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Segmentation and time-of-day patterns in foreign exchange markets

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ABSTRACT

This paper sheds light on a puzzling pattern in spot foreign exchange markets: domestic currencies appreciate (depreciate) systematically during foreign (domestic) working hours. This phenomenon spans many years and several exchange rates, and overrides calendar effects. We argue that it is mainly due to liquidity and inventory patterns that emerge from the combination of two factors: domestic agents tend to be net buyers of foreign currency and to trade mostly in their country's working hours. The prevalence of domestic (foreign) traders demanding the counterpart currency during domestic (foreign) working hours implies sell-price (buy-price) pressure on the domestic currency during domestic (foreign) working hours.

1. Introduction

This paper provides puzzling evidence on spot exchange rates: home currencies depreciate systematically during domestic working hours and appreciate during the working hours of the foreign counterpart country. Our database covers more than a decade's worth of data stored in a high-frequency database, with several currency pairs that, taken together, cover more than 63% of total market turnover by currency pair in 2007 (BIS, 2007). A clear picture emerges: first, this pervasive time-of-day pattern is highly significant in statistical terms; second, it spans many years and overrides calendar effects.

The first aim of this study is to document the statistical significance of these time-of-day patterns.[1] The second is to propose an explanation. We argue that the main explanation is related to directional liquidity patterns. In particular, these patterns are derived from a combination of two factors. First, domestic agents tend to be net buyers of foreign currency. This can be explained by increasing international diversification coupled with rapid growth in wealth worldwide over the past few decades. It is also consistent with the stylised fact that international portfolios are long (short) in foreign (domestic) currency (e.g. Lane and Milesi-Ferretti, 2007). An additional explanation is the transactions hypothesis proposed by Cornett et al. (1995), i.e. the bias to denominate and invoice international transactions in the exporting firm's currency. Second, investors have a tendency to trade mainly during their own country's working hours. Among the institutional reasons supporting this practice, there is the convention of closing or reducing open positions on exchange rates out of the liquidity clustering during the main working hours. In aggregate, the combination of these two factors creates sell-price (buy-price) pressure on the domestic currency during domestic (counterpart) working hours. In a trading environment with an imperfectly elastic supply and risk-averse agents, the purchase of foreign currency during domestic hours gives rise to cyclical patterns in terms of liquidity demand and inventory imbalances, engendering a depreciation (appreciation) of the home currency during domestic (foreign) working hours.

Our study adds to the extant literature in two key regards. First, it examines in finer detail the cross-sectional and time-series characteristics of intraday returns on spot exchange rates across different time zones, working time periods and calendar events. While research on equity markets has found some significant day-of-week or intraday patterns on returns,[2] the literature to date

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[1] In a related study, Breedon and Ranaldo (2008) focus on the economic significance of these time-of-day regularities.

[2] For example, French (1980) finds that Friday close to Monday close returns are significantly negative. More recently, Cliff et al. (2007) find that overnight returns are strongly positive and they explain most of the equity premium for US stocks.

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has little to say about the intraday patterns of exchange rate returns. In most previous studies, attention has instead been devoted to intraday volatility or bid-ask spreads.[3] The notable exceptions are Cornett et al. (1995),[4] Ito (1987), Ito and Roley (1987, 1991)[5] and Wasserfallen (1989)[6] but their papers present mixed and partial results. In particular, Cornett et al. (1995) and Wasserfallen (1989) find that the US dollar depreciates at the beginning of the US working day whereas Ito and Roley (1987, 1991) find the opposite. Moreover, these studies are unable to put forward any comprehensive explanation. The transactions hypothesis of Cornett et al. (1995) is a complementary hypothesis to explain why US firms are likely to be net buyers of foreign currency during US trading hours. But it cannot explain the round-the-clock and pervasive phenomenon. Second, the goods/services trade accounts only for one-third of end-user trading in foreign exchange markets (BIS, 2007). Thus, the dominant part of financial transactions remains unexplained.

Second, this research focuses on liquidity. While information effects have been carefully identified in the literature,[7] much less is known about how liquidity influences exchange rate movements. Berger et al. (2008) investigate the joint behaviour of order flow and exchange rates at different sampling frequencies. Breedon and Vitale (2005) propose a structural model of exchange rate determination which disentangles the portfolio-balance and information effects of order flows. Marsh and O'Rourke (2005) address the question of whether information and/or liquidity can explain the positive contemporaneous correlation between exchange rate changes and net order flows. Here, we relate cyclical appreciations and reversals of the domestic currency to directional liquidity and inventory patterns.

