Intraday Patterns in Foreign Exchange Returns and Realized Volatility

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ABSTRACT

This paper investigates intraday patterns in foreign exchange returns based on a sample of 16 currencies versus the U.S. dollar using high-frequency data for the period 2010-2015. We find that home currencies tend to depreciate during domestic trading sessions and appreciate during U.S. trading sessions after London markets are closed, indicating that intraday patterns in foreign exchange returns exist in many countries, including countries with capital controls. Intraday patterns in foreign exchange returns are significantly related to realized volatility, which reflects risk attributable to order flow and market sensitivity to order flow in domestic and foreign markets.

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1. Introduction

Ranaldo (2009) and Breedon and Ranaldo (2013) find distinct intraday patterns in foreign exchange returns. Home currencies tend to depreciate during domestic business hours and appreciate during foreign business hours, based on samples of foreign exchange spot transactions for the Australian dollar, euro, Japanese yen, Swiss franc and U.K. pound, versus the U.S. dollar, for the period 1993–2007. These intraday patterns in foreign exchange returns are statistically significant and are not affected by holiday working hours in the countries examined.

Previous studies on intraday patterns in foreign exchange returns show mixed results. Ito and Roley (1987) find that the yen tends to appreciate against the U.S. dollar during European trading hours and depreciate during New York trading hours, for the period 1980–1985. Wasserfallen (1989) finds that the Swiss franc depreciates against the U.S. dollar during European trading hours and appreciates during U.S. trading hours, in 1983. Cornett et al. (1995) examine intraday patterns in foreign currency futures contracts on the Deutsche mark, British pound, Japanese yen, Swiss franc and Canadian dollar versus the U.S. dollar, for the period 1977–1991. These authors find that foreign currencies tend to depreciate when U.S. markets are closed and appreciate when U.S. markets are open. Ferguson et al. (1998) investigate intraday patterns in volume and volatility for Deutsche mark, British pound and Japanese yen futures contracts traded on the Chicago Mercantile Exchange (CME). These authors find that trading activity in currency futures intensifies when London spot markets are open and declines after London spot markets close, indicating that currency futures markets show similar intraday patterns to foreign exchange spot markets. Cai et al. (2008) examine intraday foreign exchange returns and direction of returns across Asia, Europe and America for the period 1999–2004.

These authors find that euro-dollar and dollar-yen spot rates tend to reverse direction from U.S. trading sessions to next trading day in Asia and Europe, although return reversals are insignificant.

Two hypotheses have been advanced to explain these intraday patterns in foreign exchange returns. The transactions hypothesis suggests that international trade transactions tend to be invoiced in exporting-firm currencies and net purchases of foreign currencies by domestic agents cause the home currency to depreciate when transactions are executed during domestic trading hours (Cornett et al., 1995). The liquidity hypothesis suggests that international trade and portfolio investments create cyclical patterns in liquidity demand and order flow, causing temporary pressures on the home (foreign) currency to depreciate (appreciate) during domestic trading hours, while reversing this intraday pattern during foreign trading hours (Ranaldo, 2009). Breedon and Ranaldo (2013) show that local customers tend to be net sellers of local currencies during local business hours and that intraday patterns in foreign exchange returns are significantly related to intraday patterns in order flow. Berger et al. (2009) argue that, when analyzing the dynamics of exchange rates, it is important to account for the joint effect of order flow and price sensitivity of market participants to order flow due to such factors as inventory positions and risk tolerance of currency traders. In particular, global and regional banks manage foreign exchange risk based on prudential regulations by imposing limits on foreign exchange positions or requiring that capital be set aside against foreign exchange risk (IMF, 1998). Most currency dealers maintain zero net positions at the end of a trading day (Lyons, 1995). Therefore, market sensitivity to order flow should also reflect the holding costs of bank foreign exchange positions. Expressing intraday return as a function of order flow and market sensitivity to order flow, Berger et al. (2009) show that realized volatility, calculated as the sum of squared returns

over a fixed time interval, is a natural measure of the joint effect of order flow and market sensitivity to order flow. If intraday returns are linked to order flow, we should be able to explain the patterns in intraday foreign exchange returns via realized volatility, which is an important risk factor in asset pricing studies of the foreign exchange markets (Christiansen, 2011, Menkhoff et al., 2012, Doukas and Zhang, 2013). In a related paper, Deuskar and Johnson (2011) suggest that order flow–driven risk, measured by the joint effect of net trade demand and the price impact of that demand, represents 40% to 70% of stock market risk.

