Vehicle Currency and Price Discovery

Zhen-Xing Wu
Department of Finance
School of Finance
Zhongnan University of Economics and Law

Yin-Feng Gau
Department of Finance
School of Management
National Central University

Yu-Lun Chen*
Department of Finance
College of Business
Chung Yuan Christian University

*Corresponding author. 200 Chung Pei Rd., Jhongli, Taoyuan 32023, Taiwan, phone: +886-3-2655715, fax: +886-3-2655749, e-mail: yoloom@cycu.edu.tw. We gratefully acknowledge financial support from the Ministry of Science and Technology (MOST 109-2410-H-033 -002 -MY2).

Vehicle Currency and Price Discovery

Abstract

This paper investigates competition in price discovery between direct JPY/EUR cross-rates and the rates implied indirectly from exchanges of JPY/USD and USD/EUR. Our results highlight the role of the USD as a vehicle currency in the aspect of price discovery. We find the dominant price discovery of implied JPY/EUR rates relates to the lower transaction cost. Upon the release of macroeconomic announcements in Japan and Europe, the trading cost advantage enhances price discovery of implied rates even more. When implied JPY/EUR rates are more efficient, the USD tends to appreciate, as shown by the upward movement in the USD index.

JEL classification: F31, G15

Keywords: Vehicle currency; price discovery; triangular arbitrage; U.S. dollar index

1. Introduction

The USD has been the world's dominant vehicle currency (i.e., international medium of exchange) since World War II; that is, traders in non-USD economies (e.g., Japan or European Union) engage in currency trades indirectly using the USD rather than direct bilateral trades among their own currencies (JPY/EUR). This paper studies price discovery competition between the direct JPY/EUR exchange rates (Japanese yens per euro) and the exchange rates implied from JPY/USD (Japanese yens per US dollar) and USD/EUR (US dollars per euro).[1] The analysis of the lead-lag relationship and relative price efficiency between direct JPY/EUR cross-rates and implied rates from USD/EUR and JPY/USD can be useful for traders who are executing triangular arbitrage or setting up short-term trading strategies for JPY/EUR rates.

In frictionless markets of international trades, there is no reason for foreign exchange between countries to take place in any particular currency. However, in the real world, lower transaction costs and higher liquidity lead traders to prefer making and receiving payments in the vehicle currency, especially when all countries widely accept it. Thus, the direct JPY/EUR rate and the implied JPY/EUR (= USD/EUR × JPY/USD) rate may not incorporate and reflect relevant fundamentals simultaneously, while liquid USD exchange rates contribute to price discovery of the JPY/EUR rate.

Our paper differs from these studies with regard to a vehicle currency's benefit to international finance. By examining high-frequency exchange rate data, we provide a more comprehensive analysis of the dynamic price-discovery process among direct and implied

[1] Price discovery is the process by which the market incorporates relevant information into prices. Frijns and Zwinkels (2018) address that price discovery is an important issue in market microstructure literature, particularly when an identical asset is traded on multiple markets.

JPY/EUR rates. Most previous research on vehicle currency issue considers either bid–ask spread or international trade by using USD data at daily or lower frequencies, or it develops theoretical models to investigate the role of vehicle currencies (e.g., Krugman, 1980; Goldberg and Tille, 2008; Flandreau and Jobst, 2009; Devereux and Shi, 2013).[2] In contrast, we focus on short-term price dynamics (in minutes) and the interaction between direct cross-rates and implied exchange rates, and explore the presence of potential triangular arbitrage opportunities. Short-lived triangular arbitrage opportunities arise when at least one of the three legs of the triangle (e.g., the JPY triangle consisting of USD/EUR, JPY/USD, and JPY/EUR) adjusts to new information with a lag (Foucault, Kozhan, and Tham, 2017).[3]

By identifying which market contributes more to price discovery, using the high-frequency data, we can understand which market is more efficient in reflecting information to prices. King, Osler, and Rime (2013) argue that in research on foreign exchange market microstructure, order flow, agent heterogeneity, and private information are crucial determinants of short-run exchange rate dynamics.[4] Our study of price discovery between

---

[2] Krugman (1980) proposes a three-country model of payments equilibrium with transaction costs; he shows how transaction costs determine the structure of currency exchanges, including direct and indirect trades. Goldberg and Tille (2008) emphasize the role of industry-specific characteristics in the choice of the USD as an invoicing currency. Flandreau and Jobst (2009) find evidence of the important roles of country size, distance, and inventory costs in developing a vehicle currency. Devereux and Shi (2013) construct a dynamic general equilibrium model of a vehicle currency and point out that a vehicle currency reduces the average costs of currency trades. However, these gains are eroded by a higher inflation rate in the vehicle currency's country.

[3] According to Akram, Rime, and Sarno (2008), it is essential to study triangular arbitrage in the foreign exchange market using high-frequency data, because arbitrage opportunities are brief and can hardly be detected in previous studies using lower-frequency data.

[4] Models of purchasing power parity (PPP) and interest rate parity (IRP) are helpful in explaining long-run exchange-rate movements, but they fail to explain short-run exchange-rate adjustments.

direct cross-rates and implied exchange rates can provide insight for the short-run exchange-rate determination. If the implied JPY/EUR rate dominates the price discovery process, the implication is that prices and trading activities in the USD/EUR and JPY/USD provide essential information on the determination of JPY/EUR cross-rates. Furthermore, our high-frequency analysis of the lead-lag relationship and relative price efficiency between direct JPY/EUR cross-rates and implied rates from USD/EUR and JPY/USD can be beneficial to traders who are executing triangular arbitrage or setting up short-term trading strategies for JPY/EUR rates.

Surprisingly, very few studies use intraday foreign-exchange data to analyze the contributions of direct and the implied exchange rates to price discovery of related currencies and the dynamic interaction between direct and implied exchange rates.[5] De Jong, Mahieu, and Schotman (1998) study the intraday dynamic relations between quotes of the JPY/DEM (deutschemark) exchange rate and the rate implied by JPY/USD and DEM/USD rates during the period of October 1, 1992 to September 30, 1993. They find that although USD-implied rates lead direct JPY/DEM cross-rates, the USD-implied rates are much noisier than direct cross-rates. Lyons and Moore (2009) show that transactions of direct cross-rates and transactions through vehicle currencies have different information content in currency triangle of JPY/USD, USD/EUR, and JPY/EUR. Moore and Payne (2011) find that, in cross-rate markets, traders that engage in triangular arbitrage are best informed. Their finding of the informational advantage of the triangular arbitrageurs inspires us to explore why and how the implied JPY/EUR rates have better price discovery relative to the direct cross-rates.

---

[5] Ito et al. (2012), Chaboud et al. (2014), and Foucault et al. (2017) use high-frequency intraday data to analyze the triangular arbitrage opportunity in the foreign exchange market. However, they do not analyze the contributions of USD, EUR, or JPY to the price discovery process.

As De Jong et al. (1998) and Lyons and Moore (2009) do not further explore why this dominant contribution of indirect currency exchange to price discovery occurs, we use the data of intraday prices and trading activities to investigate the determinants of relative contributions to the price discovery of cross-rates. Previous studies (Chakravarty, Gulen, and Mayhew, 2004; Chen and Gau, 2010; Mizrach and Neely, 2008) have found that a market with higher liquidity, lower transaction costs, or fewer restrictions is likely to dominate the price discovery process. Therefore, we study how the liquidity and transaction cost affect the speed adjustments of direct and implied JPY/EUR rates in reflecting information into prices.

In this study, we focus on another aspect of vehicle currency by investigating the contributions of direct and implied JPY/EUR quotes to price discovery over the period of 2008 to 2013, using the information-share approach of Hasbrouck (1995) and the common-factor-weight approach of Gonzalo and Granger (1995). We also study the determinants of price discovery between direct and implied JPY/EUR rates, focusing on relative transaction cost, relative liquidity, and macroeconomic news announcements in Europe, Japan, and the United States. Finally, we hypothesize and test the relationship between JPY/EUR price discovery and the USD index. To the best of our knowledge, this is the first paper to explore determinants of price discovery between direct and implied JPY/EUR rates and to provide evidence that the price efficiency of USD-based exchange rates affects foreign exchange traders' trading risk and the dynamics of the USD index.

Our empirical results attribute the dominance of implied JPY/EUR rates in the price discovery process to the advantage of lower trading costs via indirect trades. We find the average values of the (percentage) bid–ask spreads in the USD/EUR, JPY/USD, and JPY/EUR markets are (0.0107%) 0.0001, (0.0152%) 0.0138, and (0.0278%) 0.0342, respectively.[6] These findings may explain why the USD is used as a vehicle currency in foreign exchange and why indirect trading involving JPY/USD and USD/EUR is more active than direct JPY/EUR cross-rate trading. When scheduled macroeconomic announcements in the Europe and Japan are released, the effect of trading cost on the price discovery process of JPY/EUR is more salient. The higher level of information asymmetry related to the release of macroeconomic announcements may induce foreign exchange dealers to widen the bid–ask spread to protect themselves from trading against informed traders. The even higher bid–ask spread in the direct JPY/EUR cross-rate may further hamper its price discovery capability on announcement days.