This paper is structured as follows. Section 2 provides statistical evidence on time-of-day market patterns. In Section 3, we propose an explanation for the time-of-day patterns. Section 4 presents the main empirical findings. Section 5 concludes the paper.

2. Time-of-day patterns

2.1. Data

The database has been kindly provided by Swiss-Systematic Asset Management SA, Zurich. It includes spot exchange rates for the following currency pairs: CHF/USD, DEM/USD, EUR/USD, GBP/USD, JPY/EUR and JPY/USD. The sample periods cover the beginning of January 1993 to the end of August 2005 for the CHF/USD, GBP/USD and JPY/USD exchange rates and from January 1999 to August 2005 for EUR/USD and JPY/EUR. Data for DEM/USD cover the period from January 1993 to December 1998. The date of the euro's introduction dictates the time periods for the euro and the deutschmark. We use the tick-by-tick FXFX Reuters midquote price (the average price between the representative ask and bid quotes). The characteristics of these data have been discussed at length in previous studies.[8] Although indicative quotes have their shortcomings,[9] the microstructure literature shows that for frequencies shorter than tick frequency, the indicative midquote is very representative (Danielsson and Payne, 2002).

We also augmented our dataset with firm quotes from the Electronic Brokerage Services (EBS) on the EUR/USD spot exchange rates from 1999 to the end of June 2007. These additional data allow us to compare indicative and firm quotes.

To conduct this study, we carefully organised our database as follows: first, we accounted for differences in daylight savings times by expressing time in terms of Greenwich Mean Time (GMT). Second, we organised our database in five-minute intervals. If no trades occurred in a given five-minute interval, we used the last quotes in the previous time interval. Finally, since our database included weekends, we excluded weekend hours according to the definitions reported in Table 1, i.e. the beginning and end of working hours in the different time zones.[10]

For the sake of presentation, we investigate exchange rate movements over four-hour periods. These time brackets are the most efficient solution for analysing non-overlapping intraday periods in the different working hours of each world region. First, they decompose round-the-clock time into homogenously and regularly spaced intervals. The four-hour timeframe coincides pretty well with the opening and closing times of the main international equity markets. In particular, trading hours from midnight to 04:00 GMT, from 08:00 to midday, and from 16:00 to 20:00 GMT mirror the main trading activity in Japan, Europe and the US, respectively. Second, a four-hour interval is a reasonable length of time for marketable intraday trading, and also minimises issues such as entry and exit timing, transaction costs, trading slippages and possible delays in 'indicative' quotes. We also analysed these patterns on an hourly basis. These additional findings are perfectly in line with those analysed here, and are available upon request.

2.2. Statistical significance

Fig. 1 presents time-of-day return patterns on EUR/USD in graphical form. It shows 24 cross-sectional averages of annualised log returns over four hours, which are computed using the nearest quotes to the end of the four-hour period. To annualise, four-hour returns are multiplied by 260. Using two-sample *t*-tests, these charts also show if the acceptance of the null hypothesis of equality in means of non-overlapping returns falls below the *p*-value of 5% or 1%. In Fig. 1, black (grey) bars mean that an average return over a specific four-hour period is different at a 1% (5%) significance level. The charts on the other exchange rates (available upon request) deliver a very similar picture. Fig. 1 clearly shows that the domestic currency tends to depreciate during domestic working hours and to appreciate during the working hours of counterpart countries. More specifically, the US dollar appreciates significantly from 08:00 to 12:00 GMT and the euro appreciates significantly from 16:00 to 22:00 GMT. It is worth noting that Reuters and EBS patterns are very similar (the correlation coefficient is 0.95). This suggests that Reuters indicative quotes are closely related to trading data.

[3] The pioneers in collecting and analysing high-frequency data were Olsen & Associates (e.g. Dacorogna et al., 1993; Olsen et al., 1997; Müller et al., 1990). Other studies that, inter alia, have made significant contributions to the literature are Andersen and Bollerslev (1997, 1998), Baillie and Bollerslev (1990), Bollerslev and Domowitz (1993), Harvey and Huang (1991), Hsieh and Kleidon (1996), Ito and Hashimoto (2005). The predictability of exchange rates has recently been studied by, among others, Dueker and Neely (2007), Guo and Savickas (2008) and Sarantis (2006).

[4] Cornett et al (1995) use several years of intraday data on foreign exchange futures from the international money market.

[5] Ito (1987) and Ito and Roley (1987, 1991) have a few snapshots of the yen-dollar exchange rate at the opening and closing in the Tokyo and New York markets.

