Journal of International Money and Finance 79 (2017) 232–254

Contents lists available at ScienceDirect

Journal of International Money and Finance

journal homepage: www.elsevier.com/locate/jimf

Macroeconomic announcements and price discovery in the foreign exchange market ☆

Yin-Feng Gau *, Zhen-Xing Wu

Department of Finance, National Central University, 300 Jhongda Rd., Jhongli, Taoyuan, Taiwan

A R T I C L E   I N F O

Article history:
Available online 1 September 2017

JEL classification:
F31
G14
G15

Keywords:
Price discovery
Realized variance
Macroeconomic announcements
Foreign exchange market
Electronic Broking Services (EBS)

A B S T R A C T

This study shows that the dominance of the overlapping trading hours of London and New York in the price discovery of the EUR/USD and USD/JPY markets only applies on days with U.S. announcements. Different from Cai et al. (2008) and Wang and Yang (2011), we highlight the informational advantage of local traders at the arrival of macroeconomic announcements in the local market, and find that macroeconomic announcements affect the pattern of price discovery across different markets, consistent with Chen and Gau (2010) and Jiang et al. (2012). We also examine changes in information shares before and after the announcement. A significant increase in price discovery before the announcement suggests the possibility of information leakage, while enhanced price discovery efficacy after the announcement suggests that prices gradually adjust to new information, not just immediately respond to the arrival of announcements.

1. Introduction

The price discovery function of a market reflects its informational efficiency that involves how fast prices react to the arrival of news information. In the foreign exchange (FX) market, the world's largest financial market, trading takes place over 24 h in multiple markets in Asia, Europe, and the United States. The contribution to the price discovery of these different markets might vary by the trader composition and the market mechanism.[1]

In the FX market, how new information is transmitted into prices across the 24-h trading process remains an important issue; trading activities are distributed around the globe and over the entire 24 h of each day. If informed traders are more

☆ We thank the editor, Kees Koedijk, two anonymous referees, Yuanchen Chang, Shiu-Sheng Chen, Robin Chou, Ji-Chai Lin, Ghon Rhee, and Jin-Huei Yeh for helpful comments and suggestions. Any errors or omissions are our own. Yin-Feng Gau gratefully acknowledges a research grant from the Ministry of Science and Technology (104-2410-H-008-014-MY3).

* Corresponding author.
E-mail addresses: yfgau@ncu.edu.tw (Y.-F. Gau), loveaf1225@gmail.com (Z.-X. Wu).

[1] Ito and Hashimoto (2006) show that trading activities during Asian, European, and U.S. business hours mainly are conducted by local participants; heterogeneous traders across different trading regions behave differently. Several previous studies investigate price discovery across different traders and trading sessions in the FX market, which is relevant to the distribution of informed trading in currency markets over a 24-h trading day (Sapp, 2002; D'Souza, 2007; Cai et al., 2008; Menkhoff and Schmeling, 2008; Wang and Yang, 2011; Menkhoff et al., 2016). In fact, both the trading mechanism and the composition of traders in a market may affect its price discovery efficacy. Thanks for the referee for pointing out this. However, it is not easy to identify the reason why the price discovery ability differs with trading hours by using the EBS data we have. Since we do not have the data of trader identity, we can only measure the pricing efficiency from the data of quotes and trading prices. Thanks for the referee for pointing out this.

https://doi.org/10.1016/j.jimonfin.2017.08.006

active in specific trading periods, different price discovery capabilities would emerge over the course of a trading day. Therefore, it is essential to study competition in price discovery across the Asian, European, and North American markets.

As macroeconomic news affects currency prices, the arrival of macroeconomic announcements can affect the price discovery process in the FX market.[2] The effect of macroeconomic news announcements on the relative contribution of different trading regions to the currency price discovery can reveal the relative informational efficiency of home-trading hours against other trading regions. Using the intraday trading data of EUR/USD and USD/JPY from Electronic Broking Services (EBS), we investigate how market-specific contributions to price discovery among the four sequential markets: Asian, European, London + New York (L + NY), and U.S. surrounding the release of macroeconomic announcements in the United States, Europe, and Japan.

Price discovery may vary with trading hours. With new information disclosures, more information gets injected into the market. Agents react to this new information and the trading price will be adjusted toward the fundamental value. Therefore, how fast the new information is incorporated into prices reflects the price discovery efficacy during the specific time period.[3]

Previous studies that explore the informational efficiency in sequential trading regions in the FX market generally focus on the relative contribution to price discovery, relative pricing errors, or information spillover among regions. Wang and Yang (2011) examine the price discovery contributions over four sequential trading regions in the FX market and find that the information share of the overlapping trading hours in London and New York is greater than that of the other three trading markets. Piccotti (2016) compares pricing errors among different trading regions in the FX market, and shows that pricing errors in exchange rates are largest during Asian trading hours and decreases until London-New York overlapping trading hours. Cai et al. (2008) study informational linkage across trading regions in the EUR/USD and USD/JPY markets by examining the spillover in trading activities, returns, and volatility among regions, and they find the evidence of spillovers of order flows from hours when the London and New York markets overlap, onto other trading periods.

However, these above studies do not characterize the effect of macroeconomic announcements on the price discovery across sequential and partially overlapping trading hours in the FX market. To comprehensively explore how price discovery pattern shifts when currency prices respond to new public news, we include major macroeconomic announcements, in the United States, Europe, and Japan. Examining the shift in price discovery also allows us to test the phenomenon of home-market advantage in the FX market argued in Ito and Hashimoto (2006) or the information advantage of home market traders addressed in Covrig and Melvin (2002). Recently, Piccotti (2016) also argues that the lower trading cost traders face during home trading hours allow traders in the home market to price their home currency more efficiently.[4]

In the FX market, most macroeconomic announcements are released at the first hour of business for each country. Although the FX trading is a 24-h market composed of sequential and partially overlapping trading in regional centers worldwide, most announcements are released at the first hour of home market for each country. Even though traders flock to periods that feature macroeconomic news releases and traders located in other time zones may react immediately too, traders in their home country may process information more efficiently due to the home-market advantage or less trading cost in response to local macroeconomic news.