We also find the dominant role of the implied JPY/EUR rate via the USD becomes more significant during U.S. business hours than during non-U.S. business hours. Different trader composition, lower bid–ask spread, and greater market liquidity within U.S. business hours enhance the informational efficiency of implied JPY/EUR rates; unlike the USD, the JPY, and the EUR cannot become vehicle currencies and do not transmit information to direct cross-rates.

Finally, going beyond existing literature, we suggest that the USD's vehicle-currency role is useful for predicting the USD index. O'Hara (2003) argues that asset prices are influenced by the transactions costs of liquidity and the risks of price discovery. Narayan et al. (2016) find that stock price discovery could predict stock excess returns. We hypothesize that the relatively greater information efficiency of indirect trades via the USD increases the incentive to dealers and slow traders to hold USD for reasons of trade flexibility, higher

[6] We obtain the percentage spread by dividing the bid–ask spread (i.e., the difference between ask and bid quotes) by the midpoint of the bid and ask quotes.

liquidity, and information advantage when faced with a faster trading environment. This holding further pushes up the USD index. We find that empirical results support our hypothesis: Price discovery risk is crucial for dealers to partly reflect the holding cost of the USD, JPY, and EUR.

The remainder of this paper is organized as follows: Section 2 describes the data, institutional details, and descriptive statistics. Section 3 outlines the measures of price discovery and shows empirical results. Section 4 demonstrates and tests the hypotheses with regard to the role of price discovery in the dynamics of the USD index, and Section 5 concludes.

2. Data

According to the Bank for International Settlements (BIS) (2019), in April 2019 the USD retained its dominant currency status, being on one side of 88.3% of all trades (Figure 1). The share of trades with the EUR on one side expanded somewhat, to 32.3%. In contrast, the share of trades involving the JPY fell by about five percentage points (from 21.6% to 16.8%), although it remained the third-most-actively-traded currency. The fall in JPY turnover may have been the result of a contraction in the important JPY/USD amid low volatility. However, trading in other popular JPY cross-rates, such as JPY/EUR, increased from 1.6% to 1.7% from 2016 to 2019. Despite the trading of JPY/EUR increased, the USD obviously remained the world's dominant vehicle currency.

<Figure 1 is inserted about here>

We obtain the tick-by-tick spot rates of USD/EUR, JPY/USD, and JPY/EUR from the Electronic Broking Services (EBS), which operates in the interdealer foreign exchange market. As pointed out in BIS (2019), EBS and Reuters Matching are the two largest interdealer trading venues, and 56.9% of the overt-the-counter (OTC) foreign exchange turnover takes place in the U.K. and U.S. markets. In the spot interdealer foreign exchange market, EBS is the leading liquidity provider for the two most active currency-pairs, USD/EUR and JPY/USD, which on average account for 37.2% of daily trading in the global foreign-exchange market. Our sample contains quotes and trading data for the USD/EUR, JPY/USD, and JPY/EUR cross-rates, covering the period from January 2008 to December 2013.

The EBS operates as a standard electronic-limit order book and contains tick-by-tick best bid and ask quotes and deal prices, together with respective trading dates, times, and trading volumes. It shows quotes and transactions continuously, 24 hours a day, from Monday to Sunday. All EBS quotes and orders are transactable, that is, all quotes are represented reliably for prevailing exchange rates. The average values of the (percentage) bid–ask spreads for the USD/EUR, JPY/USD, and JPY/EUR exchange rate pairs are (0.0107%) 0.0001, (0.0152%) 0.0138, and (0.0278%) 0.0342 over the six-year period from 2008 to 2013, demonstrating that the transaction cost of the JPY/EUR direct trade (0.0342) is higher than that of indirect trade between the USD/EUR and JPY/USD (0.0139 = 0.0001 + 0.0138).

Although the USD/EUR, JPY/USD, and JPY/EUR are major currency pairs, we find that quotes and executed trades are not as active during weekends and holidays. Therefore, in line with Ito and Hashimoto (2006), Moore and Payne (2011), and Chaboud et al. (2014), we exclude weekends (defined as the period between 12:00 Greenwich Mean Time (GMT) on Friday and 12:00 GMT on Sunday) and all major U.S., European, and Japanese holidays. In addition, because the JPY/EUR is the least active pair of the three currency pairs, we match the data to obtain simultaneous quotes of USD/EUR, JPY/USD, and JPY/EUR exchange-rate pairs.

We measure the extent of price discovery by using midpoint quotes (average of bid and ask quotes) of USD/EUR, JPY/USD, and JPY/EUR, according to De Jong et al. (1998).[7] If we let q_t^I denote the logarithm of the implied JPY/EUR quote at time *t*, and q_t^D denote the logarithm of the mid-quote of direct JPY/EUR cross-rate at time *t*, we obtain:

$$q_t^I = q_t^{\text{JPY/USD}} + q_t^{\text{USD/EUR}}, \qquad (1)$$

where $q_t^{\text{JPY/USD}}$ and $q_t^{\text{USD/EUR}}$ denote the logarithm of the mid-quotes at time *t* for JPY/USD and USD/EUR, respectively. Table 1 provides summary statistics of the levels and differences in direct and implied JPY/EUR quotes. Table 1 shows that average values, standard deviation, skewness, and kurtosis of direct and implied JPY/EUR quotes are very close. In contrast, standard deviation and kurtosis of Δq_t^D are larger than those of Δq_t^I. Results of augmented Dickey-Fuller (ADF) tests on q_t^D and q_t^I in Table 1 show that implied and direct JPY/EUR exchange rates are non-stationary, whereas both returns series, Δq_t^D and Δq_t^I, are stationary.

<Table 1 is inserted about here>

Before analyzing price discovery between the implied and direct JPY/EUR rates, we must check whether these two series are cointegrated and have a long-run equilibrium relationship (Engle and Granger, 1987). Results of Johansen cointegration tests reported in Table 1 confirm that q_t^D and q_t^I are cointegrated, that is, the direct and implied JPY/EUR rates have a long-run equilibrium relationship.

[7] In normal times, the best bid is lower than the corresponding best ask in the EBS. However, we find that the best bid price is higher than the best ask price occasionally. This reversal may reflect that credit lines keep the obvious arbitrage from happening; therefore, we eliminate such reversals. Also, we further delete those observations when the corresponding bid or ask prices are missing.

3. Empirical Analysis

3.1 VAR and VEC Models for Direct and Implied JPY/EUR Rates

To completely capture the adjustment process of direct and implied JPY/EUR rates and identify the relative contributions to price discovery of direct and implied rates, we estimate the bivariate vector autoregression (VAR) model in Equation (2) and the vector error correction (VEC) model in Equation (3) respectively as follows:

$$\begin{aligned} \Delta q_t^I &= c^I + \sum_{i=1}^{k} \gamma_{1,i} \Delta q_{t-i}^I + \sum_{i=1}^{k} \gamma_{2,i} \Delta q_{t-i}^D + e_t^I \\ \Delta q_t^D &= c^D + \sum_{i=1}^{k} \gamma_{3,i} \Delta q_{t-i}^I + \sum_{i=1}^{k} \gamma_{4,i} \Delta q_{t-i}^D + e_t^D \end{aligned} \quad \text{, and} \qquad (2)$$

$$\begin{aligned} \Delta q_t^I &= c^I + \alpha^I (q_{t-1}^I - q_{t-1}^D) + \sum_{i=1}^{k} \gamma_{1,i} \Delta q_{t-i}^I + \sum_{i=1}^{k} \gamma_{2,i} \Delta q_{t-i}^D + e_t^I \\ \Delta q_t^D &= c^D + \alpha^D (q_{t-1}^I - q_{t-1}^D) + \sum_{i=1}^{k} \gamma_{3,i} \Delta q_{t-i}^I + \sum_{i=1}^{k} \gamma_{4,i} \Delta q_{t-i}^D + e_t^D \end{aligned} \quad . \qquad (3)$$

According to the Akaike information criterion (AIC), we choose the optimal length of lags as $k = 4$ for both the VAR and VEC models. e_t^i is the respective error term, with $i = I$ (for the implied JPY/EUR rate) or D (for direct cross-rate). In Equation (3), we use a pre-specified cointegrating vector $(1, -1)$, and α^i ($i = D$ and I)—the coefficient on the error correction term—denotes the respective speed of adjustment for direct and implied JPY/EUR exchange rates. The error correction term, $q_{t-1}^I - q_{t-1}^D$ represents the deviation from the long-run equilibrium between the two exchange rates, and α^i involves the dynamics of the two exchange rates' adjustments toward their long-run relationship (i.e., the parity of no triangular-arbitrage opportunity). The lower α^i, in absolute value, indicates a smaller adjustment speed in magnitude for the exchange rate q_t^i, and implies that q_t^i is more informative and has relatively more price discovery. We focus on compare α^i in the models for direct and implied rates to quantify their relative amount of price discovery.

