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Price discovery and triangular arbitrage in currency markets

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ABSTRACT

Price discovery is the process by which markets incorporate the relevant information to arrive at the efficient price of an asset. We study the price discovery process in JPY/EUR cross-rates and the rates derived from exchanges of JPY/USD and USD/EUR indirectly. The results highlight the role of the USD as a vehicle currency in enhancing price efficiency through the triangular arbitrage. During financial crisis periods, the implied JPY/EUR rates have even more contribution to price discovery than direct rates. We show 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 zone, the trading cost advantage enhances price discovery of implied rates even more. The more contribution to price discovery of implied rates predicts the higher future volatility of direct JPY/EUR rates, indicating the slower response of direct rates to the information shock and the subsequent adjustment resulting in higher variations in the direct rates.

1. Introduction

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] Motivated by the information approach of Lyons and Moore (2009), we analyze how information is incorporated and transmitted in foreign exchange (FX) markets by studying the lead-lag relationship and relative price efficiency between direct and implied JPY/EUR cross-rates.

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. Lower trading costs and higher liquidity attract FX market participants to trade in the market of vehicle currency. When transactions convey information, the direct and implied JPY/EUR rates compete in the speed of

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[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.

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information incorporation. Our study differs from previous research regarding a vehicle currency's cost and benefit in international trade. Instead, we examine high-frequency exchange rate data and provide a comprehensive analysis of the dynamic price discovery across direct and implied JPY/EUR rates.

Most previous studies on vehicle currencies consider the USD exchange rates at daily or lower frequencies (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 et al., 2017).[3]

Using the high-frequency data enables us to identify which market is relatively faster in reflecting information to currency prices. As argued in King et al. (2013), order flow, agent heterogeneity, and private information are crucial determinants of short-run exchange rates.[4] Therefore, it is essential to link the information efficiency of currency markets to the study of exchange rate dynamics. Our study of price discovery between direct cross-rates and implied exchange rates can provide useful insights for practitioners, regulators, and researchers on the short-run exchange-rate determination, in particular with the recent prevalence of high-frequency trading in FX markets (Chaboud et al., 2021).

Surprisingly, very few studies use intraday data of FX rates to analyze the contributions of direct and the implied exchange rates to price discovery of related currencies and their dynamic interaction.[5] De Jong et al. (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 from October 1, 1992 to September 30, 1993. They find that although the implied rates lead actual JPY/DEM cross-rates, the USD-based implied rates are much noisier than the actual cross-rates. Lyons and Moore (2009) show that transactions of direct cross-rates and transactions through vehicle currencies have different information content in the 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.

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 further empirically study determinants of price discovery between direct and implied JPY/EUR 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. Furthermore, the price discovery function of a market can be better observed around macroeconomic announcements (Andersen, Bollerslev, Diebold, and Vega, 2003; Chen and Gau, 2010; Rime, Sarno, and Sojli, 2010; Gau and Wu, 2017; and others). Therefore, we explore how liquidity, transaction costs, and macroeconomic announcements affect the adjustment of direct and implied JPY/EUR markets in reflecting information into prices.

Using the quote and trade data from the EBS (Electronic Broking Services) trading system from January 2, 2008 to December 30, 2013, we take the information-share approach of Hasbrouck (1995) and the common-factor-weight approach of Gonzalo and Granger (1995) to study price discovery. We further empirically 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 volatility. 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 price efficiency of USD-based exchange rates affects the future volatility of actual JPY/EUR returns.

Our empirical results show the dominance of implied JPY/EUR rates in price discovery is linked to the advantage of lower trading costs in USD-based currency exchanges. We find the sample averages of (percentage) bid–ask spreads in USD/EUR, JPY/USD, and JPY/EUR markets are (0.0107%) 0.0001, (0.0152%) 0.0138, and (0.0278%) 0.0342, respectively.[6] The lower transaction costs involved with the indirect trading through USD/EUR and JPY/USD attract more transactions in FX markets based on USD. When transactions effectively convey incremental information, more information flows into JPY/USD and USD/EUR markets. Therefore, the implied JPY/EUR rates incorporate information at a faster speed than the actual JPY/USD cross-rates.

Furthermore, when scheduled macroeconomic announcements in the Europe and Japan are released, the effect of trading costs on

[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) and Kozhan and Tham (2012), 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.

[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.

[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.

the price discovery of JPY/EUR is more profound. Kim and Verrecchia (1994, 1997) address that public information releases may actually increase information asymmetry if market participants differ in their ability to interpret the public news. Green (2004) also provides evidence of the higher level of information asymmetry after specific macroeconomic announcements. In light of a higher level of information asymmetry after the announcement, market participants could tend to widen the bid–ask spread to protect themselves from trading against informed traders. Therefore, the even larger bid–ask spread in the direct JPY/EUR cross-rate market may further hamper its price discovery capability on announcement days.

We also find the dominant role of implied JPY/EUR rates in price discovery becomes more significant during U.S. business hours than during non-U.S. business hours.[7] We provide evidence that lower bid–ask spread, higher market liquidity, and possibly different trader composition during the U.S. trading session enhance the informational efficiency of implied JPY/EUR rates.

To explore the informational role of the USD exchange markets, we further investigate the link between the future volatility of actual JPY/EUR returns and the relative price discovery of implied and actual rates. We show that the fluctuation in actual JPY/EUR cross-rates can be forecasted by the relative contribution to price discovery of JPY/EUR rates. In response to a shock to the fundamental value of JPY/EUR, the actual cross-rates move slower than the implied rates; the delay may be caused by their higher trading costs. In the meantime, the disparity between contributions to price discovery of implied and actual JPY/EUR rates increases. It follows that implied rates lead actual rates in the adjustment toward the new equilibrium value, and the relatively higher price discovery efficacy of the implied rates corresponds to a slow adjustment process of the actual rates. Therefore, we argue that the price discovery of the implied rates is positively related to the future volatility of actual JPY/EUR returns. Our empirical results support this hypothesis and show that when implied JPY/EUR rates have more price discovery, actual JPY/EUR rates become more volatile in the future, while the future volatility of USD/EUR and JPY/USD returns remains unaffected.

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 association between price discovery and the volatility of direct rates, and Section 5 concludes.

2. Data

According to Bank for International Settlements (2019), in April 2019 the USD retained its dominant currency status, being on one side of 88.3% of all trades (Fig. 1). The share of trades with the EUR on one side expanded to 32.3%. In contrast, the share of trades involving the JPY fell 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.

