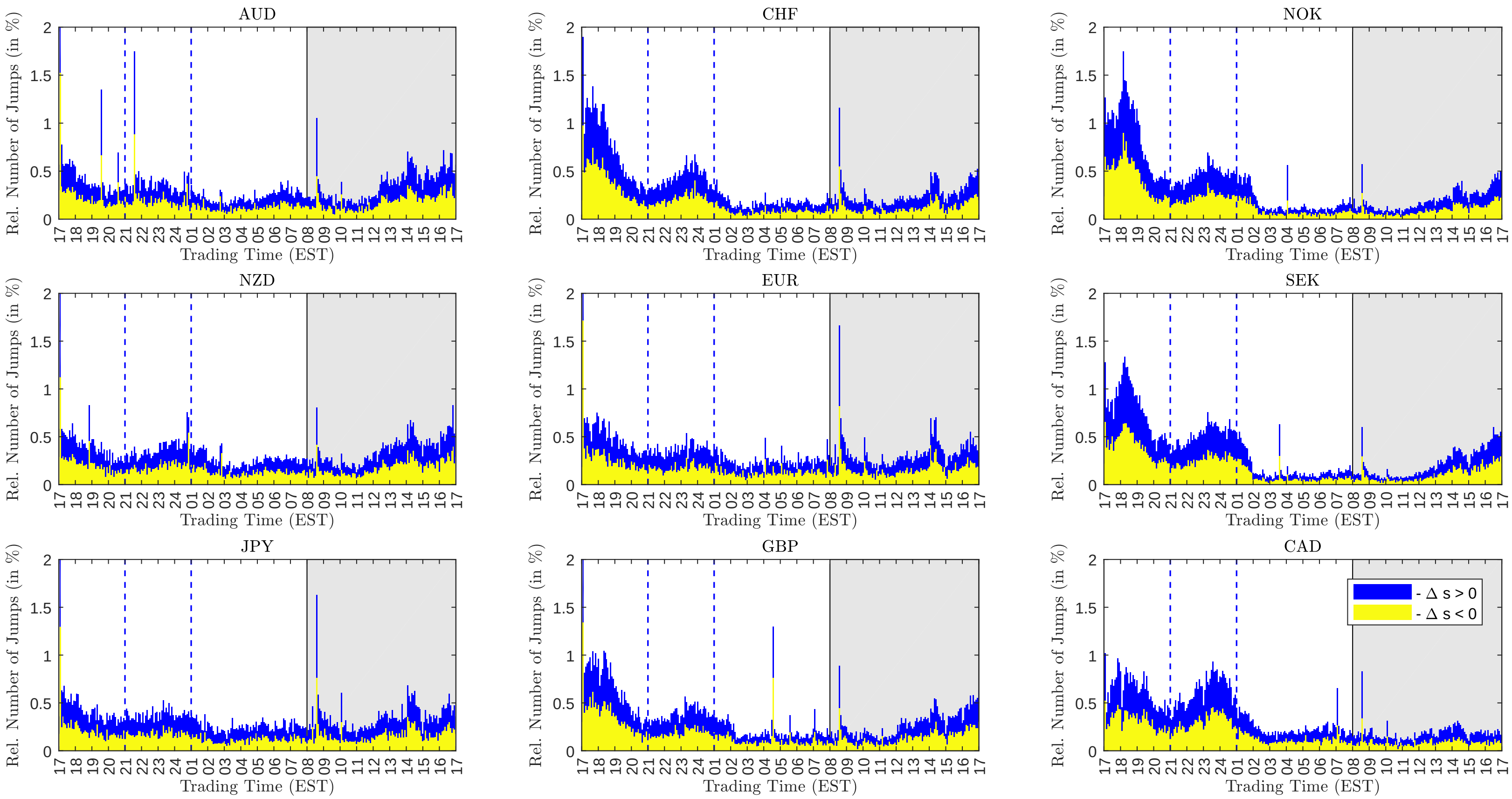

Figure 8. Intraday Crash Risk

This figure displays the relative number of jumps that occur during each 5-minute interval across the entire trading day. Jumps are detected using the Lee and Mykland (2008) jump test statistic, where intraweek periodicity is taken into account following the procedure in Boudt, Croux, and Laurent (2011). The level of significance for the jump statistic is 5%. The blue bars ($-\Delta s_t > 0$) denote positive jumps (appreciation of the foreign currency), while the yellow bars ($-\Delta s_t < 0$) refer to negative jumps (depreciation of the foreign currency). The x-axis refers to daily trading hours, measured in Eastern Standard Time (EST). They y-axis measures the relative number of jumps (in %) during each 5-minute interval.