<Table 2 is inserted about here>

Table 2 shows that all autocorrelation coefficients are significant to the fourth lag in VAR and VEC models. In the VAR and VEC models, the adjusted R^2 for Δq_t^D are considerably higher than those for Δq_t^I, implying that the implied JPY/EUR rates are more difficult to be predicted and are relatively more efficient than the direct JPY/EUR cross-rates. Most importantly, if we include the error correction term ($q_{t-1}^I - q_{t-1}^D$) in the model, values of adjusted R^2 increase to 0.1 percent and 0.2 percent for Δq_t^I. Values of adjusted R^2 increase to 20.8 percent and 39.2 percent for Δq_t^D The dramatic increases of the goodness of fit in the model considering $q_{t-1}^I - q_{t-1}^D$ suggest the adjustment of both the direct and implied JPY/EUR rates may be driven by the deviation between direct and implied rates.

Table 2 reports coefficient estimates of the VEC model. We find that α^D (0.839) is larger than α^I (−0.049), in absolute value. Consistent with Lyons and Moore (2009), this finding supports the apparent leading role of implied rates in the price discovery process of JPY/EUR. The positive coefficient of $q_{t-1}^I - q_{t-1}^D$ in Equation (3) for Δq_t^D (0.839) implies that if the magnitude of $q_{t-1}^I > q_{t-1}^D$ increases, the direct cross-rates (q_t^D) are pushed to revise upward significantly and then draw back toward the equilibrium level. At the same time, the implied rates, q_t^I, revise downward slightly, as suggested by the negative coefficient of $q_{t-1}^I - q_{t-1}^D$ for the model of Δq_t^I (−0.049). This result shows that implied exchange rates may be closer to the efficient (equilibrium) prices than direct cross-rates, whereas the direct cross-rates deviate more from the efficient price and must revise toward the efficient price with a larger adjustment size.

3.2 Price Discovery Measures

To further quantify the relative contributions of direct and implied rates to JPY/EUR price discovery, we use Hasbrouck's (1995) information-share approach and Gonzalo and Granger's (1995) common-factor-weight approach. Researchers have used these approaches widely to study the price discovery process in multiple prices of the same asset; for in-depth discussion and comparisons on the two approaches, refer to Baillie et al. (2002), De Jong (2002), Hasbrouck (2002), Lehmann (2002), and Harris, McInish, and Wood (2002a; 2002b).

Direct and implied JPY/EUR quotes are driven by the same fundamental information; therefore, they should be closely related to a common factor (or efficient price). According to Gonzalo and Granger (1995), we can decompose prices of interest into two components: a permanent (common factor) component and a transitory component. We specify the vector of direct and implied rates, q_t, as the sum of a permanent component (f_t) and a transitory component (z_t) as:

$$\begin{aligned} q_t &= A_1 f_t + A_2 z_t \\ &= A_1 \alpha'_{\perp} q_t + A_2 \beta' q_{t-1} \end{aligned}, \quad (4)$$

where A_1 and A_2 are loading matrices, and $\alpha'_{\perp}$ is a 1×2 vector of weights on respective quotes in the common factor. By definition, $\alpha'_{\perp} \alpha = 0$, and α is defined in Equation (3); z_t is the error-correction term shown in Equation (3); and β is the cointegrating vector. Following Harris et al. (2002a), we define CFW^i as the *i*-th element of $\alpha_{\perp}$ and use it to measure the price-discovery capability of direct ($i = D$) and implied ($i = I$) quotes of JPY/UER, because CFW^D and CFW^I can gauge effectively the contribution of each direct and implied quotes, respectively, to the common factor component. We calculate CFW^i with the coefficients α in Equation (3) and normalize $\alpha_\perp$ to make the elements of $\alpha_\perp$ add up to 1.

We also measure the relative contribution to price discovery of direct and implied JPY/EUR rates, by considering the information-share approach of Hasbrouck (1995). In Hasbrouck's (1995) framework, the information share of a specific market or price is the proportion of the efficient price innovation variance that can be attributed to that market price.

Following Hasbrouck (1995), we rewrite the VEC model, as shown in Equation (3), as a vector moving average (VMA) model:

$$\Delta q_t = \Psi_0 e_t + \Psi_1 e_{t-1} + \Psi_2 e_{t-2} + \Lambda = \Psi(L) e_t, \quad \text{where} \quad \Psi_0 = I, \tag{5}$$

where $\Psi_0 = I$ and *I* denotes the 2 × 2 identity matrix. The integrated form of Equation (5) is:

$$q_t = \Psi(1) \sum_{s=1}^{t} e_s + \Psi^*(L)\, e_t, \tag{6}$$

where $\Psi^*(L)$ is the lag polynomial, and $\Psi(1)$ is the sum of the VMA coefficient matrices. Hasbrouck (1995) shows that when two markets are cointegrated, all rows of matrix $\Psi(1)$ are identical. With ψ representing the common row of matrix $\Psi(1)$, we can write the variance of the efficient price innovations as $\psi \Omega \psi'$, where Ω is the covariance matrix of e_t. It follows that the information share of one market is the proportion of the variance of efficient price innovation attributed to the variance of the innovation in that market. When the covariance matrix Ω is diagonal, the information share of one market is defined as:

$$IS^{i} = \frac{\psi_i^2 \Omega_{ii}}{\psi \Omega \psi'}, \tag{7}$$

where ψ_i is the i^{th} element of ψ, and Ω_{ii} is the (i, i) element of Ω. When Ω is not diagonal, we have to use the Cholesky factorization, $\Omega = FF'$, where F is a lower triangular matrix, and rewrite the information share of market i as:

$$IS^{i} = \frac{[(\psi F)_i]^2}{\psi \Omega \psi'}, \tag{8}$$

where $(\psi F)_i$ is the i^{th} element of ψF.

Because the Cholesky decomposition depends on the order of variables in the vector autoregressive (VAR) system, we do not have a unique measure of information shares. By changing the order of variables, we can obtain a range of information shares. In line with Hasbrouck (1995), we calculate the upper and lower bounds of the information share and use the average value of the upper and lower bounds of information shares to quantify the relative price discovery capability of direct and implied rates, that is, IS^{D} and IS^{I}, respectively.

A higher value of IS^{i} or CFW^{i} indicates that market i exhibits better price discovery efficacy and its leading role in reflecting price-relevant information. If IS^{I} is higher than IS^{D}, the implied JPY/EUR rates are more informative relative to the direct cross-rates, indicating that traders may use the USD as a vehicle currency to trade JPY and EUR indirectly, rather than using direct bilateral JPY/EUR trades.

To analyze the time-varying dynamics in the price discovery of JPY/EUR, we use minute-by-minute mid-quotes data to calculate the common factor weights (CFW^{D} and CFW^{I}) and information shares (IS^D and IS^I) on a daily basis. Using the daily series of IS_t^i and CFW_t^i (for $i = I, D$), we also test our hypothesis on the equality of the two markets' contribution to price discovery of JPY/EUR.

<Table 3 is inserted about here>

Table 3 reports the estimation results of IS_t^i and CFW_t^i; it shows that the average value of IS_t^I (CFW_t^I) is higher than that of IS_t^D (CFW_t^D). Using the *t*-test and analysis of variance (ANOVA) *F*-test, we can reject the null hypothesis of no difference in price discovery capability between direct and indirect markets of JPY/EUR and confirm that the indirect trades through JPY/USD and USD/EUR contribute more to price discovery of JPY/EUR than to the direct cross-rate market, regardless of whether we use the information share (IS_t^i) or the common factor weight (CFW_t^i) to measure a market's price discovery capability.

3.3 Determinants of Relative Contribution to Price Discovery

We further explore how market characteristics relate to price discovery between direct and indirect exchanges of JPY/EUR. Using daily measures of common factor weight and information share, we study the effects of relative trading cost, market liquidity, realized volatility, and major macroeconomic announcements on price discovery of JPY/EUR (Mizrach and Neely, 2008; Chen and Gau, 2010; Fricke and Menkhoff, 2011). The regression model is specified as:

$$\ln(RC_t^i) = c + \beta' X_t + e_t^i, \quad (9)$$

where $RC_t^i = RC_t^{IS}$ or RC_t^{CFW} ; $RC_t^{IS} = (IS_t^I / IS_t^D)$; and $RC_t^{CFW} = (CFW_t^I / CFW_t^D)$ denote the relative contributions of indirect and direct exchanges to price discovery, as measured by information share and common factor weight, respectively. Explanatory variables (X_t) include RTC_t, RTN_t, RRV_t and the yearly dummy variables from 2009 to 2013 that capture year effect. The relative trading cost (RTC_t) denotes the half–sum of the bid–ask spreads in the JPY/USD and USD/EUR markets divided by the half bid–ask spreads on JPY/EUR rate on day *t*, as in Love and Payne (2008). The relative trade number (RTN_t) denotes the sum of the number of trades in both JPY/USD and USD/EUR markets divided by the number of trades in the JPY/EUR cross-rate market on day *t*. The relative realized volatility (RRV_t) denotes the realized volatility of implied JPY/EUR rates relative to the realized volatility of JPY/EUR cross-rates on day *t*.[8]

We also consider the impact of macroeconomic announcements on relative price informativeness between the indirect and direct JPY/EUR exchanges.[9] We define dummy variables D_t^{JP}, D_t^{EU}, and D_t^{US} to refer to the release of macroeconomic announcements in Japan, Europe, and the United States on day *t*, respectively. Finally, we consider the interaction terms of news announcements and trading cost to explore whether the impact of trading cost varies with the release of announcements. Many previous studies point out that the release of macroeconomic news may enhance the level of information asymmetry such that dealers must enlarge the bid–ask spread to protect themselves to trade probably with informed traders (Naranjo and Nimalendran, 2000; Chen and Gau, 2014; Foucault et al., 2017). Therefore, we

---

[8] We measure daily realized volatility with the square root of the sum of the squared 1-min quotes returns during day *t*.