We firstly obtain the tick-by-tick spot rates of USD/EUR, JPY/USD, and JPY/EUR from the EBS, which operates in the interdealer foreign exchange market. Then, we find the last quote in each minute from the raw data for EUR/USD, EUR/JPY, and USD/JPY. Finally, we keep those last quotes, and match the three currencies by the date and time on the minute-by-minute basis. As noted in Chaboud et al. (2021), the EBS trading platform is a global trading venue used by both manual and automated traders. BIS (2019) documents that, EBS and Reuters Matching are the two largest interdealer trading venues, and 56.9% of the overt-the-counter (OTC) FX turnover takes place in the U.K. and U.S. markets. In the spot interdealer FX 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 h 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), Chaboud et al. (2014), and Chaboud, Hjalmarsson, and Zikes (2021), we exclude data over 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

[7] Ito and Hashimoto (2006) depict the pattern of relative trading volume of trades that attributes to participants of a particular region across 24 h for EUR/USD and USD/JPY, traded in EBS. The evidence of intraday pattern in trading volume show that the trading volume of participants in each region is particularly high during local business hours. Thus, during the US trading hours, participants in London and New York dominate the trading. Comparing with the information shares across different trading sessions, previous literature shows that the information share in the beginning of US trading session is significantly larger than that in the other three trading sessions (Cai et al., 2008; Wang and Yang, 2010; Gau and Wu, 2017). To investigate why US trading session dominates price discovery in the FX market, Wu and Gau (2022) provide evidence that order flows in the beginning of US trading session are more informative. Accordingly, the literature evidences support different trader composition during the US trading session may enhance information efficiency.

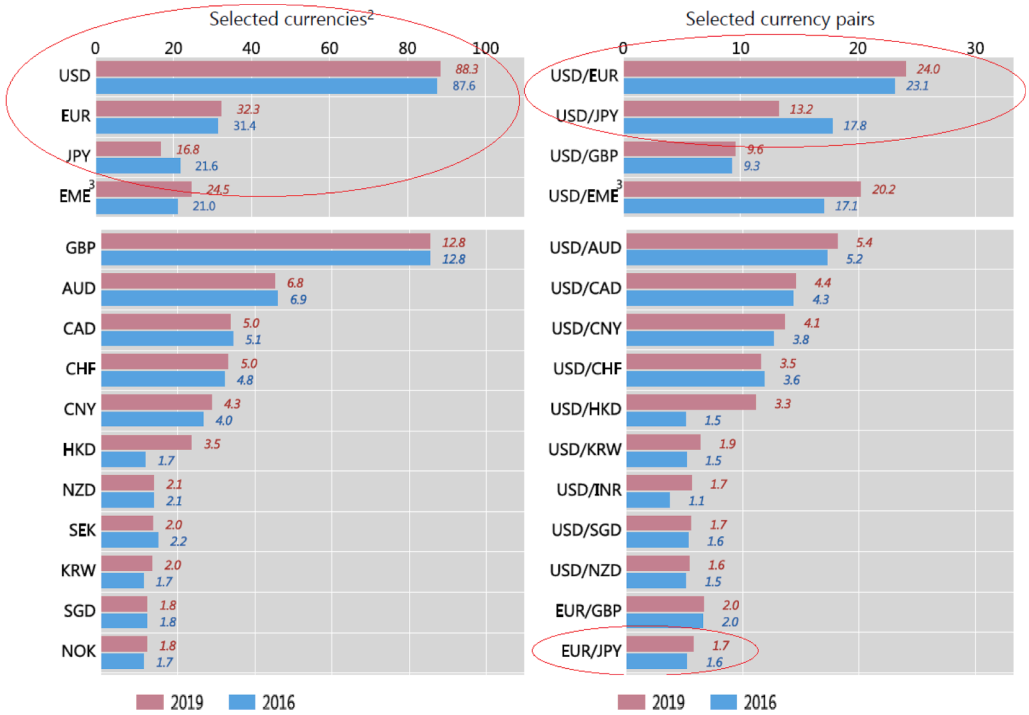

Fig. 1. Foreign exchange market turnover by currency and currency pairs. Source: BIS Triennial Central Bank Survey. (Daily averages in April, in percent).

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-rates.

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).[8] Letting q_t^I and q_t^D denote the logarithm of the implied JPY/EUR quote and the logarithm of the mid-quote of direct JPY/EUR cross-rate at time *t*, respectively, we obtain:

$$q_t^I = q_t^{JPY/USD} + q_t^{USD/EUR} \tag{1}$$

where $q_t^{JPY/USD}$ and $q_t^{USD/EUR}$ denote the logarithm of the mid-quotes at time *t* for JPY/USD and USD/EUR, respectively.

In the following price discovery analysis, we consider the impact of the Global Financial Crisis (GFC) and the Eurozone crisis (EZC) on the implied and direct JPY/EUR rates.[9] Following Duygun, Tunaru, and Vioto (2021) and Tang and Yao (2022), we consider the period from July 1, 2008 through June 30, 2009 as the GFC period, determining the end of the GFC to be June 2009 because the National Bureau of Economic Research (NBER) considers that date as the end of the recession in the US. We consider that the EZC covers the period from May 2, 2010 through December 31, 2012, as the first bailout package of the International Monetary Fund (IMF) for Greece occurred on May 2, 2010, and the Greek government bought back €21 billion of their bonds on Dec. 12, 2012.

Table 1 provides summary statistics of the levels, differences, and the percentage bid–ask spreads in direct and implied JPY/EUR quotes for the entire sample period and the three sub-sample periods, including the GFC period (7/1/2008 – 6/30/2009), the EZC period (5/2/2010 – 12/31/2012), and non-crisis period (1/2/2008 – 6/30/2008, 7/1/2009 – 4/30/2010, and 1/2/2013 – 12/31/2013). 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. We also find the standard deviations of Δq_t^D are Δq_t^I in the GFC period or in the EZC period are larger than those in non-crisis period, supporting the implied and direct JPY/EUR rates become more volatile over financial crisis period. In addition, we find that the percentage bid–ask spreads in direct and implied JPY/EUR quotes increase in the GFC period in contrast to the EZC period and non-crisis period. This result indicates investors may face higher transaction cost to trade JPY/EUR rates during the GFC period.

Results of augmented Dickey-Fuller (ADF) tests on q_t^D and q_t^I in Panel A of 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. Before analyzing price discovery between the

[8] 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.

[9] We thank an anonymous referee for suggesting the consideration of the impact of the GFC and the EZC on FX price discovery.