[6] Wasserfallen (1989) analyses the bid prices quoted by UBS on the interbank market for CHF/USD exchange rates in 1983. He also finds that the Swiss franc declines (increases) in value especially in the early morning of European (US) trading.

[7] In particular, see the seminal paper by Evans and Lyons (2002), in which the order flow is the main determinant of exchange rates because it conveys information. Other papers have investigated information asymmetry, e.g. Osler et al (2006) and Payne (2003).

[8] Including Müller et al (1990), Dacorogna et al (1993) and Goodhart et al (1996).

[9] Lyons (1995) stresses three limitations related to 'indicative' quotes: they are not tradable; they are representative only for the interbank market; during very fast markets, 'indicative' quotes may be updated with a short delay. Martens and Kofman (1998) show that futures on DEM/USD tend to lead the 'quoted' spot market by up to three minutes. On the other hand, Goodhart et al (1996) conclude that FXFX indicative quotes can be taken as a very good and close proxy for that in the Reuters 2000-2.

[10] The inclusion of weekends leaves the main results unchanged. But it has the disadvantage of blurring some of the intraday effects.

Table 1
Weekend definitions and official holidays by country.

Beginning of the week				End of the week			
Ccy	GMT	Local ccy 1	Local ccy 2	GMT	Local ccy 1	Local ccy 2	h excluded
Panel A: Weekend definitions							
CHFUSD	Mon 5:00	Mon 6:00	Sun 24:00	Fri 23:00	Fri 24:00	Fri 18:00	54
DEMUSD	Mon 5:00	Mon 6:00	Sun 24:00	Fri 23:00	Fri 24:00	Fri 18:00	54
EURUSD	Mon 5:00	Mon 6:00	Sun 24:00	Fri 23:00	Fri 24:00	Fri 18:00	54
GBPUSD	Mon 5:00	Mon 5:00	Sun 24:00	Fri 23:00	Fri 23:00	Fri 18:00	54
JPYEUR	Sun 21:00	Mon 6:00	Sun 22:00	Fri 17:00	Sat 2:00	Fri 18:00	52
JPYUSD	Sun 21:00	Mon 6:00	Sun 16:00	Fri 23:00	Sat 8:00	Fri 18:00	46
Germany		Japan	Switzerland		UK		US
Panel B: Official holidays, by country							
New Year		New Year	New Year		New Year		New Year
Good Friday		Bank holidays	Good Friday		Good Friday		M. L. King Day
Easter Monday		Coming of Age Day	Easter Monday		Easter Monday		Presidents' Day
Labour Day		Vernal Equinox Day	Ascension		Early May Bank Hol.		Memorial Day
Ascension		Greenery Day	Whit Monday		Spring Bank Hol.		Independence Day
Whit Monday		Constitution Day	Confederation Day		Summer Bank Hol.		Labor Day
Union Day		Children's Day	Christmas Day		Christmas Day		Columbus Day
Christmas Day		Marine Day	St Stephan's Day		Boxing Day		Veterans' Day
Boxing Day		Health–Sports Day	New Year's Eve				Thanksgiving Day
New Year's Eve		Culture Day					Christmas Day
		Labour Day					
		Thanksgiving Day					
		Ordinary holiday					
		The Emperor's Day					
		Autumn Equinox Day					
		Founding of the Nation					
		Respect-for-the-aged Day					

Fig. 2 shows that these time-of-day patterns continued over a number of years.[11] The trading influence from world regions other than the two counterparties is weaker, but still visible. In particular, trading during Japanese trading hours appears to support the US dollar against the euro and sterling, while US trading supports the euro against the yen and during European hours the dollar depreciates against the yen.[12] The cross-country net exchange positions offer a possible explanation for these patterns. For instance, Japanese investors held a positive net position on the US dollar during the last two decades.

Tables 2 and 3 show more detailed descriptive statistics about Reuters quotes. Here, six non-overlapping four-hour intervals represent the entire trading day. Means, medians and standard deviations are reported on an annualised basis for ease of reading. Tests for inequality in means and medians (Wilcoxon/Mann–Whitney test) corroborate the previous results. Outliers have been analysed with particular attention.[13] Among the descriptive statistics, we report the relative frequency of positive returns (excluding zero returns). The sign test shows that the proportion of upward and downward intraday returns significantly matches the time-of-day patterns plotted in Fig. 1, i.e. there are consistently more domestic currency depreciations (appreciations) during domestic (foreign) working hours.