[9] We follow Gau and Wu (2017) to collect 32 U.S., 28 European, and 15 Japanese macroeconomic news announcements from the Thomson Reuters Datastream. See the Appendix for a listing of all macro announcements.

expect that dealers' adjustments of bid–ask spread and macroeconomic news announcements jointly may affect price discovery.

<Table 4 is inserted about here>

Table 4 reports estimation results for Equation (9); it shows that relative trading cost has a significantly negative impact on relative contribution to price discovery in all models. This evidence supports the argument that the lower transaction cost of indirect exchange may attract more traders to exchange JPY (or EUR) for EUR (or JPY), indirectly using the USD and improving price discovery of implied JPY/EUR rates. The table also shows that relative trade number also has a significantly positive impact on relative contribution to price discovery. Relative volatility is insignificantly positively related to relative contribution to price discovery, RC_t^{IS} and RC_t^{CFW}.[10]

Models (2) and (6) in Table 4 show the insignificantly positive impact of news announcements in Japan (D_t^{JP}) on RC_t^{IS} and RC_t^{CFW}. In particular, the interaction terms of news announcements in Japan and relative trading cost are significantly and negatively related to the contribution of relative price discovery. Coefficients are -0.31 in Model (2) and -0.25 in Model (6), suggesting that Japanese announcements strengthen the impact of trading cost on price discovery and highlighting the low trading cost advantage of indirect trading through USD-based exchange markets.

---

[10] We consider RTC_{t-1}, RTN_{t-1}, and RRV_{t-1} simultaneously in Equation (9) to analyze their joint impact on price discovery; estimation results continue to suggest RTC_{t-1} has a significant and negative impact on the relative price discovery capacity. However, results show the coefficient on RTN_{t-1} is insignificantly positive and the coefficient on RRV_{t-1} is still insignificant. These results are available on request

Models (3) and (7) also show the insignificantly positive impact of news announcements in Europe (D_t^{EU}) on price discovery capability. The interaction terms of European announcements and relative trading cost have significant and negative impacts on relative contribution to price discovery. In addition, Models (4) and (8) show that U.S. announcements have an insignificant impact on relative contribution to price discovery.

In summary, we find that lower transaction cost in indirect exchanges plays an important role in determining relative contribution to price discovery. We also find that when macroeconomic announcements are released in Japan or Europe, the advantage of the indirect exchange via the USD strengthens. In contrast, U.S. announcements do not affect price discovery of JPY/EUR.

3.4 Vehicle Currency Role of USD in U.S. and Non-U.S. Trading Hours

Wang and Yang (2011) and Gau and Wu (2017) find the intraday price discovery of foreign exchange markets is time-varying and changes across segments of time zones, because of differences in trader compositions, market mechanisms, and market liquidity. Wang and Yang (2011) and Gau and Wu (2017) reveal that within 24-hour trading of the global foreign exchange market, trading activities during European business hours and U.S. business hours carry a large amount of price discovery, and the overlapping hours of London and New York contribute most to the price discovery of USD/EUR and JPY/USD. Therefore, we further examine price discovery of direct and indirect exchanges of JPY/EUR across different trading periods. We divide 24-hour trading into two major segments: non-U.S. business hours (GMT 23:00:00–12:59:59) and U.S. business hours (GMT 13:00:00–22:59:59).

<Table 5 is inserted about here>

Table 5 reports estimation results for IS_t^i and CFW_t^i during U.S. and non-U.S. business hours. It shows the average value of IS_t^I (CFW_t^I) remains greater than the average value of IS_t^D(CFW_t^D) in both trading periods. Particularly, IS_t^I during U.S. business hours (0.614) is higher than IS_t^I during non-U.S. business hours (0.514); results of the common-factor-weight approach show a pattern consistent that is with patterns related to information shares. With the *t*-test and ANOVA *F*-test, we also can reject the null hypothesis of no difference in price discovery between direct and implied JPY/EUR exchange rates and confirm that the indirect market via the USD contributes more to price discovery of JPY/EUR than the direct cross-rate market, especially during U.S. business hours.[11]

3.5 Vehicle Trading Role of JPY and EUR

To confirm whether the vehicle currency role belongs to the USD, we also analyze the contribution of indirect exchanges via JPY (and EUR) in price discovery by adopting the same analysis and data. If the USD provides better price discovery according to the advantage of relatively lower trading cost, JPY (or EUR) with the relatively higher trading cost should not dominate in price discovery. For indirect USD/EUR rates via JPY as the vehicle currency, JPY/EUR is divided by JPY/USD. By dividing JPY/EUR by USD/EUR, we obtain the indirect JPY/USD rate via EUR as the vehicle currency. We also compare relative price discovery between direct and indirect JPY/USD (USD/EUR) exchanges by using daily IS_t^i and CFW_t^i,

[11] We also divide the 24 trading hours into four market segments, following Wang and Yang (2011) and Gau and Wu (2017), to examining the common factor weights and information shares of direct and implied JPY/EUR rates; we still find the indirect exchange via JPY/USD and USD/EUR accounts for greater price discovery than the direct JPY/EUR cross-rate market, especially in the overlapping hours of London and New York and in U.S.-only business hours (when the European markets close).

and report the results in Table 6.

Table 6 shows that, for direct and indirect JPY/USD exchanges, the average value of IS_t^I (0.427) is smaller than the average value of IS_t^D (0.573) and CFW_t^I (0.400) is also smaller than CFW_t^D (0.600). Results of a *t*-test and an (ANOVA) *F*-test show a significant difference in contribution to price discovery of direct JPY/USD cross-rates and implied JPY/USD rates, implying that the indirect JPY/USD exchange via EUR does not dominate in the price discovery of JPY/USD. Table 6 also indicates that IS_t^I (CFW_t^I) is even lower than IS_t^D (CFW_t^D) in direct and indirect USD/EUR exchanges. These results show that only the USD plays a vehicle currency role in transmitting information through indirect vehicle-currency-based exchanges.

<Table 6 is inserted about here>

4. Vehicle Currency Role and the USD Index

After studying the vehicle currency role of USD in the improvement of price discovery, we further investigate whether the price-discovery capacity enhanced through the dollar's vehicle currency role is informative in predicting the future value of the USD index. Information implicit in trading activities or order flow can essentially have higher explanatory power in capturing exchange rate dynamics than macroeconomic fundamentals suggested by theoretical models of exchange rate determination, especially at frequencies higher than one day (Evans and Lyons, 2002). The link between exchange rate movement and order flow could be attributed to information asymmetry or portfolio-balancing effects (Berger et al., 2008; Breedon and Vitale, 2010; Evans and Lyons, 2002).

The USD index measures the value of the USD relative to a basket of several major currencies of U.S. trading partners, with the base value of 100 as of March 1973. A higher value of the index means the USD strengthens when compared with other currencies. Avdjiev et al. (2019) point out that a higher USD index is associated with larger deviations from covered interest parity (CIP) and contractions of cross-border bank lending denominated in USD. In this paper, we aim to underpin the role of the dollar in the triangle of JPY/EUR, USD/EUR, and JPY/USD from the angle of market microstructure, by exploring the predictive power of the price informativeness of the indirect trade via USD for daily USD index.

It may not be suitable to consider order flows of different bilateral exchange rates simultaneously to predict daily USD index changes. Because of the trade-weighted formula of the USD index, we must calculate the weighted order flows from different bilateral exchange rates, to follow Evans and Lyons (2002) in considering order flow as a predictor of the USD index. However, aggregated order flow may be misleading in predicting the USD index, because different order flows from different currency-pairs' exchange rates may offset some crucial information about the USD.

To the best of our knowledge, ours is the first paper to introduce the price discovery contribution of the USD's vehicle currency role into prediction of the USD index. Foucault et al. (2017) mention that short-lived triangular arbitrage opportunities caused by asynchronous adjustments of direct and indirect exchanges of currencies may be harmful for dealers. Arbitrageurs' profits are obtained at the expense of dealers with stale quotes. Dealers may face aggressive order flows from indirect and direct trading, but they cannot interpret trade motivation and future trade direction. Arbitrageurs' trading also can be harmful to other slow traders. Therefore, dealers or other slow traders may be inclined to hold more USD to keep trade flexibility and maintain an information advantage when facing faster trading environments.