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	$Spread_t^I$	$Spread_t^D$
Panel A: Full-Sample Period (1/2/2008 – 12/30/2013)						
Mean	4.814	4.814	−0.028	−0.056	0.025	0.027
Std. Dev.	0.140	0.140	299.344	322.100	0.015	0.072
Skewness	0.449	0.449	0.083	−0.915	38.022	82.209
Kurtosis	2.586	2.586	76.081	490.227	6478.920	6490.110
ADF	0.598	−1.984	−449.490***	−339.010***	−59.048***	−104.661***
Johansen Cointegration Tests for q_t^I and q_t^D						
λ_{max}	H_0: $r \le 0$	505239.50***				
	H_0: $r \le 1$	2.07				
λ_{trace}	H_0: $r \le 0$	505241.60***				
	H_0: $r \le 1$	2.07				
Panel B: Global Financial Crisis Period (7/1/2008 – 6/30/2009)						
Mean	4.906	4.906	−0.616	−0.719	0.034	0.034
Std. Dev.	0.118	0.118	451.359	591.930	0.017	0.084
Skewness	0.662	0.662	−0.130	−43.495	4.184	293.594
Kurtosis	2.199	2.199	32.467	1718.710	74.003	1077.942
Johansen Cointegration Tests for q_t^I and q_t^D						
λ_{max}	H_0: $r \le 0$	2723.22***				
	H_0: $r \le 1$	0.74				
λ_{trace}	H_0: $r \le 0$	2723.96***				
	H_0: $r \le 1$	0.74				
Panel C: Eurozone Crisis Period (5/2/2010 – 12/31/2012)						
Mean	4.684	4.684	−0.161	−0.124	0.023	0.026
Std. Dev.	0.056	0.056	472.376	587.637	0.019	0.089
Skewness	−0.276	−0.276	0.548	−13.158	8.074	760.729
Kurtosis	2.342	2.342	131.527	2147.369	342.881	6291.208
Johansen Cointegration Tests for q_t^I and q_t^D						
λ_{max}	H_0: $r \le 0$	6872.16***				
	H_0: $r \le 1$	0.18				
λ_{trace}	H_0: $r \le 0$	6872.34***				
	H_0: $r \le 1$	0.18				
Panel D: Non-Crisis Period (1/2/2008 – 6/31/2008, 7/1/2009 – 4/30/2010, and 1/2/2013 – 12/31/2013)						
Mean	4.908	4.908	0.340	0.279	0.025	0.027
Std. Dev.	0.095	0.095	243.461	269.883	0.017	0.040
Skewness	0.886	0.886	−0.102	−4.449	55.048	31.466
Kurtosis	2.733	2.733	57.442	815.366	881.229	2117.865

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 means and standard deviations of Δq_t^I and Δq_t^D are multiplied by 10^6. $Spread_t^I$ and $Spread_t^D$ denote the percentage bid–ask spread which is calculated by the bid–ask spread (i.e., the difference between ask and bid quotes) divided by mid-quotes, multiplied by 100, of implied and actual cross rates of JPY/EUR;$Spread_t^I$ is the sum of percentage spread of JPY/USD and USD/EUR rates. 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} and λ_{trace} refer to Johansen maximum eigenvalue test and trace test, respectively. 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 to the number of lags. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

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 in the entire sample period, the GFC period, and the EZC period, that is, the direct and implied JPY/EUR rates have a long-run equilibrium relationship.

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), the vector error correction (VEC) model in Equation (3), and VEC model considering the GFC and the EZC dummy variables in Equation (4) respectively as follows:

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

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

and

$$\begin{aligned}\Delta q_t^I &= c^I + \alpha_1^I\left(q_{t-1}^I - q_{t-1}^D\right) + \alpha_2^I\left(GFC_{t-1} \times \left(q_{t-1}^I - q_{t-1}^D\right)\right) + \alpha_3^I\left(ZFC_{t-1} \times \left(q_{t-1}^I - q_{t-1}^D\right)\right) \\ &\quad + \sum_{i=1}^{k}\gamma_{1,i}\Delta q_{t-i}^I + \sum_{i=1}^{k}\gamma_{2,i}\Delta q_{t-i}^D + e_t^I \\ \Delta q_t^D &= c^D + \alpha_1^D\left(q_{t-1}^I - q_{t-1}^D\right) + \alpha_2^D\left(GFC_{t-1} \times \left(q_{t-1}^I - q_{t-1}^D\right)\right) + \alpha_3^D\left(ZFC_{t-1} \times \left(q_{t-1}^I - q_{t-1}^D\right)\right) \\ &\quad + \sum_{i=1}^{k}\gamma_{3,i}\Delta q_{t-i}^I + \sum_{i=1}^{k}\gamma_{4,i}\Delta q_{t-i}^D + e_t^D\end{aligned} \tag{4}$$

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 Equations (3) and (4), 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 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. Harris et al. (1995) suggest using the error correction model to evaluate price discovery. As the cointegrating vector defines the long-run equilibrium, the corresponding error-correction mechanism can characterize the price discovery process. 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 magnitudes of the two exchange rates' adjustments toward their long-run equilibrium. Specifically, if the direct JPY/EUR rates responded more to deviations from indirect implied rates (i.e., α^D is larger), but implied rates did not respond to deviations from direct rates (i.e., α^I is smaller), there would be evidence that the price discovery process is focused in implied rates. Hence, we focus on comparing α^i in models for direct and implied rates to quantify their relative amount of price discovery in Equations (3) and (4).

Table 2 shows that all autocorrelation coefficients are significant to the fourth lag in both VAR and VEC models. In the VAR and VEC models, the adjusted R^2 for the equation of Δq_t^D are considerably higher than those for the equation of 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 $\alpha^D(0.839)$ is larger than $\alpha^I(-\ 0.049)$, 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. For example, suppose in period *t*-1 the price difference $q_{t-1}^I - q_{t-1}^D = 1$ and there is a price disequilibrium between two exchange rates, i.e., implied JPY/EUR rates are higher than direct rates. No-arbitrage condition may tie the two exchange rates together and drive two rates back to the equilibrium ($q_t^I = q_t^D$). By the VECM estimation results in Table 2, error correction coefficients of implied and direct JPY/EUR rates are -0.049 and 0.839, respectively. The price adjustments in period *t* implied by the error-correction terms are as follows: implied JPY/EUR rates decrease by 0.049 and direct JPY/EUR rates increase by 0.839 to reach the equilibrium between two rates. Hence, a smaller adjustment of implied JPY/EUR rates may imply that the implied rates are closer to the equilibrium value and they have more price discovery than the direct rates.