Our study is in line with Sapp (2002), Covrig and Melvin (2002), and Hayo and Neuenkirch (2010). Sapp (2002) finds that Deutsche Bank is the price leader following local central bank interventions, whereas Chemical Bank from the U.S. is the leader when there are no interventions. Similarly, Covrig and Melvin (2002) show that the Japanese quotes dominate in price discovery of the USD/JPY market and argue that Japanese traders have superior information on the USD/JPY exchange rate relative to non-Japanese traders. Studying the equity, bond, and FX markets, Hayo and Neuenkirch (2010) also indicate the trading is more relevant in response to local central bank communication than to its U.S. counterpart.

If investors know more about the local macroeconomic information that affects the dynamics of the exchange rates, most information in the local announcements thus will be incorporated into the exchange rates immediately, and we expect the price discovery will be enhanced significantly when local announcements are released. Yet Andersen et al. (2003), Ehrmann and Fratzscher (2004), and Hashimoto and Ito (2010) all show that U.S. macroeconomic announcements have a relatively greater impact on exchange rates than do other regions' macroeconomic announcements.

Ultimately though, the effects of various macroeconomic announcements on intraday price discovery patterns in FX markets remain uncertain. In 2007–2008, the financial crisis spilled over and became the catalyst for a broader global economic crisis. Narayan et al. (2014) find that the price discovery of CDS (credit default swaps) and equity returns is affected by the 2007 global financial crisis. As addressed in Narayan et al. (2014), the global financial crisis can be regarded as a persistent financial shock that is featured with a queue of 'mini-crises' since the onset of the financial crisis in 2007. Therefore, shocks emanating from the financial crisis are likely to be transmitted more strongly during the crisis period (see Brunnermeier and Pedersen, 2009) and may affect the price discovery of asset markets.

Longstaff (2010) also examines the information incorporation process across different markets as the subprime crisis gave way to the global financial crisis, and finds that liquidity shocks actually tend to be transmitted from less to more liquid mar-

[2] The intraday pattern of exchange rate returns, volatility, sand trading activity in the FX market shifts with the arrival of macroeconomic news (Almeida et al., 1998; Andersen and Bollerslev, 1998; Andersen et al., 2003; Ehrmann and Fratzscher, 2004; Faust et al., 2007; Hashimoto and Ito, 2010; Evans and Speight, 2011; among others).

[3] Barclay and Hendershott (2003) and He et al. (2009) study the effects of trading in different trading sessions on the magnitude and timing of price discovery and the extent of information asymmetry in equity and bond markets, respectively. They find that trading activities before and after regular trading hours contain more information than those during the day and also can generate significant price discovery.

[4] Local information advantages may enable local traders to interpret the information content of local news better than non-local traders and perform better in trading (Coval and Moskowitz, 2001; Hau, 2001; Ivković and Weisbenner, 2005; Baik et al., 2010).

kets, in the way of "flight to quality." As liquidity is one of determinants of price discovery, the liquidity shocks raised by the financial crisis may lead the price discovery in currency markets to change during the crisis period.

Carry trades in the FX market may also cause the currency price discovery to change during the crisis. Carry trading strategies involve borrowing currencies requiring the payment of low interest rates (funding currencies), such as the yen, Swiss franc, and euro, and investing such funds in currencies paying out high interest rates, such as Austrian dollar and the British pound (Galati et al., 2007). During the crisis period, the shock in the asset value affects a trader's portfolio value, which can lead to an increase in the probability of margin calls and a reduction in the supply of funds to traders, and then results in greater funding constraints in the currency markets (Melvin and Taylor, 2009). Traders adopting carry trade strategies may be forced to partially liquidate the portfolio, imposing additional price pressures on the asset. Therefore, the price discovery ability in the FX market may be affected during the financial crisis.

Following Wang and Yang (2011), we use the information share measures based on the variance ratio, and find that the European and U.S. overlapping trading hours (L + NY) dominate price discovery. The results show that, L + NY, the overlapping trading hours of London and New York, dominates price discovery across the entire sample.

When major U.S. scheduled macroeconomic announcements are released, we find that the price discovery dominance of L + NY still holds. However, on days without U.S. announcements, trading in the European trading period leads price discovery over the four sequential markets. We find evidence that macroeconomic announcements affect the pattern of price discovery across different markets, consistent with Chen and Gau (2010) and Jiang et al. (2012).[5]

Nevertheless, we do not find similar conclusion that home-trading hours provide more price discovery when macroeconomic announcements are released in home country, for the case of Japanese and European announcements, respectively. We instead find that the release of European and Japanese announcements does not affect the dominant role of the L + NY market.

Changes in the information environment may occur before or after an announcement (Riordan et al., 2013).[6] Scheduled macroeconomic announcements are released periodically; between announcement times, traders can obtain private information and face adverse-selection risk. On the other hand, trading prices around announcements tend to be noisy, due to speculation by agents and agents' heterogeneous interpretation of the information (Xiong and Yan, 2010; Jiang et al., 2012). Therefore, we further examine whether information shares before and after the announcement differ.

A significant increase in price discovery before the announcement suggests the possibility of information leakage. Huberman and Schwert (1985), Bhattacharya et al. (2000), and Bernile et al. (2016) achieve similar results when they study the impact of announcements in bond markets and stock markets. We also find evidence that price discovery efficacy changes following announcements, which suggests that prices gradually adjust to new information, not just immediately respond to the arrival of macroeconomic announcements. A possible explanation for the lagged effect of announcements on price discovery is that uninformed traders may cloud the fundamental value signals of informed traders, so announcement-relevant information is not incorporated into exchange rates immediately after the announcement.

The remainder of this article is organized as follows: Section 2 details the FX market structure, the EBS exchange rate data, and macroeconomic announcements from the United States, Europe, and Japan. Section 3 introduces the measure of information share based on the approach of variance ratio and interprets the empirical model used to estimate determinants of price discovery. Section 4 reports the empirical results regarding the information share of trading hours, and reports the robustness check with the weighted price contribution. Section 5 concludes.

2. FX market structure and data

2.1. FX market structure

The FX market is the most liquid financial market in the world. According to BIS (2013), daily average turnover in global FX markets reached \$5.3 trillion in April 2013, which is 32.5% higher than in 2010. In addition, turnover of spot transactions increased from \$1.5 trillion in April 2010 to \$2 trillion in April 2013, representing a 33% growth rate.

Trading in these FX market starts in Asia, moves to Europe and London, and then ends in the United States every day, over a 24-h period. Due to the limitation of data, we are unable to track the location of a trade occurs. We can only learn the timing of each quote and trade in the EBS data. Most related studies, including Cai et al. (2008), Wang and Yang (2011), Piccotti (2016) and others, can only break out the 24-h trading into four or five trading-hour segments related to regional trading sessions. Therefore, our analysis focuses on disentangling the impact of timing in the 24-h trading.