The present paper makes two contributions to the literature. First, we examine intraday patterns in foreign exchange returns based on a sample of 16 currencies across diverse geographic areas and time zones of the Asia-Pacific, Europe, and the Americas for the period 2010–2015. Together, these 16 currencies account for over 90% of U.S. dollar spot transactions in global foreign exchange markets. Our undertaking is motivated by the observation that previous studies on intraday patterns in foreign exchange returns focus on data for major currency pairs before the 2008 financial crisis. We investigate whether these distinct intraday patterns exist in global currency markets when the U.S. dollar appreciates sharply in our sample period. Second, we propose a risk-based model and show that intraday patterns in foreign exchange returns are related to realized volatility.

2. Data and Methodology

Intraday spot exchange rates are obtained from Thomson Reuters Datastream for the Australian dollar (AUD), Brazilian real (BRL), Canadian dollar (CAD), Chinese yuan (CNY), Danish krone (DKK), euro (EUR), Japanese yen (JPY), Indian rupee (INR), New Zealand dollar (NZD), Norwegian krone (NOK), Russian rubble (RUB), Singapore dollar (SGD), South African

rand (ZAR), Swedish krona (SEK), Swiss franc (CHF) and U.K. pound (GBP), versus the U.S. dollar, for the period May 3, 2010 to December 31, 2015.[1] The mid-market rates are available every hour from 0:00 to 23:00 Greenwich Mean Time (GMT), Monday to Friday. The hourly excess return, r_t, is defined as

$$r_t = log(P_t/P_{t-1}) \quad (1)$$

where, P_t is the mid-market rate in U.S. dollars per unit of foreign currency at time *t*. Thus, positive (negative) returns are associated with appreciation (depreciation) of the foreign currency and depreciation (appreciation) of the U.S. dollar. Each currency pair has 35,496 hourly returns for the sample period, with a total of 567,936 observations available for the analysis.

Given the OTC nature of the foreign exchange markets and business conventions, we define domestic trading hours as 08:00–16:00 local time,[2] U.S. trading hours as 08:00–17:00 New York time, and non-U.S. trading hours as the non-overlapping hours outside of domestic and U.S. trading hours. We partition U.S. trading hours into two trading sessions: the London–New York (LDN-NY) overlap trading session is 08:00–11:00 New York time and the U.S. trading session is 11:00–17:00 New York time. For example, for JPY, the domestic trading session is 23:00–07:00 GMT, the non-U.S. trading session (Europe) is 07:00–13:00 GMT, the LDN-NY overlap trading session is 13:00–16:00 GMT, and the U.S. trading session (New York winter time) is 16:00–22:00 GMT. We compute trading session returns, R_t, for each currency by cumulating hourly excess returns over domestic, LDN-NY overlap, U.S., and non-U.S. trading sessions, respectively. Daylight Saving Time (DST) is adjusted for AUD, BRL, CAD, CHF,

[1] Futures contracts are traded at CME for 14 currencies in our sample, but not for DKK and SGD.
[2] The spot rates at 16:00 London time are defined as closing spot rates (Thomson Reuters, 2017).

DKK, EUR, GBP, NOK, NZD, RUB, SEK, and USD based on the annual transition dates for each country.

As robustness checks, we allow domestic trading sessions to start at 07:00 local time. The results do not change substantially except for CNY and INR. To synchronize trading activity with Tokyo, we define domestic trading sessions as 07:00-16:00 local time for CNY and 06:00-16:00 local time for INR. We note that BRL, CNY and INR are subject to capital controls and intraday spot rates for these three currencies represent onshore rates (Thomson Reuters, 2017).

We test the following null hypotheses:

H1: Home currencies depreciate during domestic trading sessions.

H2: Home currencies appreciate during foreign (LDN-NY overlap, U.S., and non-U.S.) trading sessions.

H3: Intraday patterns in foreign exchange returns are related to realized volatility.