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FX Premia Around The Clock

Ingomar Krohn, Philippe Mueller and Paul Whelan

Appendix A: Robustness Tests

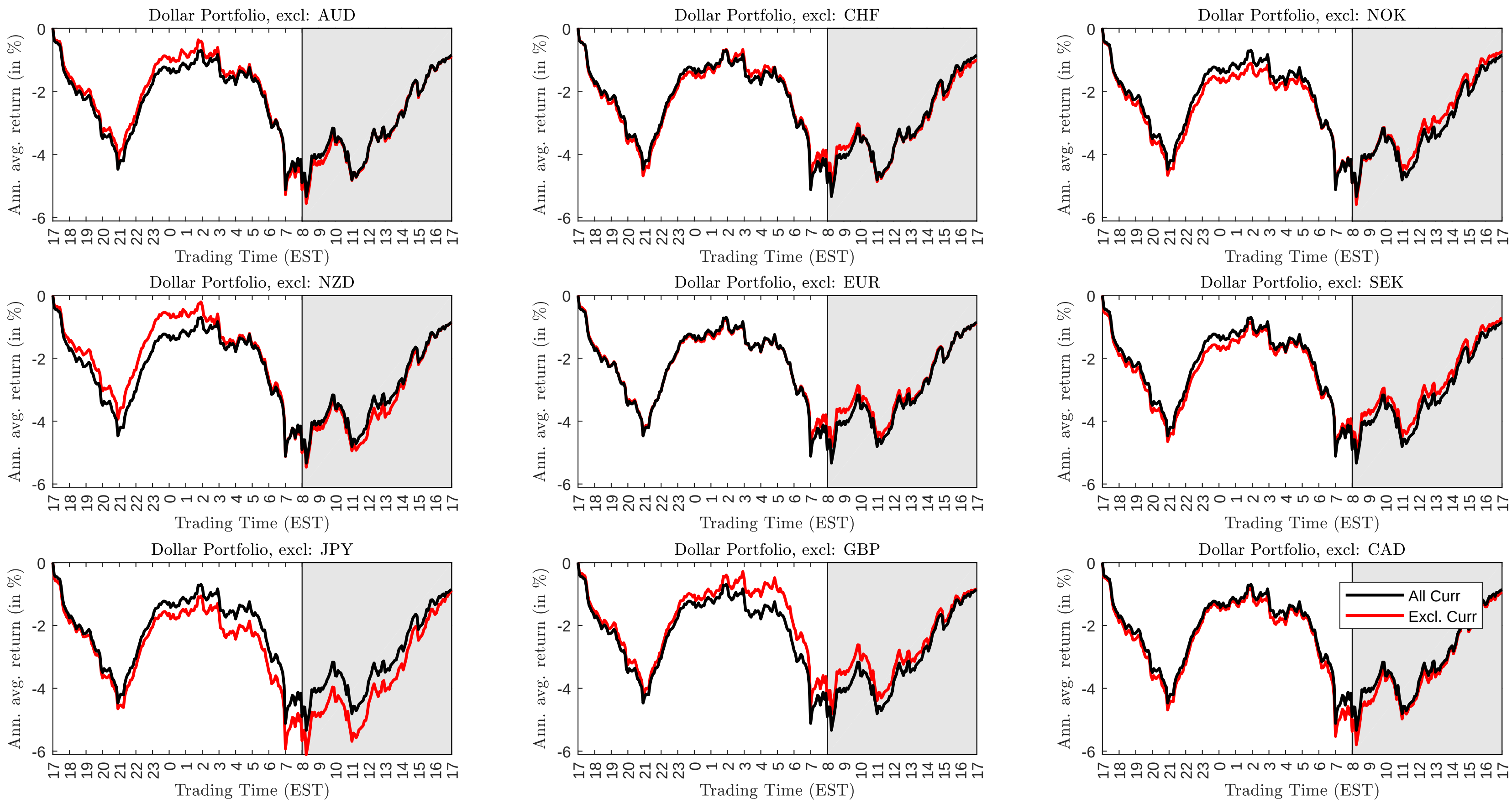

Figure 9. Dollar Portfolio: Alternative Currency Cross-Sections

This figure displays cumulative average annualized 5-min log spot changes ($-\Delta s$) of different specifications of the unconditional dollar portfolio over the course of a trading day. The black line refers to the dollar portfolio based on all nine foreign currencies. The red line refers to a dollar portfolio for which one currency pair is excluded. The dollar portfolio refers to an investment where an US invest equally invests in a set of foreign currencies at the beginning of the sample in January 1994. The grey-shaded area marks the main trading hours in New York (8:00 a.m. to 5:00 p.m. EST). Hours (x-axis) refer to Eastern Standard Time (EST). The sample period comprises all months between January 1994 to December 2017.