3. Possible explanation

The time-of-day patterns may originate from two main factors. First, the typical domestic agent is a net demander of foreign currency. This can be explained by the fact that domestic investors' portfolios are generally biased towards domestic currencies. This natural bias makes domestic agents incline towards foreign currencies. Intuitively, the net demand for foreign currency can be due to international diversification[14] coupled with a rapid growth of wealth worldwide over the past few decades. In addition, international studies show that international portfolios are long in foreign currency (Lane and Milesi-Ferretti, 2007). The transactions hypothesis (e.g. Cornett et al., 1995) is a complementary explanation that refers to the tendency to denominate exported goods/services in foreign currency. Second, currency markets are characterised by geographical and chronological segmentation. Domestic trading activity tends to cluster in domestic working hours. Evidence on the imperfect integration of foreign exchange markets is provided by Hsieh and Kleidon (1996). This can be explained by the institutional practice of executing orders during the main working hours, and by the intraday liquidity patterns stemming from risk-sharing and strategic behaviour of liquidity and informed traders (see e.g. Admati and Pfleiderer, 1988). This clustering of activity also generates cyclical inventory imbalances. The premia demanded by (risk-averse) liquidity providers may contribute to the depreciation of the domestic currency during domestic working hours and the reverse pattern in the subsequent period.[15] It is also worth noting that many banks impose overnight limits on their dealers' positions (Lyons, 1995) and that most dealers close their day with a zero net position (Lyons, 1998). This self-imposed discipline implies cyclical liquidity and inventory patterns. Finally, it is common practice in foreign

[11] Fig. 2 shows the domestic currency depreciation during domestic working time. The picture showing the opposite pattern, i.e. the domestic currency appreciation during counterpart working time, is exactly the mirror image (available upon request).

[12] It is worth noting that 21:00 GMT can be considered the end of the trading day on spot foreign exchange markets. Consistent with Chaboud and Wright (2005), this point in time has no particular effect on the patterns documented in this study.

[13] We checked for any correspondence between intraday outliers in Reuters and EBS datasets as well as daily data from Datastream. There is consistent matching. We also replicated this analysis by excluding the extreme percentiles (e.g. 5% of highest and lowest intraday returns), and obtained the same results.

[14] See Lewis (1999) for a survey of international home-bias literature.

[15] Lyons (1995), Bjørnnes and Rime (2005) and Cao et al (2006) investigate the inventory hypothesis on exchange rate markets.

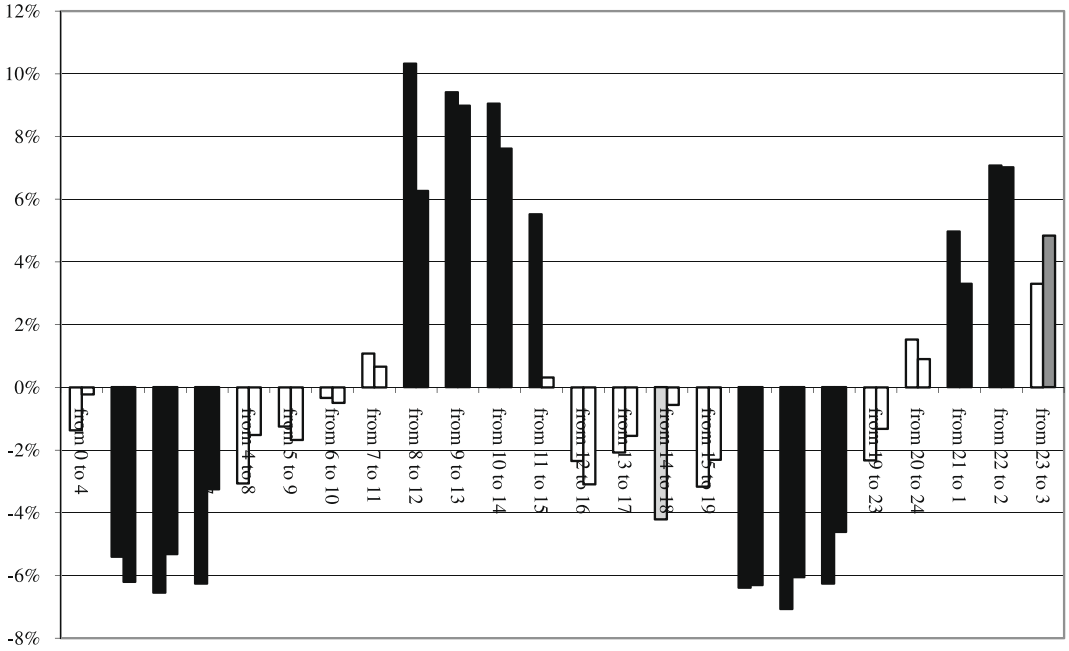

Fig. 1. The chart show 24 cross-sectional averages for annualised EUR/USD returns over four hours. *t*-Statistics were used to test (homoscedastic) equality in means. *t*-Statistics refer to two-tail statistics on the difference between a given four-hour return mean and all the other four-hour returns. Black (grey) bars mean that an average return over a specific four-hour interval is different at a 1% (5%) significance level. For each interval, the chart shows twin bars. The left-hand (right-hand) bar refers to Reuters (EBS) data. Times are expressed in GMT.