H1 and H2 are tested based on two-sample t-tests. In addition, we test whether mean returns are equal across domestic, LDN-NY overlap, U.S., and non-U.S. trading sessions based on Welch F-tests, which account for unequal variances across the four trading sessions. We estimate the following GARCH (1,1) model to account for autocorrelation and heteroscedasticity:

$$R_t = \sum_{k=1}^{K} \alpha_k R_{t-k} + \sum_{j=1}^{4} \beta_j d_j + \varepsilon_t \qquad (2)$$

$$\sigma_t^2 = \omega + \gamma \varepsilon_{t-1}^2 + \rho \sigma_{t-1}^2 \qquad (3)$$

where, R_t is trading session return at time *t*, *d* is a dummy variable with a value of 1 for trading session *j* and zero otherwise; *j* refers to domestic, LDN-NY overlap, U.S. and non-U.S. trading

sessions, respectively. ω is a constant, and α, β, γ, and ρ are parameters. The choice of k for lagged returns is determined by Schwarz criterion. The null hypothesis of $\beta_j = 0$ indicates that trading session returns are equal to zero and no patterns exist in intraday foreign exchange returns. The alternative hypothesis of $\beta_j \neq 0$ indicates that trading session returns are not equal to zero and that significant intraday patterns exist.

To test H3, that intraday patterns in foreign exchange returns are related to realized volatility, we estimate the following model:

$$R_t = \theta + \varphi RV_t + \xi_1 RV_t d_{1,t} + \xi_2 RV_t d_{2,t} + \xi_3 RV_t d_{3,t} + \varepsilon_t \qquad (4)$$

where, R_t is trading session return and RV_t is realized volatility of trading session returns. We compute realized volatility for each trading session: $RV_t = \sqrt{\sum_{t=1}^{n} r_t^2}$, where, r_t is hourly excess return and n is number of hourly returns for a trading session. d_1 (d_2, d_3) is a dummy variable with a value of 1 for LDN-NY overlap (U.S., non-U.S.) trading sessions and zero otherwise. θ is the intercept; φ is the estimated coefficient of realized volatility for domestic trading sessions. The null hypothesis of $\varphi = 0$ indicates that intraday returns are not related to realized volatility in domestic markets. The alternative hypothesis of $\varphi \neq 0$ indicates that intraday returns are related to realized volatility, which reflects risk attributable to order flow and market sensitivity to order flow in domestic markets. ξ_1 (ξ_2, ξ_3) is the difference in estimated coefficients between domestic and LDN-NY overlap (U.S., non-U.S.) trading sessions. Significant ξ_1, ξ_2 and ξ_3 indicate changes in the risk–return relationship for LDN-NY overlap, U.S., and non-U.S. trading sessions, reflecting changes in order flow and market sensitivity to order flow in domestic and foreign markets. Equation 4 is estimated by GARCH (1,1) models.