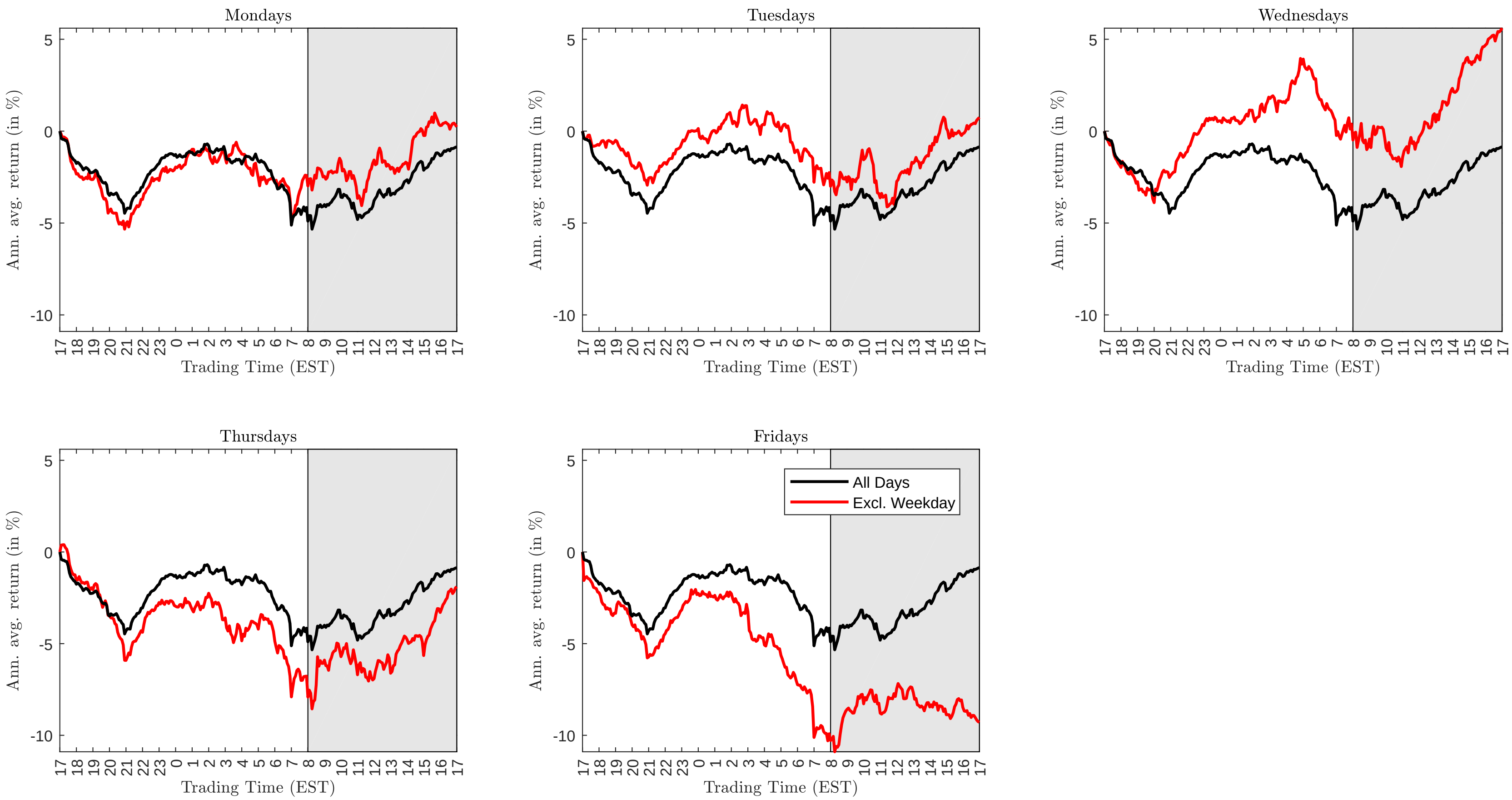

Figure 10. Dollar Portfolio: Decomposition By Weekdays

This figure displays cumulative average annualized 5-min log spot changes ($-\Delta s$) of the unconditional dollar portfolio over the course of all trading days in the week. The black line refers to the dollar portfolio constructed from returns on all days, while the red line refers to the dollar portfolio based on returns on either Monday, Tuesday, Wednesday, Thursday, or Friday. The trading day on Friday comprises all returns on Fridays until 5:00 p.m. and all returns on Sundays from 5:00 p.m. until the end of the day. The dollar portfolio refers to an investment where an investor equally invests her capital into a set of foreign currencies at the beginning of the sample in January 1994. The grey-shaded area marks the main trading hours in New York (8:00 a.m. to 5:00 p.m. EST). Hours (x-axis) refer to Eastern Standard Time (EST). The sample period comprises all months between January 1994 to December 2017.