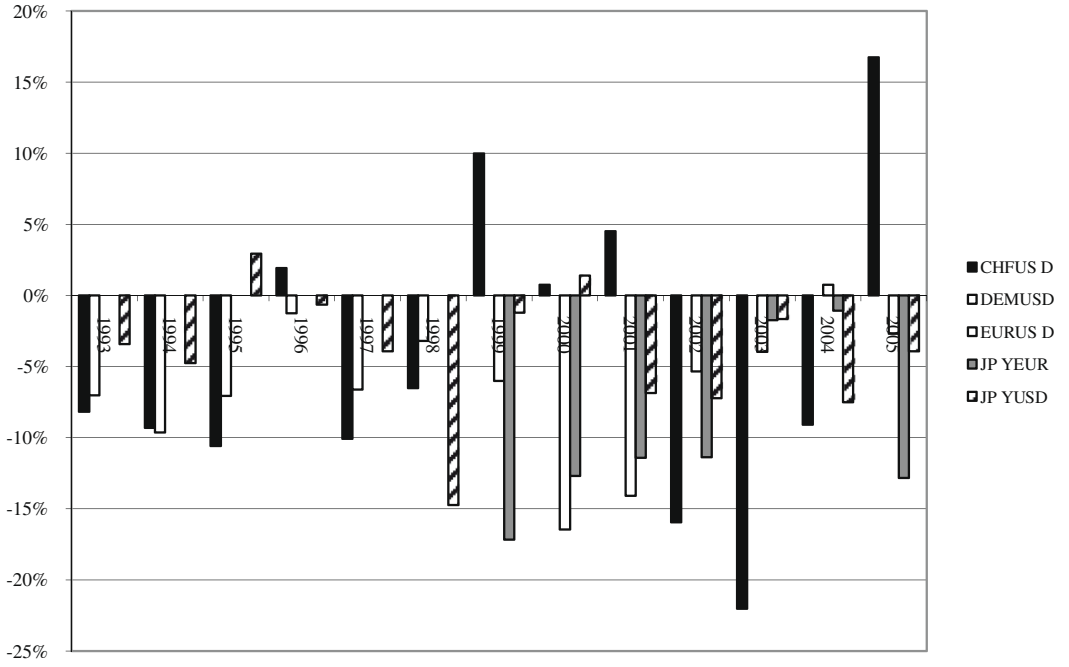

Fig. 2. For each currency pair, this chart plots the year-by-year cross-sectional return averages (in annual terms) for a representative four-hour period in domestic trading hours. It shows a depreciation in the domestic currency during domestic trading hours.

exchange markets to hedge only partially the dealer's aggregate position.

Two main hypotheses stem from the discussion above:

Hypothesis 1: domestic currency depreciation during domestic working hours.
Hypothesis 2: domestic currency appreciation during foreign working hours.

In addition, we test whether patterns change on non-overlapping holidays. Take, for instance, a case where the US is on holiday but Europe is not (e.g. 4 July). If the liquidity explanation holds, we should observe that during the European morning the US dollar appreciates more since there are fewer US traders (and liquidity suppliers) offsetting the demand pressure in favour of the US dollar exerted by the European agents. Conversely, the US dollar should depreciate less during US working hours. This reasoning can be

Table 2
Descriptive statistics on CHF/USD, DEM/USD and EUR/USD exchange rate returns.