[5] Chen and Gau (2010) show that the relative contribution to price discovery of FX spot and futures markets changes when macroeconomic announcements are released. By dividing the 24 h into four periods: 7:00–9:30 (before market open), 9:30–16:00 (regular trading hours), 16:00–18:30 (after-hours trading), and 18:30–7:00 (overnight), Jiang et al. (2012) show that the price discovery contribution of regular trading hours is lower than that of after-hours trading when news gets released after trading hours.

[6] Using data from the Toronto Stock Exchange, Riordan et al. (2013) investigate the impact of news on intraday price discovery, trading activity, and liquidity of stocks and find that newswire messages with both negative and positive content, in general, have significant impacts on trading in an electronic limit order market. The evidence of higher adverse selection costs around news messages suggests that information is gathered before news arrivals, and market participants have differential information processing capabilities after news arrivals.

We divide 24 trading hours into four market segments, following Wang and Yang (2011): Asian, European, and U.S. trading hours and the overlapping trading hours in London and New York. In winter time, the scenario for the four markets we consider on day *t* is as follows: Asian market opens at 23:00 GMT and closes at the point when the European market opens (i.e., 7:00 GMT), the European market closes at the point when the L + NY market opens at 13:00 GMT, and the L + NY market closes at the time when the U.S. market opens at 15:00 GMT.

We also consider the daylight saving time shift in Europe and the United States. Fig. 1 summarizes the Greenwich Mean Time (GMT) hours and corresponding local times for Tokyo, London, and New York in three panels, separated into normal time (winter), daylight saving time (summer), and the period when New York is under daylight saving time but London is not.[7] Fig. 2 supplements the opening and closing hours of the major worldwide FX trading locations.

2.2. Macroeconomic announcement data

We start with U.S. macroeconomic announcements from Andersen et al. (2003). We augment the list of announcements by including important macroeconomic announcements related to national economic activity, consumption, investment, prices, international economics, and the forward-looking index from U.S., Europe and Japan. Macroeconomic announcement data are collected from the Thomson Reuters Datastream.[8]

Table 1 provides a basic description of the announcement releases, including the number of observations, the agency reporting the news, and the time of the release. We consider 32 U.S. announcements, 28 European announcements, and 16 Japanese announcements between 2008 and 2012. The announcements we consider can be categorized into seven groups: real activity, GDP constituents (consumption, investment, government expenditure and net exports), prices, and forward-looking indicators.

Among the U.S. announcements, nineteen are released at 8:30 Easter Standard Time (EST), two at 9:15 EST, one at 9:45 EST, seven at 10:00 EST, one at 14:00 EST, one at 14:15, and one is released at 15:00 EST. Most of the U.S. announcements are released during the L + NY overlapping trading period. Most of the European announcements are usually released at 10:00 Western European Time (WET), corresponding to the European trading period. Most of the Japanese announcements are released at 8:50 Japanese Standard Time (JST).

2.3. EBS exchange rate data

This study focuses on the two most liquid currency-pairs, EUR/USD and USD/JPY, in the FX market. Their trading data span from January 1, 2008 to December 31, 2012. The BIS (2013) reveals the rapidly increasing popularity of electronic trading systems in FX trading. Although there are two primary global FX systems, EBS and Reuters D2000-2 (or D3000),[9] EUR/USD and USD/JPY are mostly traded in EBS. Ito and Hashimoto (2006) also note that the market share (in absolute value) for trading USD/JPY in the EBS is greater than in the D2000-2.[10] We therefore focus on these two most active currencies and use the EBS database.

For each transaction, EBS records the (1) date and time, (2) deal or quote indication, (3) ask/bid prices of quotes or the executed prices of trades, (4) trading volume, and (5) direction of the trades.[11] The quote price in EBS is the best bid and best ask of the market; that is, the bid and ask quotes include commitments to trade if someone on the other side has a credit line with the quote. The EBS screen also presents the deal prices on the bid side or the ask side. To avoid confounding the evidence in the correlation analysis, we excluded all data from weekends and holidays, which feature decidedly slower trading patterns. As suggested by Ito and Hashimoto (2006), we delete all holidays from the sample and also exclude observations with a larger bid price than the corresponding ask price.

Considering the different effect of various kinds of news announcements, we also separate days into those with U.S., European, or both types of releases and those without any scheduled news in the EUR/USD market. The groups thus include 368 days with U.S news announcements only, 178 days with European news announcements only, 462 days with both U.S. and European news announcements, and 143 days without any scheduled news release. We similarly divide the trading days in the USD/JPY market into four categories, depending on their news announcements, and obtain groups of 264, 194, 596, and 128 days, respectively.

[7] Specifically, U.S. (UK) daylight saving time in 2008 was from March 9 to November 2 (March 30 to October 26); in 2009, from March 8 to November 1 (March 29 to October 25); in 2010, from March 14 to November 7 (March 28 to October 31); in 2011, from March 13 to November 6 (March 27 to October 30); and in 2012, from March 11 to November 4 (March 25 to October 28).

[8] Thomson Reuters Datastream provides consensus forecasts results from the Reuters Economics Polls for global key economic indicators. Reuters Poll collects forecasts from economists and financial markets strategists from the sell-side as well as buy-side, plus independent researchers and some academics. Thomson Reuters reports consensus forecast (usually median), high, low and number of forecasters. Therefore, we can construct macroeconomic news surprises relative to the consensus forecasts with the announced figures of economic indicators.

[9] The BIS (2013) reveals that electronic trading accounts for 55% of all FX transactions and that 64% of spot transactions are conducted on the electronic trading platform.

[10] This domination is likely a result of EBS's acquisition of Minex, developed by the Tokyo Bank in 1995, which had a large market share for FX trading in Asia.

[11] The EBS screen provides the best bid and ask prices for trades greater than 1 million, and its execution speed is fast, resulting in higher transparency. However, the information still is limited to the best bid and ask prices.