3. Empirical Findings

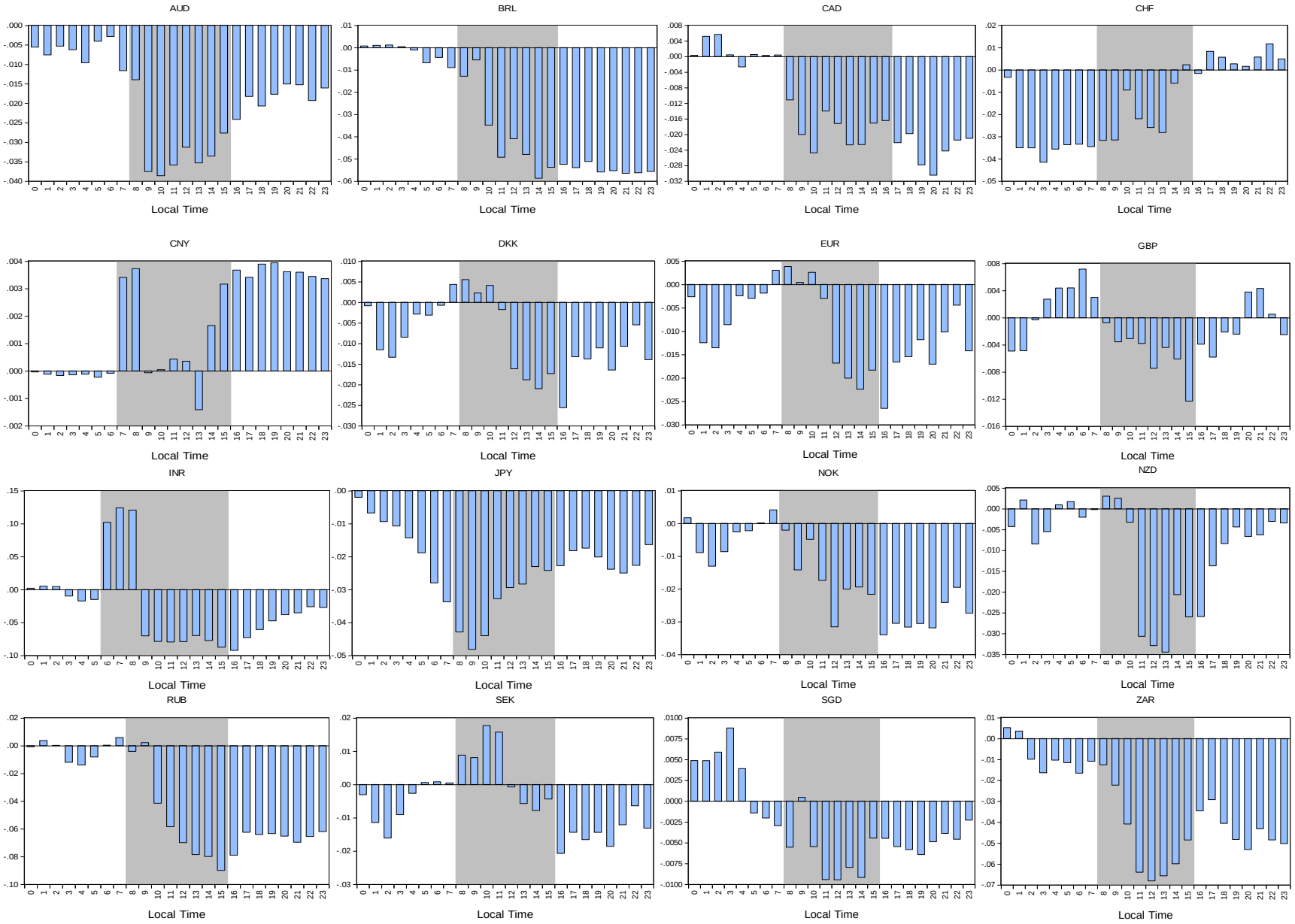
3.1 Cumulative hourly returns

To visualize intraday patterns in foreign exchange returns, Figure 1 plots mean cumulative returns, hour by hour, from 00:00 to 23:00 local time for 16 currencies versus the U.S. dollar. Shaded areas depict local trading hours. These graphs show that cumulative returns during domestic trading hours are negative for 13 currencies, but not for CHF, CNY and JPY, indicating that, in many countries, home currencies tend to depreciate during domestic trading hours.

3.2 Trading session returns

Table 1 reports mean trading session returns (in percent) for domestic, LDN-NY overlap, U.S. and non-U.S. trading sessions. Univariate t-tests are performed on the null hypotheses that mean trading session returns are equal to zero. The results indicate that domestic trading session returns are negative for 13 currencies, with significant negative returns for 8 currencies (BRL, DKK, EUR, INR, NOK, NZD, RUB and ZAR), confirming previous study findings that home currencies tend to depreciate during domestic trading hours. Similarly, LDN-NY trading session returns are negative for 10 currencies. In contrast, U.S. trading session returns are positive for 12 currencies, with significant positive returns for 6 currencies (DKK, EUR, GBP, INR, NOK and SEK), supporting previous study findings that home currencies tend to appreciate during U.S. trading hours. Non-U.S. trading session returns are insignificant for 11 currencies, with significant negative returns for BRL, CHF and JPY, and significant positive returns for AUD and NZD. Overall, these findings indicate that home currencies tend to depreciate during domestic trading sessions, depreciate during LDN-NY trading sessions, and appreciate during U.S. trading

Figure 1: Cumulative Returns over an Average Day (Local Time) 2010–2015. Local Trading Hours are in Shaded Areas.



sessions after London markets are closed. Non-U.S. trading session returns tend to be insignificant when U.S. markets are closed, with significant return reversals for AUD, JPY and NZD during European trading sessions and for CHF during Asian trading sessions.

Table 1 reports t-values and F-values from the equality tests of trading session returns. The results from two-sample t-tests indicate that mean returns differ significantly between domestic and LDN-NY trading sessions for INR, RUB and ZAR. In contrast, mean returns differ significantly between domestic and U.S. trading sessions for 10 currencies (AUD, BRL, CAD, DKK, EUR, GBP, INR, JPY, NOK and RUB).[3] Mean returns differ significantly between domestic and non-U.S. trading sessions for six currencies (AUD, CHF, INR, JPY, NZD and RUB). Finally, Welch F-tests are statistically significant for 13 currencies (AUD, BRL, CAD, CHF, DKK, EUR, GBP, INR, JPY, NOK, NZD, RUB and ZAR), confirming that intraday returns differ significantly across the four trading sessions.