EST	19–23	23-3	3–7	7–11	11–15	15–19	Whole
GMT	0–4	4–8	8–12	12–16	16–20	20–24	Daily
Working time	JP	JP–EU	EU	EU–US	US	US	
CHF/USD							
Mean	−1.0%	3.1%**	7.2%***	−6.1%***	−3.0%**	−0.8%	−0.1%
Median	−1.0%	2.8%***	7.9%***	−3.9%***	0.0%	0.0%	0.0%
Maximum	2.709	2.811	4.319	7.108	4.368	2.048	7.960
Minimum	−3.229	−3.585	−6.091	−5.405	−5.822	−3.885	−7.382
Std. Dev.	3.3%	5.1%	6.7%	5.4%	2.6%	2.9%	4.7%
Skewness	−0.12	−0.16	−0.25	−0.05	−0.25	−0.44	−0.21
Kurtosis	8.28	6.09	6.14	5.34	6.41	8.66	6.05
# of Obs	3274	3274	3274	3274	2620	2620	74,652
Freq. Up	48.3*	52**	54.8**	48.3*	49.1	49.3	49.9
DEM/USD							
Mean	0.5%	1.6%	5.0%***	−5.8%***	0.3%	0.3%	0.3%
Median	0.8%	0.0%	3.8%***	−6.6%***	0.8%	0.0%	0.0%
Maximum	1.753	2.315	3.475	6.202	4.753	1.821	6.800
Minimum	−2.490	−3.212	−4.447	−4.849	−4.928	−2.950	−5.763
Std. Dev.	2.7%	4.1%	5.7%	5.0%	2.5%	2.8%	4.1%
Skewness	−0.34	0.08	−0.03	0.22	−0.27	−0.75	−0.10
Kurtosis	6.70	6.54	7.15	6.83	8.71	10.65	7.63
# of Obs	1250	1561	1561	1561	1561	1249	35,595
Freq. Up	50.1	52.1**	53.6***	46.5***	50.1	51.0	50.2
EUR/USD							
Mean	−1.4%	−3.1%	10.3%***	−2.3%	−6.4%***	1.5%	−0.3%
Median	0.0%	−1.4%*	10.8%***	1.4%	−5.7%***	1.1%	0.0%
Maximum	2.569	2.758	4.034	3.433	4.313	1.641	5.072
Minimum	−1.751	−3.732	−4.150	−4.645	−4.828	−2.379	−8.956
Std. Dev.	3.2%	5.1%	6.2%	4.6%	2.4%	2.7%	4.4%
Skewness	0.20	−0.38	−0.14	−0.21	−0.14	−0.06	−0.22
Kurtosis	6.29	6.67	5.31	4.40	6.41	6.08	5.49
# of Obs	1371	1713	1713	1713	1713	1371	39,060
Freq. Up	49.6	48.3*	57.3***	50.6	46.1***	51.3	49.9

This table shows the descriptive statistics for intraday and daily returns, excluding weekends, for CHF/USD, DEM/USD and EUR/USD currency pairs. Intraday (log) returns are calculated over non-overlapping four-hour periods and then annualised by multiplying by 260. The first row shows the time of day (GMT) and the second row indicates which country or region is working during the different hours of the day. 'Freq. Up' denotes the proportion of positive returns (in %). The table shows the *t*-test and Chi-square for testing the null hypothesis that there is equality in means and medians. The sign test assesses the null hypothesis that positive and negative returns are proportionally equally represented. Significance at 1%, 5% and 10% is denoted by ***, ** and *, respectively.

easily applied to the four combinations of domestic/foreign holidays and domestic/foreign working hours. Hence, four additional hypotheses can be tested:

Hypothesis 3: the domestic currency should depreciate more during domestic working hours when the foreign country is on holiday.
Hypothesis 4: the domestic currency should appreciate less during foreign working hours when the foreign country is on holiday.
Hypothesis 5: the domestic currency should appreciate more during foreign working hours when the domestic country is on holiday.
Hypothesis 6: the domestic currency should depreciate less during domestic working hours when the domestic country is on holiday.

4. Empirical analysis

4.1. Empirical model

The behaviour of intraday returns of exchange rate i can be modelled as follows:

$$r_{i,t} = \rho_i r_{i,t-1} + \sum_{k=1}^{6} \alpha_k d_{t,k} + \gamma h_{i,t}^{fhdw} + \delta h_{i,t}^{fhfw} + \eta h_{i,t}^{dhfw} + \lambda h_{i,t}^{dhdw} + \varepsilon_{i,t} \quad (1)$$

where $r_{i,t}$ is the log exchange rate return over the four-hour period t, $d_{t,k}$ is a dummy variable that is equal to 1 when the intraday period is k, and zero otherwise. The decomposition of the day into six four-hour time intervals implies $k = 1, \ldots, 6$. We use the superscripts *dh* and *dw* to refer to domestic holidays and domestic working hours, and *fh* and *fw* for foreign holidays and foreign working hours. Hence, $h_{i,t}^{fhdw}$ ($h_{i,t}^{fhfw}$) is a dummy variable equal to 1 when the foreign country is on holiday during domestic (foreign) working hours, and zero otherwise, and $h_{i,t}^{dhfw}$ ($h_{i,t}^{dhdw}$) is a dummy variable equal to 1 when the domestic country is on holiday during foreign (domestic) working hours, and zero otherwise.