Because the GFC and the EZC are believed to have had a huge impact on the foreign exchange market, we consider the effect of GFC and the EZC on price discovery between direct JPY/EUR cross-rates and the implied rates in Equation (4). We also report the results of the impact of GFC and the EZC on the price discovery between direct and implied JPY/EUR rates in Table 2. To capture the impact of GFC and the EZC on the price discovery, we include the interaction terms, $GFC_{t-1} \times \left(q_{t-1}^I - q_{t-1}^D\right)$ and $EZC_{t-1} \times \left(q_{t-1}^I - q_{t-1}^D\right)$, in Equation (4) and analyze the coefficients of error-correction term and these interaction terms. We find that, during the two crisis periods, the implied JPY/EUR rates have relatively more price discovery, compared to the non-crisis period (i.e. $\left|\alpha_1^I + \alpha_2^I\right| = |-0.088 + 0.039| < \left|\alpha_1^I\right| = |-0.088|$ and $\left|\alpha_1^I + \alpha_3^I\right| = |-0.088 + 0.049| < \left|\alpha_1^I\right|$). Most importantly, we still find implied JPY/EUR rates dominate in price discovery, compared to direct JPY/EUR rates during the crisis periods (i.e., $\left|\alpha_1^I + \alpha_2^I\right| = |-0.088 + 0.039| < \left|\alpha_1^D + \alpha_2^D\right| = |0.539 + 0.005|$ and $\left|\alpha_1^I + \alpha_3^I\right| = |-0.088 + 0.049| < \left|\alpha_1^D + \alpha_3^D\right| = |0.539 + 0.023|$). These results confirm that implied JPY/EUR rate dominates the price discovery process during and outside the crisis periods.

Following Booth et al. (1999), Zhong et al. (2004), and Chen (2020), we also distinguish short-run and long-run price discovery relationships in the VEC model in Equation (3). Short-run price discovery implies that a change in prices in one market can only predict a temporary change in prices in the other market. We investigate the short-run price discovery relationships using Granger-causality tests of the joint significance of each of the other lagged endogenous variables in the VAR and VEC models. For long-run price discovery, we focus on the long-run speed of adjustment (α^i) for the two rates.

Table 2
Vector Autoregression and Vector Error Correction Models for Implied and Direct JPY/EUR Rates.

	VAR		VECM		VECM with crisis dummies	
	Δq_t^I	Δq_t^D	Δq_t^I	Δq_t^D	Δq_t^I	Δq_t^D
Constant	−0.001(0.000)	−0.001(0.000)	−0.001(0.000)	−0.001(0.000)	−0.001(0.000)	−0.001(0.000)
Δq_{t-1}^I	−0.025***(0.001)	0.725***(0.001)	0.008***(0.001)	0.046***(0.001)	0.001(0.001)	−0.010***(0.000)
Δq_{t-2}^I	−0.009***(0.001)	0.542***(0.001)	0.012*** (0.001)	0.028***(0.001)	0.012***(0.001)	−0.028***(0.001)
Δq_{t-3}^I	0.008***(0.001)	0.037***(0.001)	0.020***(0.001)	0.029***(0.001)	0.021***(0.001)	0.022***(0.001)
Δq_{t-4}^I	0.013***(0.001)	0.184***(0.001)	0.018***(0.001)	0.021***(0.001)	0.018***(0.001)	0.015***(0.001)
Δq_{t-1}^D	−0.008***(0.001)	−0.756***(0.001)	−0.022***(0.001)	−0.074***(0.001)	−0.000(0.001)	−0.017***(0.001)
Δq_{t-2}^D	−0.002***(0.001)	−0.562***(0.001)	−0.023***(0.001)	−0.047***(0.001)	−0.021***(0.001)	0.015***(0.001)
Δq_{t-3}^D	−0.019***(0.000)	−0.389***(0.001)	−0.031***(0.000)	−0.048***(0.001)	−0.031***(0.001)	−0.035***(0.001)
Δq_{t-4}^D	−0.018***(0.000)	−0.193***(0.001)	−0.023***(0.000)	−0.033***(0.001)	−0.023***(0.001)	−0.026***(0.001)
$q_{t-1}^I - q_{t-1}^D$			−0.049***(0.001)	0.839***(0.001)	−0.088***(0.002)	0.539***(0.001)
$GFC_{t-1} \times (q_{t-1}^I - q_{t-1}^D)$					0.039***(0.002)	0.005***(0.001)
$EZC_{t-1} \times (q_{t-1}^I - q_{t-1}^D)$					0.049***(0.002)	0.023***(0.001)
Granger Causality Tests						
$\Delta q_{t-1}^I = \cdots = \Delta q_{t-4}^I = 0$		28820.7***		4332.8***		4960.53***
$\Delta q_{t-1}^D = \cdots = \Delta q_{t-4}^D = 0$	1136.4***		1955.3***		1518.39***	
Adjusted R^2	0.001	0.208	0.002	0.392	0.002	0.295

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

$$\Delta q_t^I = c^I + \sum_{i=1}^{k} \gamma_{1,i} \Delta q_{t-i}^I + \sum_{i=1}^{k} \gamma_{2,i} \Delta q_{t-i}^D + e_t^I \text{, and}$$
$$\Delta q_t^D = c^D + \sum_{i=1}^{k} \gamma_{3,i} \Delta q_{t-i}^I + \sum_{i=1}^{k} \gamma_{4,i} \Delta q_{t-i}^D + e_t^D$$

The VEC model is:

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

The VEC model considering crisis dummy variables is:

$$\Delta q_{t-1}^I = c^I + \alpha_1^I (q_{t-1}^I - q_{t-1}^D) + \alpha_2^I (GFC_{t-1} \times (q_{t-1}^I - q_{t-1}^D)) + \alpha_3^I (EZC_{t-1} \times (q_{t-1}^I - q_{t-1}^D)) + \sum_{i=1}^{k} \gamma_{1,i} \Delta q_{t-i}^I + \sum_{i=1}^{k} \gamma_{2,i} \Delta q_{t-i}^D + e_t^I$$
$$\Delta q_{t-1}^D = c^D + \alpha_1^D (q_{t-1}^I - q_{t-1}^D) + \alpha_2^D (GFC_{t-1} \times (q_{t-1}^I - q_{t-1}^D)) + \alpha_3^D (EZC_{t-1} \times (q_{t-1}^I - q_{t-1}^D)) + \sum_{i=1}^{k} \gamma_{3,i} \Delta q_{t-i}^I + \sum_{i=1}^{k} \gamma_{4,i} \Delta q_{t-i}^D + e_t^D$$

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. *GFC* denotes the global financial crisis dummy variable and it equals to one during the period from July 1, 2008 to June 30, 2009 and zero otherwise. *EZC* denotes the Eurozone crisis dummy variable and it equals to one during the period from May 2, 2010 to December 31, 2012 and zero otherwise. 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.