Table 1 also reports the estimated coefficients of dummy variables from GARCH models. The results indicate that GARCH estimates tend to be highly significant, with the same sign and statistical significance as the mean trading session returns reported above, confirming the existence of intraday patterns in foreign exchange returns.

3.3 Intraday returns and realized volatility

Table 2 reports the estimated coefficients of realized volatility for domestic, LDN-NY overlap, U.S., and non-U.S. trading sessions. For domestic trading sessions, the estimated coefficients are negative and significant for 12 currencies, indicating that higher volatility tends to reduce intraday returns (depreciation of home currencies) during domestic trading hours. In

[3] Domestic trading hours for CAD are synchronous with U.S. trading hours (New York winter time) at 13:00–22:00 GMT; the LDN-NY trading session is 13:00–16:00 GMT; the U.S. trading session is 16:00–22:00 GMT; and the non-U.S. trading session (Asia and Europe) is 22:00–13:00 GMT.

Table 1

Intraday Patterns in Foreign Exchange Returns 2010–2015

	Mean Trading Session Returns (%)				Two-sample t-tests				GARCH (1.1) Estimates of Eq. (2)			
	Domestic Session	LDN-NY Overlap	U.S. Session	Non-U.S. Session	Domestic vs LDN-NY	Domestic vs U.S.	Domestic vs Non-U.S.	Welch F-tests	Domestic (β_1)	LDN-NY (β_2)	U.S. (β_3)	Non-U.S. (β_4)
Asia-Pacific												
AUD	-0.0165	-0.0161*	0.0071	0.0185*	-0.02	-1.72*	-2.41**	3.37**	-0.0064	-0.0125	0.0085	0.0149**
CNY	0.0032	-0.0001	-0.0002	0.0005	1.10	1.11	0.81	0.52	0.0010	-0.0015	-0.0001	-0.0022
INR	-0.0705***	0.0291***	0.0152***	0.0052	-8.35***	-7.18***	-5.91***	26.00***	-0.0516***	0.0291***	0.0137	0.0027
JPY	0.0095	0.0090	-0.0212***	-0.0136*	0.04	2.74***	2.04**	4.28***	0.0054	-0.0036	-0.0193***	-0.0145**
NZD	-0.0260**	-0.0185*	-0.0047	0.0310***	-0.49	-1.34	-3.51***	5.12***	-0.0171**	-0.0147	-0.0032	0.0300***
SGD	-0.0016	0.0003	0.0053	-0.0061	-0.27	-0.97	0.59	1.08	0.0020	0.0030	0.0007	-0.0047
Europe-Africa												
CHF	0.0374**	0.0270**	0.0134	-0.0412***	0.47	1.18	3.77***	9.85***	0.0267***	-0.0161	0.0122	-0.0252
DKK	-0.0213*	-0.0066	0.0201***	-0.0041	-0.99	-3.03***	-1.29	4.03***	-0.0214***	0.0002	0.0174**	-0.0052
EUR	-0.0210*	-0.0063	0.0221***	-0.0067	-0.98	-3.16***	-1.07	4.85***	-0.0217***	0.0003	0.0204**	-0.0078
GBP	-0.0148	-0.0044	0.0166***	-0.0039	-0.82	-2.63***	-0.92	3.82***	-0.0134***	0.0037	0.0126*	-0.0026
NOK	-0.0255*	-0.0138	0.0144*	-0.0037	-0.61	-2.26**	-1.27	2.35*	-0.0179**	-0.0039	0.0133	-0.0028
RUB	-0.0806***	0.0102	0.0154	-0.0052	-3.68***	-2.88***	-2.75***	4.40***	-0.0384***	0.0223***	0.0015	0.0040
SEK	-0.0047	-0.0151	0.0145*	-0.0062	0.58	-1.13	0.09	1.79	-0.0033	-0.0086	0.0158	-0.0131
ZAR	-0.0377**	0.0287**	-0.0122	-0.0121	-3.05***	-1.32	-1.34	3.48**	-0.0310**	0.0400***	-0.0023	-0.0170
Americas												
BRL	-0.0448**	-0.0496***	0.0082	-0.0128***	0.17	-2.01**	-1.46	2.95**	0.0011	-0.0211	0.0183	-0.0227
CAD	-0.0169	-0.0250***	0.0080	-0.0041	0.58	-1.88*	-0.92	3.29***	-0.0053	-0.0171*	0.0113	-0.0079