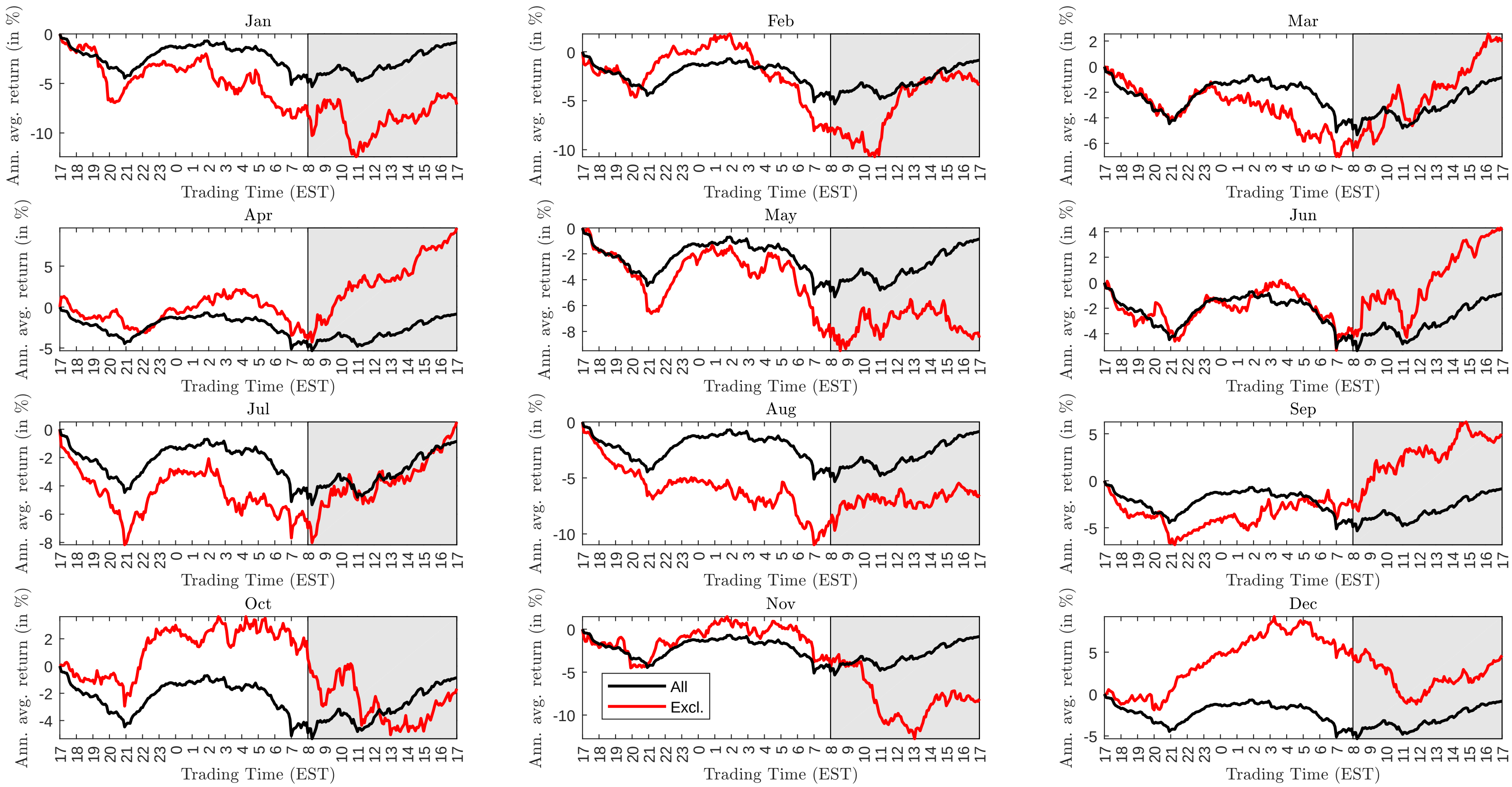

Figure 11. Dollar Portfolio: Decomposition By Months

This figure displays cumulative average annualized 5-min log spot changes ($-\Delta s$) of the unconditional dollar portfolio over the course of a trading day in every months of the year. The black line refers to the dollar portfolio constructed from returns across all months, while the red line refers to the dollar portfolio based on returns in one specific calendar month. The dollar portfolio refers to an investment where an investor equally invests her capital into a set of foreign currencies at the beginning of the sample in January 1994. The grey-shaded area marks the main trading hours in New York (8:00 a.m. to 5:00 p.m. EST). Hours (x-axis) refer to Eastern Standard Time (EST). The sample period comprises all months between January 1994 to December 2017.