For example, dealers who hold more USD can exchange them for JPY or EUR faster, to reflect changes in the economic conditions of Europe, Japan, and the United States. Trading in USD-based exchange rates (JPY/USD and USD/EUR) may be better than trading in the direct JPY/EUR cross-rate market because of the higher liquidity, higher informational efficiency, and smaller bid–ask spread of USD-based markets. In contrast, if dealers hold more JPY (or EUR) to exchange for EUR (or JPY) directly, they may encounter less liquidity and slower adjustments in prices to reflect relevant information about changes in the economic conditions of Europe and Japan. Accordingly, we hypothesize that the relatively better price discovery of indirect exchanges via USD attracts dealers and slow traders to demand more USD, which then pushes up the USD index.

To explore whether relative price discovery relates to the movement of the USD index, we first estimate the following base model:[12]

$$R_t^{USD} = \beta_0 + \beta_1 R_{t-1}^{USD} + \beta_2 e_{t-1} + e_t, \quad (10)$$

where R_t^{USD} denotes the log-difference of the USD index on day *t*. Then, we add RC_{t-1}^{IS} or RC_{t-1}^{CFW} to Equation (10) and compare the explanatory power of various model specifications considered in Table 7.

<Table 7 is inserted about here>

Table 7 displays that the incorporation of RC_{t-1}^{IS} (RC_{t-1}^{CFW}) into the ARMA(1,1) model of R_t^{USD} improves the goodness of fit; the adjusted R^2 increases by about 0.24% (0.29%),

[12] The specification of ARMA(1,1) model is determined by the AIC.

suggesting RC_{t-1}^{IS} or RC_{t-1}^{CFW} is significantly related to the movement of the USD index. Moreover, RC_{t-1}^{IS} and RC_{t-1}^{CFW} are significantly and positively associated with R_t^{USD} in Models (2) and (3). Because the higher $RC_{t-1}^{IS} (= IS_{t-1}^{I} / IS_{t-1}^{D})$ indicates the implied JPY/EUR rates have a higher information share over direct JPY/EUR cross-rates, we can infer that the relatively more informative USD-based exchange markets (EUR/USD and JPY/USD) induce an appreciation of the USD, as shown by an increase in the USD index.

To compare with other factors that potentially affect the change in the USD index, we also consider the log-difference of the S&P 500 index (R_{t-1}^{SP}), the three-month Treasury bill (T-bill) market rate (R_{t-1}^{TB}), and the TED spread (TS_{t-1}) in Equation (10) separately; we report the respective estimation results in Table 7.[13] According to Yang and Hamori (2014), we use the daily three-month Treasury bill rate as a proxy for the Federal funds rate, which is the key indicator of the Fed's monetary policies. The TED spread, calculated as the spread between the three-month London inter-bank offered rate (LIBOR) based on USD and the three-month T-bill rate, is used as an indicator of credit risk in the economy.

In Table 7, the insignificance of R_{t-1}^{SP}, R_{t-1}^{TB}, and TS_{t-1} in the predictive regression model of R_t^{USD} indicates that RC^{IS} and RC^{CFW} outperform the S&P 500 index returns, T-bill rate, and TED spread in forecasting the USD index. This results reveals the price discovery

[13] The data of S&P 500 index, the three-month T-bill market rate, and the TED spread, come from the Federal Reserve economic data (FRED) website (https://fred.stlouisfed.org/). On the other side, one problem in analyzing the relationship between price index variables and rate of change of the USD index is that price index variables are available only monthly. For comparison, however, we perform the analysis using the CPI and the PPI; results are available on request.

function in USD-based exchange rates is linked to the value of the USD.

To analyze the dynamic interaction between the USD index and the price discovery capacity of implied JPY/EUR rates, we also perform Granger causality tests in the bivariate VAR model of R_t^{USD} and RC_t^{IS} (or RC_t^{CFW}).[14] Table 8 shows that the relative price-discovery contribution of the implied JPY/EUR rate against the direct cross-rate (measured by RC_t^{IS} or RC_t^{CFW}) Granger causes the changes in the USD index, but not vice versa, no matter whether we measure price discovery with information share or common factor weight. This result suggests the informative efficiency with respect to the indirect trading through USD-based exchange markets has predictive ability for the future movements of the USD index.

<Table 8 is inserted about here>

5. Conclusions

We examine the relative contributions of direct and indirect JPY/EUR markets to the price discovery process to analyze the USD's vehicle currency role. Using the information-share measure of Hasbrouck (1995) and common-factor-weight measure of Gonzalo and Granger (1995), we find the implied JPY/EUR rate has a higher extent of price discovery than the direct JPY/EUR cross-rate. This evidence suggests traders tend to use the USD as a vehicle currency to trade rather than the direct bilateral JPY/EUR cross-rate. The advantage of low trading cost of the implied rates is a crucial factor for better price discovery of implied JPY/EUR rates.

We find that upon arrival of Japanese and European macroeconomic news, the larger bid–ask spread may hamper further the price discovery capability of the direct JPY/EUR market.

[14] The length of lag $k = 2$ is chosen for the VAR model, according to the AIC.

We also find the dominance of the implied rate in the price discovery process of JPY/EUR becomes more significant during U.S. business hours; the higher information share of implied rates may be attributed to lower bid–ask spread and higher market liquidity of USD-based exchange rates during U.S. trading hours.

Finally, in a new contribution to literature, we find that price discovery risk matters in the dynamics of the USD index. The dominance of the implied JPY/EUR rate in price discovery over the direct cross-rate market via the exchanges of USD may attract dealers and slow traders to hold more USD to gain trade flexibility and information advantages, thereby inducing an appreciation of the USD. We provide evidence that information efficiency and inventory costs are crucial in determining the short-term exchange rates dynamics and USD index changes, beyond the scope of traditional exchange-rate determination models that rely solely on macroeconomic fundamentals.

References

Akram, Q. F., Rime, D., and Sarno, L. (2008). Arbitrage in the foreign exchange market: Turning on the microscope. Journal of International Economics, 76, 237-253.

Avdjiev, S., Du, W., Koch, C., and Shin, H. S. (2019). The dollar, bank leverage, and deviations from covered interest parity. American Economic Review: Insights, 1, 193-208.

Baillie, R. T., Booth, G. G., Tse, Y., and Zabotina, T. (2002). Price discovery and common factor models. Journal of Financial Markets, 5, 309-321.

Bank for International Settlements (2019). BIS Triennial Central Bank Survey: Foreign exchange turnover in April 2019.

Berger, D. W., Chaboud, A. P., Chernenko, S. V., Howorka, E., and Wright, J. H. (2008). Order flow and exchange rate dynamics in electronic brokerage system data. Journal of International Economics, 75, 93-109.

Breedon, F., and Vitale, P. (2010). An empirical study of portfolio-balance and information effects of order flow on exchange rates. Journal of International Money and Finance, 29, 504-524.

Chaboud, A. P., Chiquoine, B., Hjalmarsson, E., and Vega, C. (2014). Rise of the machines: Algorithmic trading in the foreign exchange market. Journal of Finance, 69, 2045-2084.

Chakravarty, S., Gulen, H., and Mayhew, S. (2004). Informed trading in stock and option markets. Journal of Finance, 59, 1235-1257.

Chen, Y. L., and Gau, Y. F. (2010). News announcements and price discovery in foreign exchange spot and futures markets. Journal of Banking and Finance, 34, 1628-1636.

Chen, Y. L., and Gau, Y. F. (2014). Asymmetric responses of ask and bid quotes to information in the foreign exchange market. Journal of Banking and Finance, 38, 194-204.

De Jong, F. (2002). Measures of contributions to price discovery: A comparison. Journal of Financial Markets, 5, 323-327.

De Jong, F., Mahieu, R., and Schotman, P. (1998). Price discovery in the foreign exchange market: An empirical analysis of the yen/dmark rate. Journal of International Money and Finance, 17, 5-27.

Devereux, M. B., and Shi, S. (2013). Vehicle currency. International Economic Review, 54, 97-133.

Engle, R. F., and Granger, C. W. (1987). Co-integration and error correction: Representation, estimation, and testing. Econometrica, 55, 251-276.

Evans, M. D., and Lyons, R. K. (2002). Order flow and exchange rate dynamics. Journal of Political Economy, 110, 170-180.

Flandreau, M., and Jobst, C. (2009). The empirics of international currencies: Network externalities, history and persistence. Economic Journal, 119, 643-664.

Foucault, T., Kozhan, R., and Tham, W. W. (2017). Toxic arbitrage. Review of Financial Studies, 30, 1053-1094.

Fricke, C., and Menkhoff, L. (2011). Does the "Bund" dominate price discovery in Euro bond futures? Examining information shares. Journal of Banking and Finance, 35, 1057-1072.

Frijns, B., and Zwinkels, R. C. (2018). Time-varying arbitrage and dynamic price discovery. Journal of Economic Dynamics and Control, 91, 485-502.

Gau, Y. F., and Wu, Z. X. (2017). Macroeconomic announcements and price discovery in the foreign exchange market. Journal of International Money and Finance, 79, 232-254.

Goldberg, L. S., and Tille, C. (2008). Vehicle currency use in international trade. Journal of International Economics, 76, 177-192.

Gonzalo, J., and Granger, C. (1995). Estimation of common long-memory components in cointegrated systems. Journal of Business and Economic Statistics, 13, 27-35.