The results of the Granger causality test for changes in direct and implied JPY/EUR rates are displayed in Table 2. The reported *F*-test statistics in VEC models of Table 2 show changes in the implied rates Granger cause changes in the direct rates, and vice versa (bi-directional causality). However, the analysis indicates that the influence of lagged changes in implied rates on current changes in direct rates is more significant than the influence of lagged changes in direct rates on current change in implied rates. That is, we find a bi-directional causality between changes in the implied and direct JPY/EUR rates, but the effect appears stronger in the direction from implied rate to direct JPY/EUR rates.

Finally, we study the price discovery for direct and implied JPY/EUR rates using an impulse response analysis for VEC model in Equation (3).[10] We use the generalized impulse response function proposed by Pesaran and Shin (1998) to construct an orthogonal set of innovations that does not depend on the ordering of variables in the VAR or VEC models. We examine the generalized impulse response for Equation (3) and plot them in Fig. 2. In Fig. 2b, we find that the response of implied JPY/EUR rate to one standard deviation of shocks in direct JPY/EUR rates approaches 0 after 2 min. Fig. 2a reveals that the impact of the innovation in implied JPY/EUR rates on direct JPY/EUR rates also disappears after 2 min. However, these results show that the responses of direct rate returns to an unexpected shock in implied rate returns have been relatively larger than the responses of implied rate returns to a shock in direct rate returns. These results may imply that the implied JPY/EUR rate dominates the price discovery process.

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)

[10] We thank an anonymous referee for suggesting the consideration of Granger-causality and impulse response analyses to analyze price discovery.

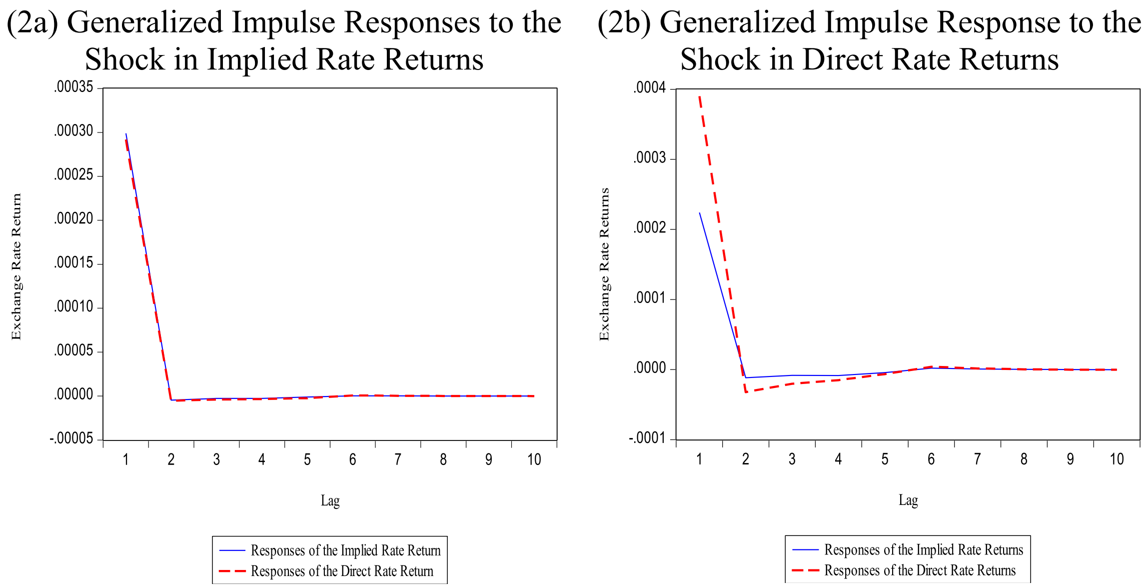

Fig. 2. Generalized Impulse Responses Analysis in the VEC Model. This figure presents generalized impulse responses of returns of direct and implied JPY/EUR rates based on the VEC model in Equation (3). Fig. 2a shows the effect of an unexpected 1 standard deviation increase in returns of the implied rate on the direct and implied rate returns. Fig. 2b displays the effect of an unexpected 1 standard deviation increase in returns of the direct rate on the direct and implied rate returns. Generalized impulse responses proposed by Pesaran and Shin (1998) are robust to variable ordering in the VEC model and are plotted for up to ten lags.

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, Booth, Tse, and Zabotina (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).[11] 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:

$$\begin{aligned} q_t &= A_1 f_t + A_2 z_t \\ &= A_1 \alpha'_{\perp} q_t + A_2 \beta' q_{t-1} \end{aligned} \tag{5}$$

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:

$$\Delta q_t = \Psi_0 e_t + \Psi_1 e_{t-1} + \Psi_2 e_{t-2} + \cdots = \Psi(L) e_t, \tag{6}$$

where $\Psi_0 = I$ and I denotes the 2×2 identity matrix. The integrated form of Equation (6) is:

$$q_t = \Psi(1) \sum\nolimits_{s=1}^{t} e_s + \Psi^*(L)\, e_t \tag{7}$$

[11] Implied JPY/EUR rate equals to (JPY/USD × USD/EUR) and fundamental information about JPY and EUR currencies would incorporate into implied and direct JPY/EUR rates. Although implied JPY/EUR rate involves USD in contrast with direct JPY/EUR, it would not affect by fundamental information about USD currency mainly. For example, when the actual U.S. GDP is higher than the market participants expected, it should cause an appreciation of the USD, and the JPY/USD (USD/EUR) rates rise (fall). There is an offset for the USD information role in implied JPY/EUR rate. Hence, direct and implied JPY/EUR quotes are majorly driven by the same fundamental information.

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:

$$IS^i = \frac{\psi_i^2 \Omega_{ii}}{\psi\Omega\psi'} \tag{8}$$

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:

$$IS^i = \frac{\left[(\psi F)_i\right]^2}{\psi\Omega\psi'} \tag{9}$$

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

Because the Cholesky decomposition depends on the order of variables in the 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. When IS^I is higher than IS^D, implied JPY/EUR rates incorporate information better and faster relative to the direct cross-rates. Therefore, FX participants have incentives to choose the market with lower trading cost and higher liquid to maximize their profit. Hence, they may avoid trading in the direct exchange of JPY/EUR and intend to use the USD as a vehicle currency to exchange indirectly.