GMT	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Normal (Winter)																								
Asian trading period (Tokyo local time)	**9**	**10**	**11**	**12**	**13**	**14**	**15**	16	17	18	19	20	21	22	23	0	1	2	3	4	5	6	7	**8**
European trading period (London local time)	0	1	2	3	4	5	6	7	**8**	**9**	**10**	**11**	**12**	**13**	14	15	16	17	18	19	20	21	22	23
European-US overlapping trading period (London local time)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	**14**	**15**	16	17	18	19	20	21	22	23
US trading period (New York local time)	–19	–20	–21	–22	–23	0	1	2	3	4	5	6	7	8	9	10	**11**	**12**	**13**	**14**	**15**	**16**	**17**	18
Daylight saving time (Summer)																								
Asian trading period (Tokyo local time)	**9**	**10**	**11**	**12**	**13**	**14**	**15**	16	17	18	19	20	21	22	23	0	1	2	3	4	5	6	7	**8**
European trading period (London local time)	1	2	3	4	5	6	7	8	**9**	**10**	**11**	**12**	**13**	14	15	16	17	18	19	20	21	22	23	0
European-US overlapping trading period (London local time)	1	2	3	4	5	6	7	8	9	10	11	12	13	**14**	**15**	16	17	18	19	20	21	22	23	0
US trading period (New York local time)	–20	–21	–22	–23	0	1	2	3	4	5	6	7	8	9	10	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	19
Daylight saving time in New York only																								
Asian trading period (Tokyo local time)	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	17	18	19	20	21	22	23	0	1	2	3	4	5	6	7	**8**
European trading period (London local time)	0	1	2	3	4	5	6	7	8	**9**	**10**	**11**	**12**	13	14	15	16	17	18	19	20	21	22	23
European-US overlapping trading period (London local time)	0	1	2	3	4	5	6	7	8	9	10	11	12	**13**	**14**	**15**	16	17	18	19	20	21	22	23
US trading period (New York local time)	–20	–21	–22	–23	0	1	2	3	4	5	6	7	8	9	10	11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**

Fig. 1. Definition of four sequential markets. This figure illustrates the division of the trading hours for four sequential markets. Bold font denotes local trading hours in local time.

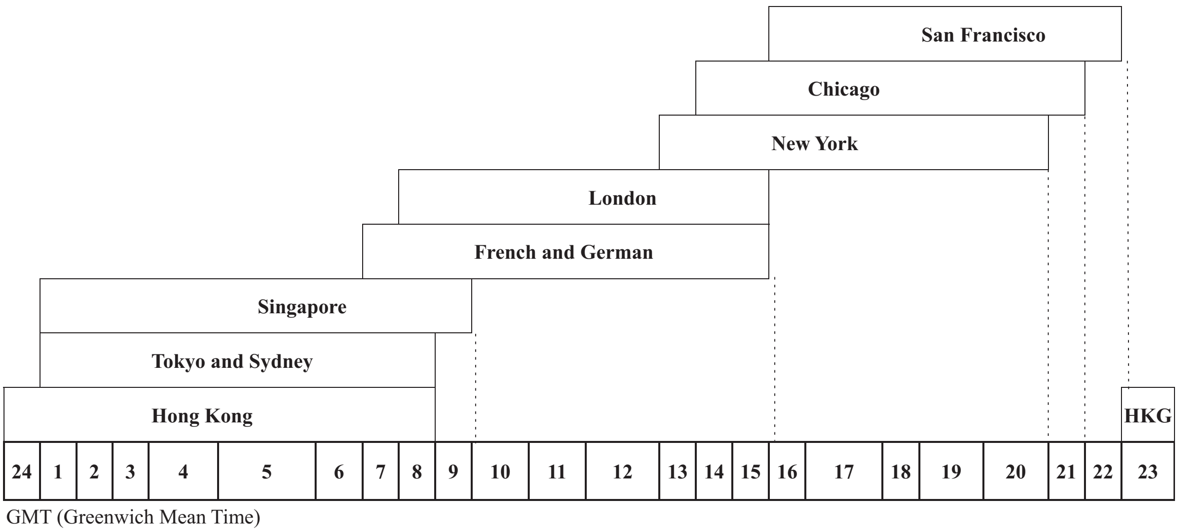

Fig. 2. Global currency trading: the trading day. The currency trading day extends 24 h per day.

Fig. 3 shows the intraday variation in average hourly trading volume initiated by buyers and sellers, respectively, in the EUR/USD and USD/JPY markets. It illustrates the intraday variation in trading activities during a day.

Table 2 contains the summary statistics for trading activities for EUR/USD and USD/JPY for all four trading periods. We consider the effective spread and hourly trading volume for each market.[12] The effective spread is the average of $2|(p_{iz} - q_{iz})/q_{iz}|$ of all interval z during each market on day t, where p_{iz} and q_{iz} are the trading price and the mid-quote price at time interval z of market i.

[12] We calculate the hourly trading volume for each trading period, because the four regions we study have different trading hours. A trading period may have a higher trading volume simply due to its long trading hours. Therefore, we use average hourly trading volume for comparison.

Table 1
Macroeconomic announcements (January 2008–December 2012).