We pool the intraday return data across all exchange rates in our sample and perform a regression analysis based on a panel fixed-effects specification. After appropriately organising the data, we obtain six time series of dummy variables for the six four-hour intervals during the day and four dummy variables capturing the domestic/foreign holidays during domestic/foreign trading hours. The fixed-effects specification imposes the same time-of-day return pattern across exchange rates, i.e. α_k equal for each exchange rate, and the same holiday effects, i.e. same γ, δ, η, and λ across the panel. In order to avoid inconsistent estimates of the coefficients in the dynamic panel (Pesaran and Smith, 1995), the autoregressive coefficients (ρ_i) are not constrained to be equal but instead vary across exchange rates. The regression estimation is based on robust standard errors.

The US dollar is always taken as the domestic currency, except in the case of EUR/JPY, where the euro is used. However, to obtain a consistent definition of returns across the panel, the EUR/JPY

Table 3
Descriptive statistics on GBP/USD, JPY/EUR and JPY/USD exchange rate returns.

EST	19–23	23-3	3–7	7–11	11–15	15–19	Whole
GMT	0–4	4–8	8–12	12–16	16–20	20–24	Daily
Working time	JP	JP–EU	EU	EU–US	US	US	
GBP/USD							
Mean	−1.0%	3.4%***	2.4%***	−3.5%***	−5.0%***	−2.8%***	−0.3%
Median	−0.9%	2.4%***	2.4%***	−2.7%***	−3.7%***	2.6%***	0.0%
Maximum	2.450	3.017	3.935	5.135	3.865	2.807	5.135
Minimum	−1.831	−3.009	−3.785	−4.319	−5.002	−1.294	−5.002
Std. Dev.	2.1%	2.9%	4.1%	5.1%	3.7%	1.9%	3.5%
Skewness	0.05	0.20	0.03	−0.09	−0.11	0.27	−0.06
Kurtosis	6.77	6.12	5.76	5.59	10.22	7.65	8.67
# of Obs	2623	3281	3281	3281	3281	2621	75,452
Freq. Up	47***	51.8*	52.5***	47 5***	45 2***	53.3***	49.7
JPY/EUR							
Mean	2.8%*	−2.80%	−8.0%***	−0.90%	6.2%***	0.10%	−0.60%
Median	1.30%	−1.4%*	−4.2%***	0.00%	5.7%***	0.90%	0.00%
Maximum	4.791	4.961	4.239	5.525	3.88	4.627	8.942
Minimum	−7.435	−4.56	−5.09	−4.791	−6.033	−9.409	−9.409
Std. Dev.	4.2%	6.0%	6.4%	4.8%	3.5%	4.6%	4.9%
Skewness	−0.07	−0.01	−0.33	−0.08	−0.31	−2.68	−0.18
Kurtosis	13.16	8.23	5.96	5.51	8.26	51.72	7.3
# of Obs	1713	1713	1713	1713	1370	1712	39,836
Freq. Up	51.5	48.2	47.7**	50.2	54.1***	51.5	50.3
JPY/USD							
Mean	2.7%**	−2.40%	−0.60%	−4.0%***	2.8%**	0.30%	−0.20%
Median	1.3%*	−1.3%*	0.00%	−3.7%***	2.5%**	1.10%	0.00%
Maximum	5.521	4.587	7.894	6.045	9.862	5.384	14.365
Minimum	−9.998	−6.118	−15.034	−8.348	−8.773	−4.153	−21.739
Std. Dev.	3.9%	5.4%	5.1%	5.3%	3.3%	4.8%	4.7%
Skewness	−0.66	−0.34	−1.89	−0.42	−0.04	−0.32	−0.75
Kurtosis	17.4	13.63	39.72	11.03	15.18	15.02	24.96
# of Obs	3274	3274	3274	3274	3274	3597	79,219
Freq. Up	51.2	47.9**	50.3	47.8***	50.2	51.2	50.3

This table shows the descriptive statistics for intraday and daily returns, excluding weekends, for GBP/USD, JPY/EUR and JPY/USD currency pairs. Intraday (log) returns are calculated over non-overlapping four-hour periods and then annualised by multiplying by 260. The first row shows the time of day (GMT) and the second row indicates which country or region is working during the different hours of the day. 'Freq. Up' denotes the proportion of positive returns (in%). The table shows the *t*-test and Chi-square for testing the null hypothesis that there is equality in means and medians. The sign test assesses the null hypothesis that positive and negative returns are proportionally equally represented. Significance at 1%, 5% and 10% is denoted by ***, ** and *, respectively.

returns between 08:00 and midday GMT are multiplied by –1. This adjustment ensures that a depreciation of the yen and euro during their respective working hours has a positive sign, as against the US dollar.