To analyze the time-varying dynamics in price discovery of JPY/EUR, we use minute-by-minute mid-quotes during a day to calculate the common factor weights (CFW^D and CFW^I) and information shares (IS^D and IS^I) each day. Using the daily series of IS_t^i and CFW_t^i (for $i = D, I$), we conduct the mean equality test to compare contributions to price discovery of direct and implied JPY/EUR rates.

We analyze the daily common factor weights (CFW^D and CFW^I) and information shares (IS^D and IS^I) in entire sample and the three sub-periods included the GFC period, the EZC period, and non-crisis period in Table 3. Panel A of Table 3 reports the estimation results of IS_t^i and CFW_t^i in entire sample; 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 exchange through JPY/USD and USD/EUR contributes more to price

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
Panel A: Full sample period (1/2/2008 – 12/30/2013)				
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***		
Panel B: The Global Financial Crisis period (7/1/2008 – 6/30/2009)				
Mean	0.550	0.450	0.582	0.418
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	19.63***	22.17***		
ANOVA F-test	167.79***	171.52***		
Panel C: The Eurozone crisis period (5/2/2010 – 12/31/2012)				
Mean	0.558	0.442	0.588	0.412
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	16.66***	14.16***		
ANOVA F-test	160.37***	172.31***		
Panel D: Non-crisis periods (1/2/2008 – 6/30/2008, 7/1/2009 – 4/30/2010, and 1/2/2013 – 12/31/2013)				
Mean	0.528	0.472	0.524	0.476
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	5.28***	6.37***		
ANOVA F-test	23.23***	40.69***		

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 VECM with the length of 4 lags determined by the AIC. ***, **, and * indicate significance at the 1%, 5%, and 10% levels, respectively.

discovery of JPY/EUR, regardless of whether we consider information share (IS_t^i) or common factor weight (CFW_t^i) to measure a market's price discovery capability.

In addition, Panels B, C and D of Table 3 also shows that the average value of IS_t^I (CFW_t^I) is significantly higher than that of $IS_t^D(CFW_t^D)$. The average value of IS_t^I (CFW_t^I) in the GFC or EZC period is higher than that of IS_t^I (CFW_t^I) in non-crisis period. These findings support that implied JPY/EUR rates dominate in price discovery, compared to direct JPY/EUR rates, during GFC and the EZC periods. The implied JPY/EUR rates have relatively more price discovery, compared to the period outside the GFC and EZC.[12]

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 (Love and Payne, 2008; Mizrach and Neely, 2008; Chen and Gau, 2010; Fricke and Menkhoff, 2011). The regression model is specified as:

$$ln(RC_t^i) = c + \beta' X_t + e_t^i \quad (10)$$

where $RC_t^i = RC_t^{IS}$ or RC_t^{CFW}, and $RC_t^{IS} = (IS_t^I/IS_t^D)$. $RC_t^{CFW} = (CFW_t^I/CFW_t^D)$ denotes the relative contributions of implied and actual JPY/EUR rates to price discovery, as measured by information share and common factor weight, respectively. Explanatory variables (X_t) include RTN_{t-1}, RTC_{t-1}, RRV_{t-1} and crisis dummy variables. The relative trading cost (RTC_{t-1}) denotes the half–sum of the bid–ask spreads in the JPY/USD and USD/EUR markets divided by the half bid–ask spread of JPY/EUR rates on day t, as in Love and Payne (2008). The relative trade number (RTN_{t-1}) 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-1}) refers to the realized volatility of implied JPY/EUR rates relative to the realized volatility of JPY/EUR cross-rates on day t. GFC_t denotes the global financial crisis dummy variable and it equals to one during the period from July 1, 2008 to June 30, 2009 and zero otherwise. EZC_t denotes the Eurozone crisis dummy variable and it equals to one during the period from May 2, 2010 to December 31, 2012 and zero otherwise.[13]

We further examine the impact of macroeconomic announcements on relative price informativeness between implied and actual JPY/EUR rates.[14] 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. We also consider the interactive terms of news announcements and relative trading cost to explore whether the impact of trading cost varies with news announcements. Arguably, the release of macroeconomic news may increase the information asymmetry due to heterogeneous interpretations of news and changes in expectations among market participants; therefore, an increase in the bid-ask spread is induced by the higher adverse-selection cost component (Naranjo and Nimalendran, 2000; Chen and Gau, 2014; Foucault et al., 2017).

Table 4 reports estimation results for Equation (10); it shows that relative trading cost has a significant and negative impact on the relative contribution to price discovery in all models. This evidence supports the argument that the lower transaction cost of indirect exchange possibly attracts more market participants to exchange JPY (or EUR) for EUR (or JPY) indirectly using the USD, which improves the price discovery of implied JPY/EUR rates. The table also shows *RTN* (relative trade numbers) and *RRV* (relative realized volatility) have insignificantly positive association with the relative contribution to price discovery.

Models (1) and (5) in Table 4 show the positive impact of Japanese announcements (D_t^{JP}) on RC_t^{IS} and RC_t^{CFW}. In particular, the interaction terms of Japanese announcements and relative trading cost are significantly and negatively related to the relative contribution of price discovery. Coefficients are −0.30 in Model (1) and −0.16 in Model (5), suggesting that Japanese announcements strengthen the impact of trading cost on price discovery. This result highlights the advantage of lower trading cost of the indirect exchange through USD-based markets.

Models (2) and (6) also show the positive impact of European announcements (D_t^{EU}) on relative price discovery. The interaction terms of European announcements and relative trading cost are significantly and negatively related to relative contribution to price discovery. In addition, Models (3) and (7) display that U.S. announcements have an insignificant impact on relative contribution to price discovery. In Models (4) and (8), we consider all announcement variables with *RTN, RRV,* and *RTC* simultaneously and they show the similar results with Models (1)-(3) and (5)-(7).

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 trading cost advantage

[12] For a robustness check, we also consider the 1-second and 15-second data to re-calculate respective common factor weights and information shares for implied and direct JPY/EUR rates each day to examine the dynamics of price discovery. The results are qualitatively similar and our conclusions remain unchanged, showing implied JPY/EUR rates are dominant in price discovery in contrast to direct rates. These results are available upon request. We thank the referee for suggesting the robustness check for the data at different frequencies.

[13] We thank an anonymous referee for noting an endogeneity concern in Equation (10). In line with Boehmer and Kelley (2009), we conducted regressions of Equation (10) using explanatory variables lagged by one period to reduce the potential effect of contemporaneous explanatory variables. The lagged explanatory variables can be interpreted as instruments for the corresponding current values. In addition, we measure daily realized volatility with the square root of the sum of the squared 1-min quotes returns during day t.