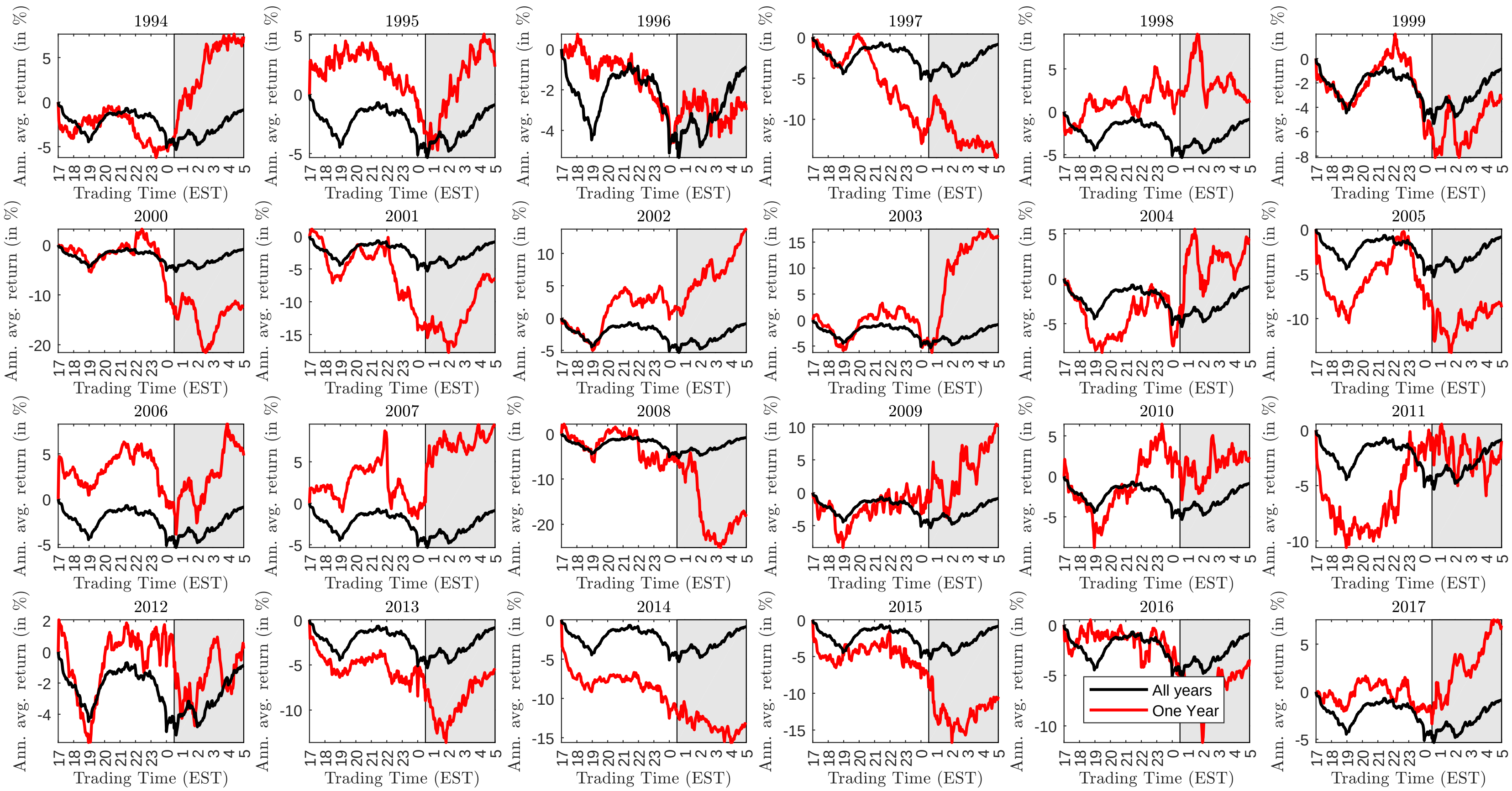

Figure 12. Dollar Portfolio: Decomposition By Years

This figure displays cumulative average annualized 5-min log spot changes ($-\Delta s$) of the unconditional dollar portfolio over the course of a trading day for every year in our sample. The black line refers to the dollar portfolio constructed from returns across all years, while the red line refers to the dollar portfolio based on returns in one specific calendar year. The dollar portfolio refers to an investment where an investor equally invests her capital into a set of foreign currencies at the beginning of the sample in January 1994. The grey-shaded area marks the main trading hours in New York (8:00 a.m. to 5:00 p.m. EST). Hours (x-axis) refer to Eastern Standard Time (EST). The sample period comprises all months between January 1994 to December 2017.