Harris, F. H. D., McInish, T. H., and Wood, R. A. (2002a). Common factor components versus information shares: A reply. Journal of Financial Markets, 5, 341-348.

Harris, F. H. D., McInish, T. H., and Wood, R. A. (2002b). Security price adjustment across exchanges: An investigation of common factor components for Dow stocks. Journal of Financial Markets, 5, 277-308.

Hasbrouck, J. (1995). One security, many markets: Determining the contributions to price discovery. Journal of Finance, 50, 1175-1199.

Hasbrouck, J. (2002). Stalking the "efficient price" in market microstructure specifications: An overview. Journal of Financial Markets, 5, 329-339.

Ito, T., and Hashimoto, Y. (2006). Intraday seasonality in activities of the foreign exchange markets: Evidence from the electronic broking system. Journal of the Japanese and International Economies, 20, 637-664.

Ito, T., Yamada, K., Takayasu, M., and Takayasu, H. (2012). Free lunch! Arbitrage opportunities in the foreign exchange markets. Working Paper, National Bureau of Economic Research.

King, M. R., Osler, C. L., and Rime, D. (2013). The market microstructure approach to foreign exchange: Looking back and looking forward. Journal of International Money and Finance, 38, 95-119.

Krugman, P. R. (1980). Vehicle currencies and the structure of international exchange. Journal of Money, Credit and Banking, 12, 513-526.

Lehmann, B. N. (2002). Some desiderata for the measurement of price discovery across markets. Journal of Financial Markets, 5, 259-276.

Love, R., and Payne, R. (2008). Macroeconomic news, order flows, and exchange rates. Journal of Financial and Quantitative Analysis, 43, 467-488.

Lyons, R. K., and Moore, M. J. (2009). An information approach to international currencies. Journal of International Economics, 79, 211-221.

Mizrach, B. and Neely C. J. (2008). Information shares in the US Treasury market. Journal of Banking and Finance, 32, 1221-1233.

Moore, M. J. and Payne, R. (2011). On the sources of private information in FX markets. Journal of Banking and Finance, 35, 1250-1262.

Naranjo, A., and Nimalendran, M. (2000). Government intervention and adverse selection costs in foreign exchange markets. Review of Financial Studies, 13, 453-477.

Narayan, P. K., Phan, D. H. B., Thuraisamy, K., and Westerlund, J. (2016). Price discovery and asset pricing. Pacific Basin Finance Journal, 40, 224-235.

Newey, W. K. and West K. D. (1987). A simple, positive semi-definite, heteroskedasticity and autocorrelation consistent covariance matrix. Econometrica, 55, 703-708.

O'Hara, M. (2003). Presidential address: Liquidity and price discovery. Journal of Finance, 58, 1335-1354.

Wang, J., and Yang, M. (2011). Housewives of Tokyo versus the gnomes of Zurich: Measuring price discovery in sequential markets. Journal of Financial Markets, 14, 82-108.

Yang, L., and Hamori, S. (2014). Spillover effect of US monetary policy to ASEAN stock markets: Evidence from Indonesia, Singapore, and Thailand. Pacific-Basin Finance

Journal, 26, 145-155.

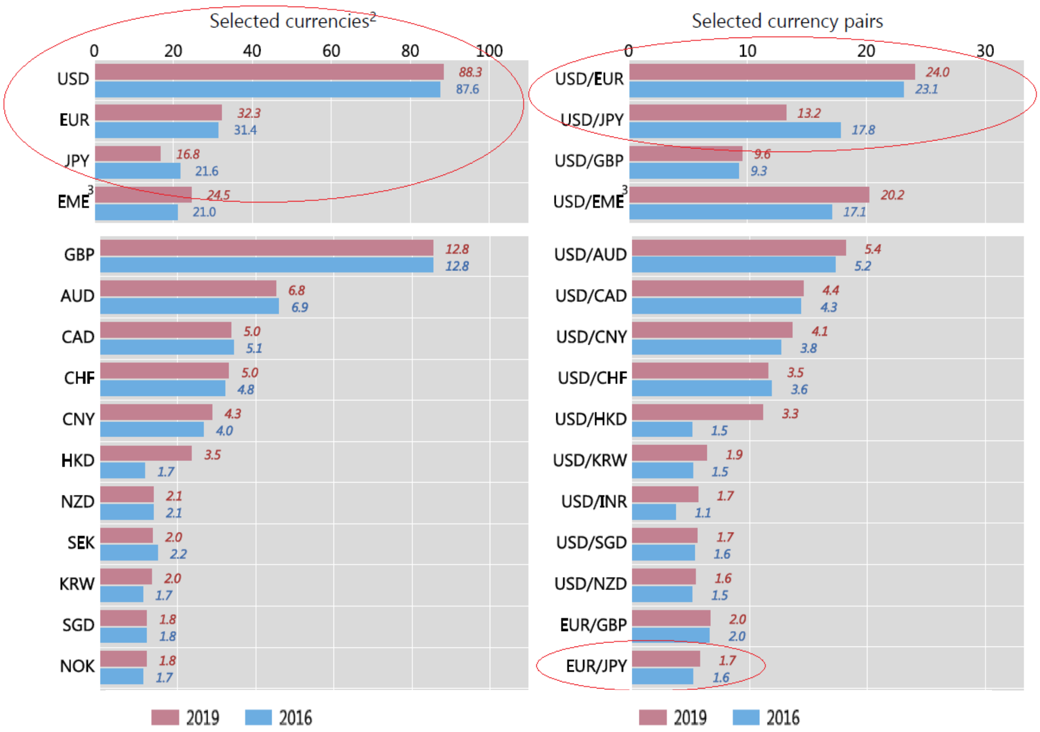

Figure 1 Foreign exchange market turnover by currency and currency pairs

Source: BIS Triennial Central Bank Survey. (Daily averages in April, in percent)

Table 1
Summary Statistics, Unit Root Tests, and Johansen Cointegration Tests for Implied and Direct JPY/EUR Quotes

	q_t^I	q_t^D	Δq_t^I	Δq_t^D
Mean	4.814	4.814	-0.028	-0.056
Std. Dev.	0.140	0.140	299.344	322.100
Skewness	0.449	0.449	0.083	-0.915
Kurtosis	2.586	2.586	76.081	490.227
ADF	0.598	-1.984	-449.490***	-339.010***
Johansen Cointegration Tests for q_t^I and q_t^D				
λ_{max} H0: $r \leq 0$	505239.50***			
H0: $r \leq 1$	2.07			
λ_{trace} H0: $r \leq 0$	505241.60***			
H0: $r \leq 1$	2.07			

Note: q_t^D and q_t^I denote the logarithm of the mid-quote of JPY/EUR cross-rate and the logarithm of implied JPY/EUR exchange rate at time *t*, respectively. The number of observations for (q_t^I, q_t^D) is 1,773,430. The means (standard deviations) of Δq_t^I and Δq_t^D time 10^6.The augmented Dickey-Fuller (ADF) test considers one lagged term, as determined by the Akaike information criterion (AIC). The ADF test is conducted under the null hypothesis H_0 that the series has a unit root. For the cointegration test, the null hypothesis H_0 states that the system contains at most *r* cointegrating vectors. λ_{max} is the Johansen maximum eigenvalue test statistic, and λ_{trace} is the Johansen trace test statistic. The number of lags used in the Johansen tests is 4, as determined by the AIC. The conclusion of the cointegration test, however, is robust with respect to the number of lags. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Table 2
Vector Autoregression (VAR) and Vector Error Correction (VEC) Models for Implied and Direct JPY/EUR Quotes

	VAR		VEC	
	Δq_t^I	Δq_t^D	Δq_t^I	Δq_t^D
c	-0.001	-0.001	-0.001	-0.001
	(0.000)	(0.000)	(0.000)	(0.000)
Δq_{t-1}^I	-0.025***	0.725***	0.008***	0.046***
	(0.001)	(0.001)	(0.001)	(0.001)
Δq_{t-2}^I	-0.009***	0.542***	0.012***	0.028***
	(0.001)	(0.001)	(0.001)	(0.001)
Δq_{t-3}^I	0.008***	0.037***	0.020***	0.029***
	(0.001)	(0.001)	(0.001)	(0.001)
Δq_{t-4}^I	0.013***	0.184***	0.018***	0.021***
	(0.001)	(0.001)	(0.001)	(0.001)
Δq_{t-1}^D	-0.008***	-0.756***	-0.022***	-0.074***
	(0.001)	(0.001)	(0.001)	(0.001)
Δq_{t-2}^D	-0.002***	-0.562***	-0.023***	-0.047***
	(0.001)	(0.001)	(0.001)	(0.001)
Δq_{t-3}^D	-0.019***	-0.389***	-0.031***	-0.048***
	(0.000)	(0.001)	(0.000)	(0.001)
Δq_{t-4}^D	-0.018***	-0.193***	-0.023***	-0.033***
	(0.000)	(0.001)	(0.000)	(0.001)
$q_{t-1}^I - q_{t-1}^D$			-0.049***	0.839***
			(0.001)	(0.001)
Adjusted R^2	0.001	0.208	0.002	0.392