[14] 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.

Table 4
Determinants of Relative Contributions of Implied and Direct JPY/EUR Exchange Rates 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	0.39***	0.33***	0.29***	0.35***	0.63***	0.64***	0.58***	0.67***
	(0.05)	(0.07)	(0.07)	(0.08)	(0.10)	(0.10)	(0.09)	(0.10)
GFC_t	0.03	0.02	0.02	0.02	0.01	0.01	0.01	0.01
	(0.09)	(0.05)	(0.05)	(0.03)	(0.09)	(0.07)	(0.07)	(0.05)
EZC_t	0.02	0.06	0.06	0.06	0.05	0.05	0.05	0.05
	(0.04)	(0.04)	(0.04)	(0.05)	(0.04)	(0.05)	(0.05)	(0.05)
$\ln(RTN_{t-1})$	0.01	0.01	0.01	0.01	0.00	0.00	0.01	0.01
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
$\ln(RTC_{t-1})$	−0.28**	−0.33**	−0.36**	−0.34**	−0.89***	−0.77***	−0.82***	−0.78***
	(0.10)	(0.15)	(0.15)	(0.16)	(0.21)	(0.21)	(0.21)	(0.21)
$\ln(RRV_{t-1})$	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
D_t^{JP}	0.22***			0.02	0.04			0.04
	(0.04)			(0.03)	(0.04)			(0.04)
$D_{t-1}^{JP} \times \ln(RTN_{t-1})$	0.00			0.00	0.00			0.00
	(0.00)			(0.00)	(0.00)			(0.00)
$D_{t-1}^{JP} \times \ln(RTC_{t-1})$	−0.30**			−0.05*	−0.16**			−0.06**
	(0.13)			(0.03)	(0.08)			(0.03)
D_t^{EU}		0.05*		0.02		0.06		0.06
		(0.03)		(0.03)		(0.05)		(0.05)
$D_{t-1}^{EU} \times \ln(RTN_{t-1})$		−0.01		0.01		0.00		0.00
		(0.00)		(0.00)		(0.00)		(0.00)
$D_{t-1}^{EU} \times \ln(RTC_{t-1})$		−0.17*		−0.19*		−0.24**		−0.29**
		(0.09)		(0.09)		(0.12)		(0.13)
D_t^{US}			0.01	−0.01			−0.00	0.01
			(0.03)	(0.03)			(0.05)	(0.05)
$D_{t-1}^{US} \times \ln(RTN_{t-1})$			−0.00	−0.00			−0.00	−0.00
			(0.01)	(0.02)			(0.00)	(0.01)
$D_{t-1}^{US} \times \ln(RTC_{t-1})$			−0.01	−0.01			−0.06	−0.03
			(0.09)	(0.10)			(0.12)	(0.13)
Adjusted R^2	0.02	0.02	0.01	0.02	0.02	0.02	0.01	0.02

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. *GFC* denotes the global financial crisis dummy variable and it equals to one during the period from July 1, 2008 to June 30, 2009 and zero otherwise. *EZC* denotes the Eurozone crisis dummy variable and it equals to one during the period from May 2, 2010 to December 31, 2012 and zero otherwise. 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*) 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*) 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*) 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.

of the indirect exchange via the USD further improves the price discovery of implied rates. In contrast, U.S. announcements do not affect the relative price discovery of implied and direct JPY/EUR rates.

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 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

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
	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	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.

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.[15]

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, 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.

4. Vehicle currency role and volatility of direct exchange rates

After studying the vehicle currency role of USD in the improvement of price discovery, we further investigate whether the price-discovery capacity affects the future volatility of JPY/EUR returns. Ross (1989) posits that the volatility of an asset's return is associated with the information flow. Andrei and Hasler (2015) suggest that stock return variance increases with the investors' attention to news. In addition, Ben-David et al. (2018) declare that the exchange-traded fund (ETF) may be the vehicle for the price discovery process of its underlying securities. Further, they show the presence of ETFs allows prices of underlying securities to react more quickly to fundamentals and increases the volatilities of underlying securities' returns (i.e., the price discovery hypothesis). Overall, this argument implies that asset return volatilities are related to the way in which how information is incorporated into prices.

From the above discussions, we infer that when a shock to the fundamental value of the JPY/EUR occurs, the implied rates (from USD-based exchange rates) move first and the direct rates follow with a delay due to stale pricing and higher trading costs. Meanwhile, the difference between contributions to price discovery of implied and direct JPY/EUR rates increases. As time goes on, the direct rate will slowly adjust to the information shock, and eventually move towards the new equilibrium value. Therefore, the relative contribution to price discovery of the two rates positively relates to the future volatility of direct JPY/EUR rates.

To explore whether relative price discovery relates to the future realized volatility of USD/EUR, JPY/USD, and JPY/EUR returns, we estimate the following model:

$$RV_t^j = \beta_0 + \beta_1 RC_{t-1}^i + \beta_2 JPGV_{t-1} + \beta_3 RV_{t-1}^j + e_t \tag{11}$$

where RV_t^j represents the realized volatility of returns in direct USD/EUR, JPY/USD, and JPY/EUR returns on day *t*. We calculate RV_t^j with all one-minute returns within a day, for j = USD/EUR, JPY/USD, and JPY/EUR. RC_{t-1}^i, with $i = IS$ or CFW, denotes the relative contributions of implied and direct JPY/EUR exchanges to price discovery on day/t, as measured by the information share (*IS*) and common factor weight (*CFW*), respectively. We also consider the proxy of global FX market volatility, *JPGV*, the JP Morgan Global

[15] 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).

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.

Foreign Exchange Volatility Index.[16]

Models (1)-(4) in Table 7 indicate that both RC_{t-1}^{IS} and RC_{t-1}^{CFW} are insignificantly and positively associated with $RV_t^{USD/EUR}$ and $RV_t^{JPY/USD}$, suggesting that the higher $RC_{t-1}^{IS}(=IS_{t-1}^I/IS_{t-1}^D)$ is associated with a higher future volatility of USD/EUR and JPY/USD rates, although insignificantly at the 10% level. This may be attributed to the fast adjustment of USD/EUR and JPY/USD in response to information-relevant shocks and therefore no subsequent adjustments needed.

Most importantly, both RC_{t-1}^{IS} and RC_{t-1}^{CFW} are significantly and positively related to $RV_t^{JPY/EUR}$, as shown in Models (5)-(6). This supports our hypothesis that the relatively higher price discovery of implied rates predicts a higher future volatility of direct JPY/EUR rates, resulted by the on-going subsequent adjustments in exchange rates after the shock. In addition, RV_t^j is significantly and positively related to $JPGV_{t-1}$ and RV_{t-1}^j, as shown in Models 1–6 of Table 7.