Announcement	Announcement time	Reporting agency	Number of observations
US announcements			
1. Current Account Balance	8:30 EST	BEA	20
2. Durable Goods Orders	8:30 EST	BC	56
3. Existing Home Sales	10:00 EST	BC	52
4. Factory Orders	10:00 EST	BC	53
5. FOMC Rate Decision	14:15 EST	FRB	30
6. GDP Price Index	8:30 EST	BEA	57
7. House Price Index	10:00 EST	BC	51
8. Housing Starts	8:30 EST	BC	59
9. Import Price Index	8:30 EST	BEA	60
10. Industrial Production	9:15 EST	FRB	59
11. Initial Jobless Claims	8:30 EST	ETA	248
12. Leading Index	8:30 EST	CB	55
13. Monthly Budget Statement	14:00 EST	DT	46
14. New Home Sales	10:00 EST	BC	55
15. PCE Cor	8:30 EST	BEA	51
16. PCE Deflator	8:30 EST	BEA	51
17. Personal Consumption	8:30 EST	BEA	57
18. Personal Income	8:30 EST	BEA	51
19. Personal Spending	8:30 EST	BEA	51
20. PPI	8:30 EST	BLS	61
21. Retail Sales Advance	8:30 EST	BC	60
22. Business Inventories	10:00 EST	BC	60
23. Trade Balance	8:30 EST	BEA	57
24. Unemployment Rate	8:30 EST	ETA	58
25. Capacity Utilization	9:15 EST	FRB	59
26. Manufacture Payrolls	8:30 EST	BLS	58
27. Nonfarm Payrolls	8:30 EST	BLS	58
28. Chicago PMI	9:45 EST	NAPMCI	57
29. Construction Spending	10:00 EST	BC	55
30. Consumer Confidence Index	10:00 EST	CB	57
31. Consumer Credit	15:00 EST	FRB	37
32. Continuing Claims	8:30 EST	DL	248
European announcements			
33. Business Climate Indicator	10:00 WET	EC	60
34. Construction Output	10:00 WET	Eurostat	60
35. Consumer Confidence	10:00 WET	EC	60
36. CPI Core	10:00 WET	Eurostat	60
37. Current Account NSA	9:00 WET	ECB	60
38. ECB Current Account SA	9:00 WET	ECB	60
39. Economic Confidence	10:00 WET	EC	60
40. Employment	10:00 WET	Eurostat	30
41. EU27 New Car Registrations	7:00 WET	ECB	56
42. GDP	10:00 WET	Eurostat	20
43. Govt Debt/GDP Ratio	10:00 WET	Eurostat	20
44. Govt Expenditure	10:00 WET	Eurostat	20
45. Gross Fixed Capital Formation	10:00 WET	Eurostat	20
46. Household Consumption	10:00 WET	Eurostat	20
47. Industrial Confidence	10:00 WET	EC	60
48. Industrial Production	10:00 WET	Eurostat	60
49. Money Supply	9:00 WET	ECB	60
50. PMI Composite-A	9:00 WET	ME	60
51. PMI Manufacturing-A	9:00 WET	ME	60
52. PMI Services-A	9:00 WET	ME	60
53. PMI Services-F	9:00 WET	ME	60
54. PPI	10:00 WET	Eurostat	60
55. Retail Sales	10:00 WET	Eurostat	60
56. Sentix Investor Confidence	9:30 WET	SG	60
57. Services Confidence	10:00 WET	EC	60
58. Trade Balance	10:00 WET	Eurostat	60
59. Unemployment Rate	10:00 WET	Eurostat	60
60. ZEW Survey Expectations	10:00 WET	ZEW	60
Japanese announcements			
61. Capital Spending	8:50 JST	MOF	20
62. Coincident Index	14:00 JST	CO	60
63. Domestic CGPI	8:50 JST	MIC	58
64. GDP	8:50 JST	CO	20

(*continued on next page*)

Table 1 (*continued*)

Announcement	Announcement time	Reporting agency	Number of observations
65. Housing Starts	14:00 JST	BOJ	53
66. Industrial Production	8:50 JST	METI	55
67. Jobless Rate	8:30 JST	MIC	57
68. Large Retailers' Sales	8:50 JST	CO	54
69. Leading Index	14:00 JST	MOF	58
70. Machine Orders	8:50 JST	ESRI	59
71. Money Supply M2	8:50 JST	BOJ	54
72. Trade Balance	8:50 JST	MOF	58
73. Tokyo CPI	8:30 JST	MIC	56
74. Tankan Large Mfg Index	8:50 JST	BOJ	20
75. Tankan Large Non-Mfg Index	8:50 JST	BOJ	20
76. Retail Sales	8:50 JST	METI	56

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

Comparing the trading activities across the four trading periods, we find the effective spread in the Asian and U.S. periods is significantly greater than that in the European and L + NY periods for both EUR/USD and USD/JPY (Panel A, Table 2), at the 10% level of significance. Furthermore, hourly trading volumes in the European and L + NY trading periods are significantly greater than those in the Asian and U.S. periods, at the 1% level of significance, suggesting that the market liquidity of the European and L + NY periods is better than that of the other two markets. Overall, the trading volume in the L + NY period is highest among the four trading periods.

As Panel B of Table 2 displays, the effective spread in L + NY period is the smallest, whereas the U.S. period is the largest, for the USD/JPY market. The trading volume results are similar, in that trading volume in the L + NY period is the greatest, followed by the European period and the Asian period, and the U.S. period is the smallest. Our comparison of trading activity in the USD/JPY market confirms that the L + NY period is the most liquid. These findings regarding the trading activity patterns are reasonable, in that London and New York are widely regarded as the most important financial centers for FX trading.

To find the news effects on trading activity in the FX market, we examine the spread and trading volume on days with and without announcements. Panel A of Table 2 shows that the mean of the effective spread for the Asian period on days with U. S. and European announcements only is greater than that on days without announcements, although insignificantly. Although the spread on days with both U.S. and European announcements is not greater than those on days without any announcements, the spread in the Asian period is largest on days with both U.S. and European announcements. This finding is consistent with Chae's (2005) assertion that traders suspect the increase in information risks before the news is even released, and the spread is wider before the announcement.

Panel A of Table 2 also shows that spreads decrease on days with European and U.S. announcements for the European, L + NY, and U.S. periods, although insignificantly. We conjecture that this result reflects information asymmetry. However, we cannot state conclusively whether the increase in information risk takes place before or after the announcements. Rather, we note that information asymmetry could decrease in the several hours following the European macroeconomic announcements, because spreads in the L + NY and U.S. periods become smaller on days with European announcements, which are scheduled to release before the L + NY and U.S. trading periods.

Panel B of Table 2 shows that the spreads in Asian and European periods are greater on days without announcements than on days with U.S. and Japanese announcements, respectively. In support of Chae's (2005) prediction, our results indicate that traders suspect the forthcoming news and enlarge their spreads to avoid information risk. Panel B also indicates that the spreads of European and L + NY periods are smaller on days with Japanese announcements, which could be because the announcements reduce the information asymmetry risk. Thus, our results for both EUR/USD and USD/JPY support the prediction offered by Tetlock (2010), namely, that public announcements resolve asymmetric information.