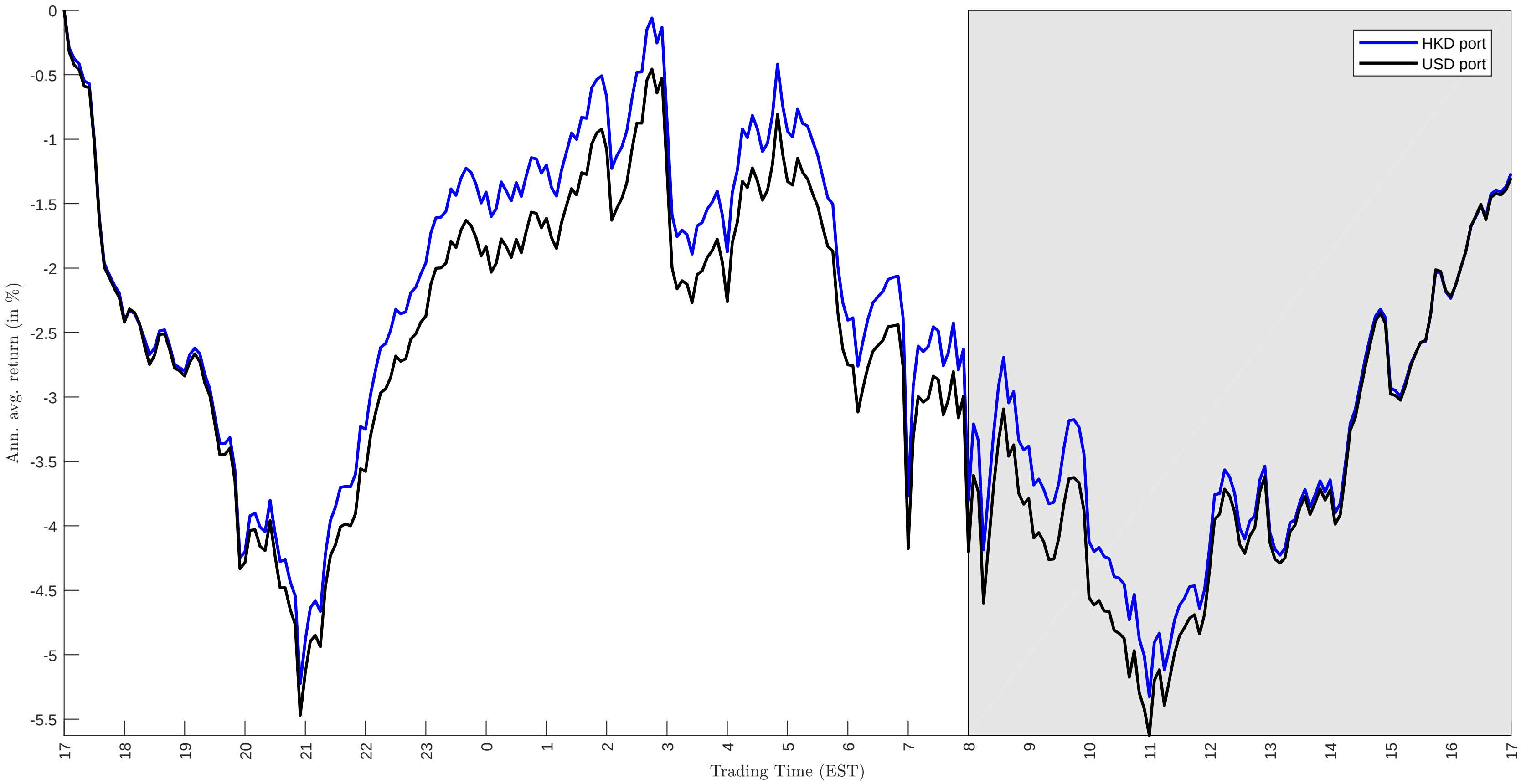

Figure 13. Unconditional Hong Kong Dollar Portfolio

This figure displays the development of the unconditional U.S. dollar portfolio (black line) and Hong Kong dollar (blue line) portfolio over the course of the trading day. The grey area marks the main trading hours in New York (8:00 a.m. to 5:00 p.m.) An increase of the portfolio implies that foreign currencies appreciate against the U.S. dollar and Hong Kong dollar. Trading hours (x-axis) refer to Eastern Standard Time (EST). The sample period comprises all months between January 1994 to December 2017.