To analyze the dynamic interaction between the volatility of actual JPY/EUR rates and the price discovery capacity of implied JPY/EUR rates, we also perform Granger causality tests for the bivariate VAR model of $RV_t^{JPY/EUR}$ and RC_t^{IS} (or RC_t^{CFW}).[17] 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 volatility of direct JPY/EUR rates, but not vice versa, no matter whether we measure price discovery with information share or common factor weight. This result suggests the measure of informative efficiency in the indirect exchange through USD-based markets is a useful predictor of the future volatility of JPY/EUR returns.

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 from the information approach. 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. During financial crisis periods, the implied JPY/EUR rates have even more contribution to price discovery than direct rates. 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 lower trading cost of the implied rates is a crucial factor for better price discovery of implied JPY/EUR rates.

We find that upon the arrival of Japanese and European macroeconomic news, the larger bid–ask spread may further hamper the price discovery capability of the direct JPY/EUR market. 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, with a new contribution to the literature, we show that the price efficiency of USD-based exchange rates can predict the future volatility of direct JPY/EUR rates, highlighting the direct JPY/EUR rate adjusts towards the equilibrium level slower than the implied rate. Our finding provides valuable insights for triangular arbitrageurs and strategic traders in FX markets.

Our study of the price discovery between direct cross-rates and implied exchange rates can shed light on short-run exchange-rate determination. For example, if the implied JPY/EUR rate dominates the price discovery process, the implication is that prices and order flows in the USD/EUR and JPY/USD markets provide essential information on the determination of JPY/EUR cross-rates. We suggest that future research could address the issue to explore the role of order flows of currencies traded in the triplet of EUR, JPY and USD in the price discovery process.

CRediT authorship contribution statement

Zhen-Xing Wu: Conceptualization, Methodology, Software, Data curation, Writing – original draft, Writing – review & editing,

[16] JP Morgan Global Foreign Exchange Volatility Index is a turnover-weighted index of the implied volatility of three-month at-the-money options on 23 USD currency pairs.

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

Table 7
The Relative Price Discovery and Volatility of Direct JPY/EUR Exchange Rates.

	$RV_t^{USD/EUR}$		$RV_t^{JPY/USD}$		$RV_t^{JPY/EUR}$	
	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)	Model (6)
Constant	−0.032	−0.057	−0.497	−0.547	0.169	0.262
	(1.011)	(1.012)	(1.389)	(1.395)	(0.545)	(0.530)
RC_{t-1}^{IS}	0.092		0.213		0.424^{**}	
	(0.368)		(0.551)		(0.188)	
RC_{t-1}^{CFW}		0.128		0.273		0.521^{***}
		(0.278)		(0.404)		(0.130)
$JPGV_{t-1}$	0.196^{**}	0.197^{**}	0.275^{**}	0.277^{**}	0.313^{***}	0.315^{***}
	(0.082)	(0.082)	(0.113)	(0.113)	(0.049)	(0.043)
RV_{t-1}^{j}	0.087^{***}	0.082^{***}	0.092^{**}	0.091^{***}	0.085^{**}	0.074^{**}
	(0.033)	(0.031)	(0.036)	(0.034)	(0.036)	(0.034)
Adj. R^2	0.015	0.015	0.017	0.018	0.062	0.071

Note: The table reports the estimation results for the following regression of daily USD/EUR, JPY/USD, and JPY/EUR exchange rates volatility on the relative price discovery and controls, with the ordinary least squares (OLS) estimation method:

$RV_t^j = \beta_0 + \beta_1 RC_{t-1}^i + \beta_2 JPGV_{t-1} + \beta_3 RV_{t-1}^j + e_t,$

where RV_t^j is the realized volatility of direct USD/EUR, JPY/USD, and JPY/EUR exchange rate changes on day $t.RC_{t-1}^i = RC_{t-1}^{IS}$ or RC_{t-1}^{CFW}, 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. The control variables include the lagged own realized volatility (RV_{t-1}^j) and the lagged JP Morgan Global Foreign Exchange Volatility Index ($JPGV_{t-1}$). 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 8
Granger Causality Tests for Relative Price Discovery and Volatility of Direct JPY/EUR Exchange Rates.

Pairwise Granger Causality Tests	*F* test	*p*-value
Panel A. Relative contribution to price discovery measured by the information share		
RC_t^{IS} does not Granger cause $RV_t^{JPY/EUR}$	4.677	0.009
$RV_t^{JPY/EUR}$ does not Granger cause RC_t^{IS}	0.153	0.858
Panel B. Relative contribution to price discovery measured by the common factor weight		
RC_t^{CFW} does not Granger cause $RV_t^{JPY/EUR}$	6.755	0.001
$RV_t^{JPY/EUR}$ does not Granger cause RC_t^{CFW}	0.263	0.768

Note: This table reports the results of the pairwise Granger causality tests on ($RV_t^{JPY/EUR}$, RC_t^{IS}) and ($RV_t^{JPY/EUR}$, 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. $RV_t^{JPY/EUR}$ is the realized volatility of direct JPY/EUR exchange rate returns.

Project administration. **Yin-Feng Gau:** Conceptualization, Writing – original draft, Writing – review & editing, Investigation, Validation, Project administration. **Yu-Lun Chen:** Conceptualization, Methodology, Software, Data curation, Writing – original draft, Writing – review & editing, Investigation, Validation, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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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

.

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

(*continued on next page*)

(*continued*)

Macroeconomic news	Announcement time	Reporting agency
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:

Abbreviations of reporting agencies are as follows:

1. BLS = Bureau of Labor Statistics.
2. BC = Bureau of Census.
3. BEA = Bureau of Economic Analysis.
4. CB = Conference Board.
5. ETA = Employment and Training Administration.
6. FRB = Federal Reserve Board.
7. DT = Department of the Treasury.
8. NAPMCI = National Association of Purchasing Management, Chicago Affiliate.
9. DL = Department of Labor.
10. EC = European Commission.
11. ECB = European Central Bank.
12. ME = Markit Economics.
13. SG = Sentix GmbH.
14. ZEW = Zentrum für Europäische Wirtschaftsforschung.
15. CO = Cabinet Office.
16. BOJ = Bank of Japan Research and Statistics Department.
17. MOF = Ministry of Finance.
18. ESRI = Economic and Social Research Institute.
19. 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.

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