Note: This table reports trading session returns for domestic, LDN-NY overlap, U.S., and non-U.S. trading sessions, in percent. Two-sample t-tests are performed on the null hypotheses that trading session returns are equal between domestic and LDN-NY overlap (U.S., non-U.S.) trading sessions. Welch F-tests are performed on the null hypotheses that trading session returns are equal across the four trading sessions. GARCH (1,1) models are estimated for Eq. (2) $R_t = \sum_{k=1}^{K} \alpha_k R_{t-k} + \sum_{j=1}^{4} \beta_j d_j + \varepsilon_t$ where R_t is trading session return, d is a dummy variable with a value of 1 for trading session j and zero otherwise; j refers to domestic, LDN-NY overlap, U.S., and non-U.S. trading sessions, respectively. *, **, and *** denote for significance at 0.10, 0.05 and 0.01 levels, respectively. Trading session returns for BRL, CNY and INR reflect onshore rates.

contrast, for the LDN-NY overlap, U.S., and non-U.S. trading sessions, the estimated changes in coefficients are positive and significant for 8, 12 and 10 currencies, respectively. This finding indicates that the risk–return relationship changes across domestic and foreign markets, and that higher volatility tends to increase intraday returns during foreign trading sessions. Note that the adjusted R^2 is low for most currencies, but reaches 0.16 for CHF, which is volatile over the period 2010–2015. As robustness checks, we estimate Equation 4 with one-period lagged realized volatility, which is insignificant for most currencies. Overall, these findings suggest that intraday patterns in foreign exchange returns are significantly related to realized volatility.

Table 2
Intraday Foreign Exchange Returns and Realized Volatility 2010–2015

	Intercept (θ)	Domestic (φ)	LDN-NY (ξ_1)	U.S. (ξ_2)	Non-U.S. (ξ_3)	R^2_{adj}
Asia-Pacific						
AUD	0.0070	-0.0571***	0.0141	-0.0013	0.0766***	0.0009
CNY	0.0042***	-0.1616***	-0.6488	-0.0703	0.2361***	0.0485
INR	0.0087*	-0.1859***	0.4469***	0.3366***	0.1389***	0.0508
JPY	0.0014	-0.1863***	0.1911***	0.2492***	0.1720***	0.0117
NZD	0.0165*	-0.1264***	0.0455**	0.0623***	0.1661***	0.0056
SGD	0.0028	-0.0197	0.0099	0.0176	-0.0226	0.0002
Europe-Africa						
CHF	-0.0651***	0.3272***	-0.0812***	0.0254	-0.2200***	0.1588
DKK	-0.0083	-0.0258*	0.0292*	0.1605***	0.0592**	0.0021
EUR	-0.0064	-0.0306**	0.0263	0.1652***	0.0401*	0.0020
GBP	-0.0065	-0.0044	0.0374	0.1294***	0.0120	0.0015
NOK	-0.0011	-0.0529***	0.0496**	0.1179***	0.0662**	0.0012
RUB	-0.0091	-0.1012***	0.3051***	0.1726***	0.1151***	0.0301
SEK	-0.0039	-0.0240	0.0020	0.0887***	0.0477*	0.0002
ZAR	0.0118	-0.0797***	0.1152***	0.0415**	0.0074	0.0008
Americas						
BRL	-0.0114	-0.0307**	0.1204***	0.0899***	-0.2560***	0.0049
CAD	0.0134*	-0.0920***	-0.0587***	0.1053***	0.0281	0.0046

Note: This table reports GARCH (1,1) estimated coefficients of Eq. (4) $R_t = \theta + \varphi RV_t + \xi_1 RV_t d_{1,t} + \xi_2 RV_t d_{2,t} + \xi_3 RV_t d_{3,t} + \varepsilon_t$ where R_t is trading session return, RV is realized volatility. d_1 (d_2, d_3) is a dummy variable with a value of 1 for LDN-NY overlap (U.S., non-U.S.) trading sessions and 0 otherwise. *, **, and *** denote significance at 0.10, 0.05 and 0.01 levels, respectively.

4. Conclusion

This paper investigates intraday patterns in foreign exchange returns based on a sample of 16 currencies versus the U.S. dollar for the period 2010–2015. The results show that home currencies tend to depreciate during domestic trading sessions and appreciate during U.S. trading sessions after London markets are closed, indicating that intraday patterns in foreign exchange returns exist in many countries, including countries with capital controls. Distinct intraday patterns in foreign exchange returns are related to realized volatility, which reflects risk attributable to order flow and market sensitivity to order flow in domestic and foreign markets.

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