For EUR/USD, the trading volume of the Asian market (see Panel A, Table 2) is higher on days with U.S. and European announcements than on days without announcements, at the 10% level of significance. Compared with days without announcements, the trading volumes of the European, L + NY, and U.S. periods diminish on days with U.S. and European announcements. The hourly trading volumes in the L + NY and U.S. markets decline on European announcement days; these trading hours are after the news releases. This evidence may be explained by Admati and Pfleiderer (1988) that argue trading volume decreases with information asymmetry, such that discretionary liquidity traders might delay their trading until the

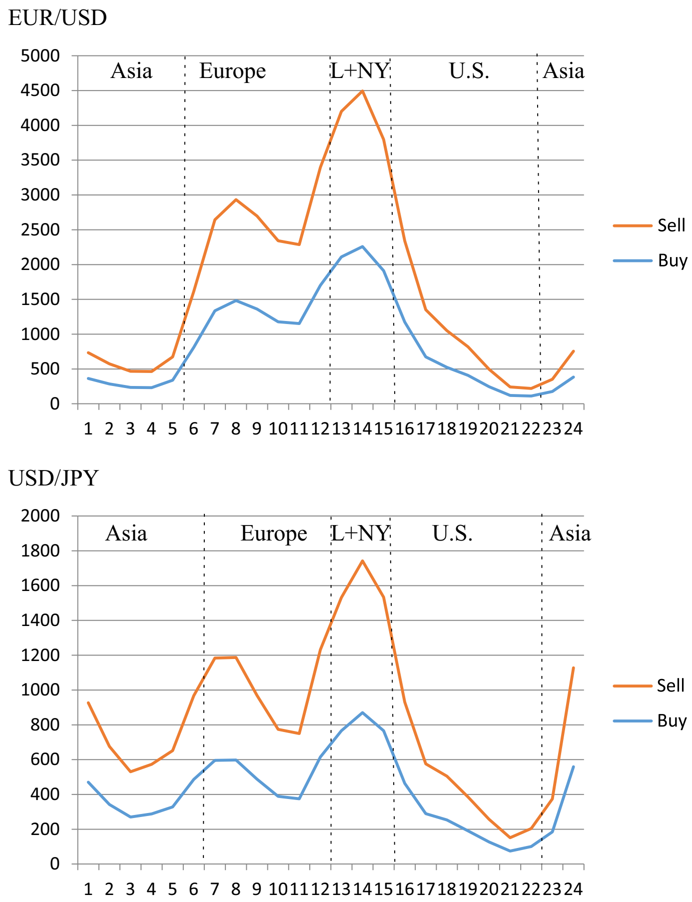

Fig. 3. Average hourly trading volume. This figure shows means of hourly trading volume (in million) initiated by buyers and sellers in the EUR/USD and USD/JPY markets.

announcement, and information asymmetry gets resolved because they receive exogenous trade demands prior to the announcements.

Panel A indicates that spreads in European, L + NY, and U.S. periods increase on days with local news. The evidence of increased trading cost at the news announcement supports Kim and Verrecchia (1994) that predicts news announcements increase heterogeneity, because some investors have information advantages about the forthcoming or soon-to-be released news.

Chae (2005) also suggests that the trading volume falls after the news announcement if the information asymmetry gets resolved after the news is announced. Therefore, Chae concludes that trading volume is negatively correlated with levels of information asymmetry before scheduled announcements, but the relation flips after scheduled announcements. Consistent with this assertion, Panel A indicates that the level of spread, which is a proxy for information asymmetry, becomes smaller after European announcements in the L + NY and U.S. periods.

In the USD/JPY market, trading volumes in Asian and European periods, which are before U.S. announcements, are significantly greater on days with U.S announcements (at the 10% level of significance) and on days with both U.S. and Japanese news (at the 5% level of significance) than on days without scheduled news releases (Panel B, Table 2). In contrast with Admati and Pfleiderer (1988), Kyle (1985) shows that trading volume increases with information asymmetry, which may be because informed traders attempt to exploit their private information. In addressing these mixed results from prior literature, our findings indicate that in EUR/USD and USD/JPY markets, the relationship between trading volume and information risk might shift with the conditions of a specific market.

Panel B reports another different result compared with Panel A of Table 2. That is, mean trading volume in the Asian period does not change on Japanese announcement days, but it increases in the L + NY and U.S. periods on days that U.S. macronews gets announced. Ito and Hashimoto (2006), using the EBS data, find that the trading volume and price volatility do not significantly increase around Japanese announcements but become significantly larger with the U.S. announcements. We also find that trading volume in the European, L + NY, and U.S. periods significantly decreases on days with Japanese

Table 2
Summary statistics for trading activities. The data cover the period from January 2008 to December 2012. We divide each 24 h of trading into four markets in winter time as follows: 23:00–07:00 GMT (Asian period), 7:00–14:00 GMT (European period), 14:00–16:00 GMT (overlapping hours of London and New York, L + NY), and 16:00–23:00 GMT (U.S. period). We adjust the ranges of trading hours in response to the daylight saving time (DST) shift in the European and U.S. regions in summer. The sample period is further separated into four subperiods: days including U.S. announcements only, days including European (or Japanese) announcements only, days including both U.S. and European (or Japanese) announcements, and days without announcements for EUR/USD (or USD/JPY). We report the mean of the effective spread and volume in the four markets. $Spread_{i,t}$ is the relative effective spread of the corresponding market on day t, calculated as the average of $2|(p_{iz} - q_{iz})/q_{iz}|$ during each market on day t, where p_{iz} and q_{iz} are the trading price and quote price at time interval z of market i, respectively. Volume is the hourly trading volume in millions of U.S. dollars.

	All days	Days without announcements	Days with U.S. announcements	Days with European (Japanese) announcements	Days with both announcements
Panel A. EUR/USD					
Spread					
Asian	5.88	5.84	5.87	6.07	5.83
European	5.59	5.54	5.59	5.59	5.60
L + NY	5.60	5.53	5.61	5.52	5.65
US	5.99	5.84	5.88	5.59	6.23
Volume					
Asian	508	525	495	503	515
European	1632	1612	1607	1629	1659
L + NY	2311	2261	2304	2260	2351
US	740	745	730	711	757
Panel B. USD/JPY					
Spread					
Asian	7.81	7.83	7.88	7.88	7.79
European	7.38	7.25	7.49	7.25	7.41
L + NY	7.34	7.23	7.43	7.11	7.40
US	8.15	8.04	8.25	8.05	8.16
Volume					
Asian	547	523	535	523	565
European	700	677	696	652	724
L + NY	1080	1045	1092	961	1123
US	362	352	376	333	369

announcements, at the 10% level of significance. Therefore, it appears that U.S. announcements is more influential than Japanese announcements in the USD/JPY market.

3. Empirical models

Wang and Yang (2011) find that the measure of the variance ratio can proxy for information shares for non-overlapping sequential markets within 24-h trading in the FX market. Using the variance ratio calculated from realized variances, we therefore obtain daily information shares for the four sequential markets separately. Unlike Wang and Yang (2011), who examine the overall information share of four sequential markets in the 24-h FX trading period, we study the information share on announcement days and non-announcement days separately. We also use the regression analysis to examine the association of information shares with news announcements and market quality variables. Furthermore, to ensure the robustness of our measures, we examine the effect of the financial crisis on the information share pattern.