Notes: We estimate the following VAR and VEC models with 4 lags of autocorrelation determined by the AIC. The VAR Model is:

$$\Delta q_t^I = c^I + \sum_{i=1}^{k} \gamma_{1,i} \Delta q_{t-i}^I + \sum_{i=1}^{k} \gamma_{2,i} \Delta q_{t-i}^D + e_t^I$$

, and

$$\Delta q_t^D = c^D + \sum_{i=1}^{k} \gamma_{3,i} \Delta q_{t-i}^I + \sum_{i=1}^{k} \gamma_{4,i} \Delta q_{t-i}^D + e_t^D$$

The VEC Model is:

$$\Delta q_t^I = c^I + \alpha^I (q_{t-1}^I - q_{t-1}^D) + \sum_{i=1}^{k} \gamma_{1,i} \Delta q_{t-i}^I + \sum_{i=1}^{k} \gamma_{2,i} \Delta q_{t-i}^D + e_t^I$$

,

$$\Delta q_t^D = c^D + \alpha^D (q_{t-1}^I - q_{t-1}^D) + \sum_{i=1}^{k} \gamma_{3,i} \Delta q_{t-i}^I + \sum_{i=1}^{k} \gamma_{4,i} \Delta q_{t-i}^D + e_t^D$$

where q_t^D and q_t^I denote the logarithm of the mid-quote of JPY/EUR cross-rate and the logarithm of implied JPY/EUR exchange rate at time *t*, respectively. We use a pre-specified cointegrating vector $(1,-1)$; α^i is the coefficient of the error correction term in models for the implied ($i = I$) and direct ($i = D$) rates. The heteroscedasticity-and-autocorrelation consistent (HAC) standard errors (Newey and West, 1987) are reported in parentheses; ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Table 3

Contributions of Implied and Direct JPY/EUR Exchange-Rates to Price Discovery

	IS_t^I	IS_t^D	CFW_t^I	CFW_t^D
Mean	0.541	0.459	0.562	0.438
Test for Equality of Means Between Series (IS_t^I and IS_t^D)			(CFW_t^I and CFW_t^D)	
	H_0: $IS_t^I = IS_t^D$		H_0: $CFW_t^I = CFW_t^D$	
t-test	19.68***		22.13***	
ANOVA *F*-test	387.27***		489.60***	

Note: This table reports the daily average value of the information share (IS^j) and common factor weight (CFW^j) of implied ($j = I$) and direct ($j = D$) JPY/EUR exchange rates in the full sample. We estimate the VEC models with 4 lags of autocorrelation determined by the AIC. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Table 4
Determinants of Relative Contributions of Implied and Direct JPY/EUR Exchange-Rate to the Price Discovery Process

Explanatory Variables	Dependent Variable: $\ln(RC_t^{IS})$				Dependent Variable: $\ln(RC_t^{CFW})$			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Constant	-0.74***	-0.74***	-0.72***	-0.77***	-0.78***	-0.75***	-0.72***	-0.69**
	(0.19)	(0.19)	(0.20)	(0.27)	(0.21)	(0.22)	(0.24)	(0.30)
D_t^{2009}	-0.12	-0.11	-0.11	-0.10	-0.18	-0.16	-0.17	-0.16
	(0.09)	(0.08)	(0.09)	(0.08)	(0.11)	(0.11)	(0.11)	(0.11)
D_t^{2010}	-0.29***	-0.28***	-0.28***	-0.27***	-0.35***	-0.34***	-0.33***	-0.33***
	(0.07)	(0.07)	(0.07)	(0.07)	(0.09)	(0.09)	(0.09)	(0.09)
D_t^{2011}	-0.31***	-0.29**	-0.27**	-0.23**	-0.34**	-0.32**	-0.31**	-0.27**
	(0.12)	(0.12)	(0.12)	(0.11)	(0.14)	(0.15)	(0.14)	(0.13)
D_t^{2012}	-0.18*	-0.18*	-0.14	-0.12	-0.17	-0.17	-0.14	-0.11
	(0.10)	(0.09)	(0.09)	(0.09)	(0.12)	(0.12)	(0.12)	(0.12)
D_t^{2013}	-0.29***	-0.26***	-0.23**	-0.23**	-0.19	-0.16	-0.13	-0.13
	(0.10)	(0.10)	(0.10)	(0.09)	(0.13)	(0.12)	(0.12)	(0.12)
$\ln(RTN_t)$	0.27***	0.34***	0.33***	0.27**	0.21**	0.27**	0.27**	0.17
	(0.08)	(0.10)	(0.10)	(0.13)	(0.09)	(0.11)	(0.12)	(0.15)
$\ln(RTC_t)$	-0.66***	-0.54**	-0.57**	-0.75**	-0.94***	-0.85***	-0.83**	-1.04**
	(0.24)	(0.25)	(0.28)	(0.36)	(0.27)	(0.28)	(0.32)	(0.44)
$\ln(RRV_t)$	0.01	0.03	0.02	0.01	0.02	0.02	0.02	0.02
	(0.02)	(0.02)	(0.02)	(0.02)	(0.03)	(0.03)	(0.02)	(0.02)
D_t^{JP}		0.12				0.07		
		(0.42)				(0.47)		
$D_t^{JP} \cdot \ln(RTN_t)$		-0.33				-0.22		
		(0.50)				(0.56)		
$D_t^{JP} \cdot \ln(RTC_t)$		-0.31***				-0.25**		
		(0.10)				(0.12)		
D_t^{EU}			0.26				0.26	
			(0.31)				(0.31)	
$D_t^{EU} \cdot \ln(RTN_t)$			-0.11				-0.21	

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
			(0.38)				(0.41)	
$D_t^{EU} \cdot \ln(RTC_t)$			-0.29***				-0.28***	
			(0.10)				(0.12)	
D_t^{US}				0.40				0.17
				(0.29)				(0.33)
$D_t^{US} \cdot \ln(RTN_t)$				0.28				0.28
				(0.42)				(0.47)
$D_t^{US} \cdot \ln(RTC_t)$				-0.18				-0.07
				(0.14)				(0.16)
Adjusted R^2	0.08	0.10	0.10	0.10	0.08	0.10	0.10	0.10

Note: This table reports the estimation results of the following model: $\ln(RC_t^i) = c + \beta X_t + e_t^i$, where $RC_t^i = RC_t^{IS}$ or RC_t^{CFW}, $RC_t^{IS} = (IS_t^I / IS_t^D)$ and $RC_t^{CFW} = (CFW_t^I / CFW_t^D)$ denote the relative contributions of indirect and direct JPY/EUR markets to price discovery, as measured by the information share (*IS*) and common factor weight (*CFW*), respectively. Explanatory variables include yearly dummy variables from 2008 to 2013; D_t^{JP}, D_t^{EU}, and D_t^{US} indicate the release of macroeconomic news announcements, such that they take a value of 1 when a news announcement occurs on day *t* and otherwise 0, for Japan, Europe, and the United States, respectively. The relative trading cost (RTC_t) denotes half the sum of the bid–ask spreads on the JPY/USD and USD/EUR rates over half bid–ask spreads on JPY/EUR rate on day *t*. The relative trade number (RTN_t) denotes the sum of the trades number on JPY/USD and USD/EUR markets over trades number on the JPY/EUR market on day *t*. The relative realized volatility (RRV_t) denotes the realized volatility of the indirect JPY/EUR rate over the realized volatility of direct JPY/EUR rate on day *t*. We use the Newey-West covariance estimator to adjust for the presence of heteroskedasticity and autocorrelation in errors (Newey and West, 1987). Robust standard errors are reported in parentheses; ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Table 5
Comparison of Relative Contributions of Implied and Direct JPY/EUR Exchange-Rates to Price Discovery during U.S. and Non-U.S. Trading Hours

	U.S. Business Hours				Non-U.S. Business Hours			
	IS_t^I	IS_t^D	CFW_t^I	CFW_t^D	IS_t^I	IS_t^D	CFW_t^I	CFW_t^D
Mean	0.614	0.386	0.681	0.319	0.514	0.486	0.542	0.458

	H0: $IS_t^I = IS_t^D$	H0: $CFW_t^I = CFW_t^D$	H0: $IS_t^I = IS_t^D$	H0: $CFW_t^I = CFW_t^D$
t-test	48.11***	69.85***	28.89***	55.23***
ANOVA *F*-test	2314.68***	4879.92***	834.64***	3051.29***

Note: This table reports the average value of the information share (IS^j) and common factor weight (CFW^j) of implied ($j = I$) and direct ($j = D$) JPY/EUR exchange rates in U.S. and non-U.S. business-hour periods. We estimate the VEC models with 4 lags of autocorrelation determined by the AIC. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Table 6
Comparison of Vehicle Currency Role of EUR and JPY in Price Discovery