4.2. Empirical findings

Table 4 summarises the main results. For ease of reading, the table also reports the six hypotheses stated above and the expected

Table 4
Regression analysis

Coefficient name	Time (GMT)	Estimate	*t*-Stat	Hypothesis	Expected sign
Alpha 1	00:00–4:00	0.013*	1.897	2	+
Alpha 2	04:00–08:00	0.011*	1.856	2	+
Alpha 3	08:00–12:00	0.045***	7.424	2	+
Alpha 4	12:00–16:00	−0.029***	−4.714	1	–
Alpha 5	16:00–20:00	−0.033***	−5.486	1	–
Alpha 6	20:00–24:00	0.010	1.428	1	–
Gamma	FH-DW	−0.07**	−2.054	3	–
Delta	FH-FW	−0.072**	−2.107	4	–
Nu	DH-FW	0.096***	2.841	5	++
Lambda	DH-DW	0.022	0.649	6	+
Rho CHF/USD		−0.010	−1.322		
Rho DEM/USD		−0.022**	−1.975		
Rho EUR/USD		−0.011	−1.026		
Rho GBP/USD		−0.035***	−3.691		
Rho EUR/JPY		−0.023***	−2.831		
Rho JPY/USD		−0.039***	−5.562		

This table shows the results of a panel regression of pooled data for six exchange rates. The dependent variables are log exchange rate returns over four-hour periods, alpha 1–6 are the coefficients related to six dummy variables that are equal to 1 when the intraday period corresponds to the intervals listed in the second column, and zero otherwise. DH and DW refer to domestic holidays and working hours, and FH and FW to foreign holidays and working hours. Gamma, delta, nu and lambda are the coefficients capturing holiday patterns. The regression analysis is performed on the basis of a panel fixed-effects specification. The fixed-effects specification imposes the same time-of-day return patterns and holiday effects across exchange rates. Exchange rate-specific autoregressive patterns are captured by AR(1) coefficients, i.e. rho. The right-hand part of the table shows the hypotheses to test and the implied coefficient signs. Significance at 1%, 5% and 10% is denoted by ***, ** and *, respectively.

coefficient signs. A positive (negative) sign in the last column of the table means that the hypothesis implies an appreciation (depreciation) of the domestic currency. Regarding specific holiday effects, a twofold positive (negative) sign refers to a stronger-than-usual appreciation (depreciation) of the domestic currency.

The table shows clear patterns for European and US working hours, in which the US dollar significantly appreciates between 08:00 and midday GMT, and then depreciates during the domestic working day (from midday to 20:00 GMT). The appreciation of the dollar during Asian working hours is less marked although still significant (from midnight to 08:00 GMT). To a lesser extent, we find some support for holiday effects. The dollar tends to depreciate more during domestic working hours if the counterpart country is on holiday, and it appreciates more during foreign working hours if the US is on holiday. Intraday returns are significantly auto-correlated in four of the six exchange rates.

4.3. Robustness checks

We carried out several robustness checks and additional analysis. Further specifications of the panel regressions (e.g. excluding EUR/JPY) yielded essentially the same findings. Regarding holiday patterns, we conducted a non-parametric analysis which revealed exactly the same picture. The regression analysis was also conducted for each exchange rate separately. Some specific patterns emerged. For instance, the time-of-day patterns in the EUR/USD seem to be the most pronounced, while the JPY/USD regularities are weaker although still significant. Additionally, we controlled for more lags for the dependent variable and regressors as well as GARCH effects and time-of-day seasonalities in the conditional variance. The GARCH analysis was performed after the manner of Andersen and Bollerslev (1997). These additional results are available upon request. Overall, they are very consistent with the findings reported here.

5. Conclusion

This study shows that domestic currencies tend to depreciate during domestic working hours and appreciate during the working hours of the counterpart country. We argue that domestic traders tend to buy foreign currencies during domestic working hours. Intraday time-series analysis and holiday effects provide preliminary support for this explanation. Future research on order flow data and cross-border capital inflows, possibly disaggregated across time-of-day intervals and geographical origin of the orders, should shed more light on this phenomenon.

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