3.1. Information shares measured by the realized variance

Studies of price discovery mostly examine the function of price discovery across multiple simultaneous markets. Using the vector autoregression (VAR) framework, the information share approach proposed by Hasbrouck (1995) and Gonzalo and Granger (1995) is widely applied in price discovery studies.[13] Hasbrouck (1995) indicates that trading price p_t can be written as $p_t = m_t + u_t$, where m_t is the efficient price, reflecting new information about the fundamental value, and u_t is a noise term, indicating a transitory change in prices. Then the information flow can be measured by the variation in the efficient price. Following Hasbrouck (1995), Wang and Yang (2011) modify that the information share of a particular time zone can be calculated by its share of the total variance of the efficient price in a trading day.

[13] Barclay et al. (1990) argue that a large trading volume is required before private information can be incorporated into prices. Barclay and Hendershott (2008) use the weighted price contribution to gauge the extent of price discovery and find that the fraction of trading, log market capitalization, and trading volume affect price discovery efficacy. They also suggest that informed traders with a low intraday rate of information decay delay their trades until uninformed traders are more active and trading costs are lower. In addition, Jiang et al. (2012), using a cross-sectional regression analysis, find a positive relation of price discovery with trading volume, news surprise, firm size, and effective spread.

For the four sequential non-overlapping markets (or trading-periods) during a 24-h trading day, we denote $p_{i,t}$ as the closing price of market i, where $i = 1, 2, 3, 4$ indicates the Asian, European, L + NY, and U.S. markets (or periods), respectively, for day t. The closing price of each market $p_{i,t}$ can be written as $p_{i,t} = m_{i,t} + u_{i,t,}$ where $m_{i,t}$ is the efficient price reflecting the fundamentals, and $u_{i,t}$ is a noise term attributed to transitory shocks. Changes in the efficient price in market 1 is $\Delta m_{1,t} = m_{1,t} - m_{4,t-1}$, and changes in the efficient price in market i (for $i = 2, 3, 4$) is $\Delta m_{i,t} = m_{i,t} - m_{i-1,t}$. As noted in Wang and Yang (2011), with respect to the information set available at the opening of market i on day t, $\Delta m_{i,t}$ is a martingale difference; therefore, $\Delta m_{i,t}$ and $\Delta m_{j,t}$ (for $i \neq j$) are uncorrelated with each other over time. The change of the efficient price over day t is $\Delta m_t = m_{4,t} - m_{4,t-1} = \Delta m_{1,t} + \Delta m_{2,t} + \Delta m_{3,t} + \Delta m_{4,t}$. Since information flow in market i is measured by the variance of $\Delta m_{i,t}$ (Hasbrouck, 1995), the information share of the ith market during day t can be written as

$$IS_{i,t} = \frac{Var(\Delta m_{i,t})}{Var(\Delta m_t)} = \frac{Var(\Delta m_{i,t})}{\sum_{i=1}^{4} Var(\Delta m_{i,t})} \tag{1}$$

Andersen and Benzoni (2008) show that the conditional variance of the efficient price over a period can be measured by the integrated variance when the efficient price is treated as a continuous time process. Dividing Market i into M_i sampling intervals, returns in market i on day t over sampling interval s can be written as $r_{i,t,s} = \Delta m_{i,t,s} + \Delta u_{i,t,s}$, where $\Delta m_{i,t,s}$ refers to the change in the efficient price over sampling interval s and reflects the permanent shift in the asset value, and $\Delta u_{i,t,s}$ is the intraday noise in return. When $M_i \to \infty$, $\sum_{s=1}^{M_i} \Delta m_{i,t,s}$, the sum of squared $\Delta m_{i,t,s}$, converges to the integrated variance in market i on day t. However, if we use the usual formula of realized variance (RV), $RV_{i,t} = \sum_{s=1}^{M_i} r_{i,t,s}^2$, to estimate the variance of $\Delta m_{i,t}$, we will obtain a biased and inconsistent estimate for the integrated variance in market i in the presence of noise term $u_{i,t,s}$.

Since the efficient price ($m_{i,t,s}$) and the noise term ($u_{i,t,s}$) are not observable, many approaches have been proposed to remove the impact of noise term on the estimation of the integrated variance. Among these methods, the two-scales (TS) estimator of Zhang et al. (2005) is the first consistent estimator of the integrated variance.[14] Barndorff-Nielsen, Hansen, Lunde, and Shephard (2005) further show the TS estimator can be expressed in the form of Bartlett-type kernel estimator as follows:

$$RV_{i,t}^E = \left[1 - \frac{M_i - H_i}{M_i(H_i + 1)}\right] \sum_{s=1}^{M_i} r_{i,t,s}^2 + \sum_{h=1}^{H_i} \left(1 - \frac{h}{H_i + 1}\right) \sum_{s=h+1}^{M_i - h} (r_{i,t,s-h} r_{i,t,s} + r_{i,t,s+h} r_{i,t,s}) - \frac{\upsilon_{i,t,H_i+1}}{H_i + 1}, \tag{2}$$

where M_i is the number of sampling intervals in market i and H_i is the number of autocovariances (Newey and West, 1994).[15] The adjustment factor υ_{i,t,H_i+1} is defined as $\upsilon_{i,t,1} = 0$ and $\upsilon_{i,t,h} = \upsilon_{i,t,h-1} + (r_{i,t,1} + \ldots + r_{i,t,h-1})^2 + (r_{i,t,M_i-h-2} + \ldots + r_{i,t,M_i})^2$ for $h = 2, \ldots, H_i + 1$.