	EUR as Vehicle Currency for JPY/USD				JPY as Vehicle Currency for USD/EUR			
	IS_t^I	IS_t^D	CFW_t^I	CFW_t^D	IS_t^I	IS_t^D	CFW_t^I	CFW_t^D
Mean	0.427	0.573	0.400	0.600	0.393	0.607	0.351	0.649
	H_0: $IS_t^I = IS_t^D$		H_0: $CFW_t^I = CFW_t^D$		H_0: $IS_t^I = IS_t^D$		H_0: $CFW_t^I = CFW_t^D$	
t-test	-36.14***		-41.84***		-55.52***		-68.60***	
ANOVA *F*-test	1306.68***		1750.74***		3082.59***		4706.79***	

Note: This table reports the daily average value of the information share (IS_t^j) and common factor weight (CFW_t^j) of implied ($j = I$) and direct ($j = D$) exchange rates for cases with EUR and JPY as the vehicle currency for JPY/USD and USD/EUR, respectively. We estimate the VEC models with 4 lags of autocorrelation determined by the AIC. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Table 7
USD Index Regression Analysis

	R_t^{USD}					
	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)	Model (6)
R_{t-1}^{USD}	0.924***	-0.593	-0.599	-0.564	-0.685	-0.574
	(0.055)	(0.458)	(0.484)	(0.410)	(0.452)	(0.423)
e_{t-1}	-0.923***	0.615	0.620	0.587	0.604	0.596
	(0.055)	(0.452)	(0.476)	(0.404)	(0.463)	(0.417)
RC_{t-1}^{IS}		0.0002**				
		(0.0001)				
RC_{t-1}^{CFW}			0.0002**			
			(0.0001)			
R_{t-1}^{SP}				-0.001		
				(0.009)		
R_{t-1}^{TB}					-0.001	
					(0.002)	
TS_{t-1}						0.0004
						(0.0003)
Adj. R^2	0.0004	0.0024	0.0029	0.0009	0.0004	0.0010

Note: The dependent variable is the log-difference of the USD index. Model (1) is an ARMA(1,1) model with the lag length determined by the AIC. Models (2) and (3) are the ARMA(1,1) models including the relative information share (RC^{IS}) and common factor weight (RC^{CFW}), respectively. Specifications of Models (1) – (6) are as follows:

Model (1): $R_t^{USD} = \beta_0 + \beta_1 R_{t-1}^{USD} + \beta_2 e_{t-1} + e_t$,

Model (2): $R_t^{USD} = \beta_0 + \beta_1 R_{t-1}^{USD} + \beta_2 e_{t-1} + \beta_3 RC_{t-1}^{IS} + e_t$,

Model (3): $R_t^{USD} = \beta_0 + \beta_1 R_{t-1}^{USD} + \beta_2 e_{t-1} + \beta_3 RC_{t-1}^{CFW} + e_t$,

Model (4): $R_t^{USD} = \beta_0 + \beta_1 R_{t-1}^{USD} + \beta_2 e_{t-1} + \beta_3 R_{t-1}^{SP} + e_t$,

Model (5): $R_t^{USD} = \beta_0 + \beta_1 R_{t-1}^{USD} + \beta_2 e_{t-1} + \beta_3 R_{t-1}^{TB} + e_t$,

Model (6): $R_t^{USD} = \beta_0 + \beta_1 R_{t-1}^{USD} + \beta_2 e_{t-1} + \beta_3 TS_{t-1} + e_t$,

where R_t^{USD} denotes the log-difference of the USD index on day *t* and R_{t-1}^{SP} denotes the log-difference of the S&P 500 index on day *t*-1. R_{t-1}^{TB} denotes the 3-month T-bill rate on day *t*-1; TS_{t-1} denotes the TED spread, which is the spread between the 3-month LIBOR based on the USD and the interest rate of the 3-month T-bill on day *t*-1. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

Table 8
Granger Causality Tests for US Dollar Index and Relative Price Discovery

Granger causality tests	F test	p-value
RC_t^{IS} does not Granger cause R_t^{USD}	2.966	0.051
R_t^{USD} does not Granger cause RC_t^{IS}	0.711	0.491
RC_t^{CFW} does not Granger cause R_t^{USD}	3.473	0.031
R_t^{USD} does not Granger cause RC_t^{CFW}	0.453	0.635

Note: This table reports the results of the Granger causality tests on (R_t^{USD}, RC_t^{IS}) and (R_t^{USD}, RC_t^{CFW}), based on a VAR(2) model determined by the AIC, where RC_t^{IS} is the relative contribution to price discovery measured by the information share, and RC_t^{CFW} is the relative contribution to price discovery measured by the common factor weight.

Appendix

Macroeconomic News Announcements (January 2008–December 2013)

Macroeconomic news	**Announcement time**	**Reporting agency**
U.S. News		
Current Account Balance	8:30 EST	BEA
Durable Goods Orders	8:30 EST	BC
Existing Home Sales	10:00 EST	BC
Factory Orders	10:00 EST	BC
FOMC Rate Decision	14:15 EST	FRB
GDP Price Index	8:30 EST	BEA
House Price Index	10:00 EST	BC
Housing Starts	8:30 EST	BC
Import Price Index	8:30 EST	BEA
Industrial Production	9:15 EST	FRB
Initial Jobless Claims	8:30 EST	ETA
Leading Index	8:30 EST	CB
Monthly Budget Statement	14:00 EST	DT
New Home Sales	10:00 EST	BC
PCE Core Price Index	8:30 EST	BEA
PCE Deflator	8:30 EST	BEA
Personal Consumption	8:30 EST	BEA
Personal Income	8:30 EST	BEA
Personal Spending	8:30 EST	BEA
PPI	8:30 EST	BLS
Retail Sales Advance	8:30 EST	BC
Business Inventories	10:00 EST	BC
Trade Balance	8:30 EST	BEA
Unemployment Rate	8:30 EST	ETA
Capacity Utilization	9:15 EST	FRB
Manufacture Payrolls	8:30 EST	BLS
Nonfarm Payrolls	8:30 EST	BLS
Chicago Purchasing Manager	9:45 EST	NAPMCI
Construction Spending	10:00 EST	BC
Consumer Confidence Index	10:00 EST	CB
Consumer Credit	15:00 EST	FRB
Continuing Claims	8:30 EST	DL

(Continued)

Macroeconomic news	Announcement time	Reporting agency
European News		
Business Climate Indicator	10:00 WET	EC
Construction Output	10:00 WET	Eurostat
Consumer Confidence	10:00 WET	EC
CPI Core	10:00 WET	Eurostat
Current Account NSA	9:00 WET	ECB
ECB Current Account SA	9:00 WET	ECB
Economic Confidence	10:00 WET	EC
Employment	10:00 WET	Eurostat
EU27 New Car Registrations	7:00 WET	ECB
GDP SA	10:00 WET	Eurostat
Govt Debt/GDP Ratio	10:00 WET	Eurostat
Govt Expend	10:00 WET	Eurostat
Gross Fix Cap	10:00 WET	Eurostat
Household Cons	10:00 WET	Eurostat
Industrial Confidence	10:00 WET	EC
Industrial Production SA	10:00 WET	Eurostat
M3 Money Supply	9:00 WET	ECB
PMI Composite-A	9:00 WET	ME
PMI Manufacturing-A	9:00 WET	ME
PMI Services-A	9:00 WET	ME
PMI Services-F	9:00 WET	ME
PPI	10:00 WET	Eurostat
Retail Sales	10:00 WET	Eurostat
Sentix Investor Confidence	9:30 WET	SG
Services Confidence	10:00 WET	EC
Trade Balance NSA	10:00 WET	Eurostat
Unemployment Rate	10:00 WET	Eurostat
ZEW Survey Expectations	10:00 WET	ZEW

(Continued)

Macroeconomic news	**Announcement time**	**Reporting agency**
Japanese News		
Coincident Index	14:00 JST	CO
Domestic CGPI	8:50 JST	MIC
GDP	8:50 JST	CO
Leading Index CI	14:00 JST	MOF
Machine Orders	8:50 JST	ESRI
Money Stock M2	8:50 JST	BOJ
Trade Balance	8:50 JST	MOF
Tokyo CPI	8:30 JST	MIC
Tankan Large Mfg Index	8:50 JST	BOJ
Tankan Large Non-Mfg Index	8:50 JST	BOJ
Retail Sales	8:50 JST	METI

Notes:

1. Abbreviations of reporting agencies are as follows: BLS = Bureau of Labor Statistics; BC = Bureau of Census; BEA = Bureau of Economic Analysis; CB = Conference Board; ETA = Employment and Training Administration; FRB = Federal Reserve Board; DT = Department of the Treasury; NAPMCI = National Association of Purchasing Management, Chicago Affiliate; DL = Department of Labor; EC = European Commission; ECB = European Central Bank; ME = Markit Economics; SG = Sentix GmbH; ZEW = Zentrum für Europäische Wirtschaftsforschung; CO = Cabinet Office; BOJ = Bank of Japan Research and Statistics Department; MOF = Ministry of Finance; ESRI = Economic and Social Research Institute.
2. EST represents Eastern Standard Time, which is the Eastern time zone of the United States and Canada, five hours behind Coordinated Universal Time (UTC); WET represents Western European Time, which is the Western time zone of Europe and Africa, and it has no offset from UTC. JST represents Japan Standard Time, which is the standard time zone in Japan, nine hours ahead of UTC.