We use the kernel-based estimator as shown in Eq. (2) to obtain the TS estimator, $RV_{i,t}^E$, for the integrated variance of market i on day t. The information share of market i on day t (for $i = 1, 2, 3, 4$) then is computed as follows:

$$IS_{i,t} = \frac{RV_{i,t}^E}{\sum_{i=1}^{4} RV_{i,t}^E} \tag{3}$$

3.2. Price discovery and macroeconomic announcements

Macroeconomic news has an important role in affecting the dynamics of exchange rates. Ederington and Lee (1993) study the effect of scheduled macroeconomic announcements and find that major price movements in the FX markets take place in the minute after the release of macroeconomic announcements, and then prices are considerably more volatile for about 15 min. Similarly, previous research into announcement effects on prices, volatility, and trading volume shows that news gets immediately impounded into exchange rates after its release (e.g., Andersen et al., 2003; Hashimoto and Ito, 2010; Love and Payne, 2008).We use the announced indicator value and the median market survey expectation to construct announcement surprises. Following Balduzzi et al. (2001), we obtain the standardized news surprise as:

$$S_{k,t} = \frac{|Actual_{k,t} - Expected_{k,t}|}{\sigma(Actual_{k,t} - Expected_{k,t})} \tag{4}$$

[14] By definition, the TS estimator is a linear combination of the standard RVs at two different frequencies: the highest frequency possible and a lower frequency. As addressed in Wang and Yang (2011), the RV at the low frequency can have many ways to calculate, for example, with 1-min returns there are five ways to construct 5-min RV. The estimation error of the average of the low-frequency RVs depends on the variance of the noise term $u_{i,t,s}$. Zhang et al. (2005) prove that the TS estimator, i.e., the linear combination of the high-frequency RV and the average of the low-frequency RVs can correct the impact of noise term on the average of low-frequency RVs and consistently estimate the integrated variance.

[15] For example, there are 96 5-min intervals in the Asian trading period, so M_1 is equal to 96 at the 5-min frequency. When sampled at high frequency, i.e. $M_i \to \infty$, the sum of squared $\Delta m_{i,t}$, $\sum_{s=1}^{M_i} \Delta m_{i,t,s}$, will converge to the integrated variance of market i on day t. The optimal number of autocovariances used in our analysis is determined by the Schwarz information criterion (SIC).

where $Actual_{k,t}$ is the announced actual value of indicator k at time t, $Expected_{k,t}$ is the median forecast value of indicator k provided by Thomson Reuters Datastream, and $\sigma(Actual_{k,t} - Expected_{k,t})$ denotes the standard deviation of the difference between the actual and expected values of indicator k.

To identify whether the release of macroeconomic announcements affects the relative contributions of the Asian, European, L + NY, and U.S. periods on the price discovery of EUR/USD and USD/JPY, we consider the effect of individual announcement from the U.S. and local markets. The model is specified as follows:

$$\begin{aligned}\overline{IS}_{i,t} &= \alpha_0 + \alpha_1 MKT_{1,i,t} + \alpha_2 MKT_{2,i,t} + \alpha_3 MKT_{3,i,t} + \sum_{j=1}^{J}\beta_j S_{j,t} \\ &\quad + \sum_{m=1}^{3}\sum_{j=1}^{J}\lambda_{m,j} \times MKT_{m,i,t} \times S_{j,t} + \delta \times Volatility_{i,t} + \eta \times Spread_{i,t} + \theta \times Volume_{i,t} + \varepsilon_{i,t}\end{aligned} \tag{5}$$

where we use the per-hour information share $\overline{IS}_{i,t}$ of market i on day t in the analysis for normalization. As each trading period has a different number of trading hours, we obtain the per-hour information share by dividing the ith market's information share measured by Eq. (3) by the number of trading hours of the ith market.

We define $MKT_{1,i,t} = 1$ if market i on day t is the Asian market, 0 otherwise. Similarly, $MKT_{2,i,t} = 1$ if market i on day t is the European market, 0 otherwise; $MKT_{3,i,t} = 1$ if market i on day t is the U.S. market, 0 otherwise. $S_{j,t}$ is the standardized news surprise for indicator j ($j = 1, \ldots, 75$) on day t.[16] For the jth indicator, the coefficient on $S_{j,t}$ denotes the contemporaneous effect of the news surprise on day t.

Information might be incorporated into prices before announcements. Huberman and Schwert (1985) find that 85% of the news delivered by consumer price index announcements has been anticipated and incorporated into the prices of Israeli indexed bonds, so no surprises occur on announcement days. Bhattacharya et al. (2000) and Andersen et al. (2003) observe that trading does not react to news on announcement days, suggesting the possibility of information leakage before announcement releases. Bernile et al. (2016) provide evidence of informed trading ahead of macroeconomic announcements, which they propose might be due to information leakage directly from the news media or other insiders' mimicking behavior. Another possible explanation is that some investors have superior abilities to predict and trade, ahead of impending release of announcements.

Prices also might not respond completely to macroeconomic announcements right after the release of announcement. Ederington and Lee (1993) show that exchange rates continue to be slightly more volatile for several hours after news releases. The continuous adjustments likely reflect the gradual releases of public announcements. Huberman and Schwert (1985) find that announcements of the consumer price index account for another 15% adjustment of the Israeli indexed bonds in the 15 days after the announcement. According to Marshall et al. (2012), implied volatility increases not only on the announcement day but also for the five days surrounding the scheduled announcements, which may be a result of the clustering of information arrival and gradual learning about information. Bauwens et al. (2005) study the impact of nine categories of scheduled and unscheduled news announcements on the EUR/USD volatility and find that volatility increases both before and after announcement days.

We also incorporate market quality variables into the regression model. As noted in Kaul and Sapp (2009), trading activity is an important indicator of market quality in the FX market. We consider $Volume_{i,t}$, per-hour trading volume in market i on day t, to account for the effect of trading activities on the price discover. Studying the price discovery in the bond markets, Mizrach and Neely (2008) also document the bid-ask spread, number of traders, and realized volatility are related to the information share of a market. $Spread_{i,t}$ refers to the relative effective spread of the corresponding trading period on day t, or as we noted previously, the average of $2|\frac{(p_{iz}-q_{iz})}{q_{iz}}|$ during each trading period on the day t, where p_{iz} and q_{iz} are trading price and mid-quote price at time interval z in trading period i, respectively. $Volatility_{i,t}$ is calculated by the squared root of the squared 5-min returns during trading period i on day t.

4. Empirical results

We can examine the variation in information shares across the four sequential markets (Asian, European, L + NY, and U.S.) by categorizing the hourly information share into four subsample periods, including days with U.S. announcements only, days with European or Japanese announcements only, days with both U.S. and local (European or Japanese) announcements, and days without U.S. or either local (European or Japanese) announcements.

4.1. Price discovery across four sequential markets

Tables 3 and 4 present the averages of per-hour information shares of EUR/USD and USD/JPY markets for the entire sample and the four subsamples related to announcements.

[16] We begin with the specification of $S_{j,t-l}$ to consider the leading and lagged effect of an individual indicator surprise on the price discovery. According to the Schwarz information criterion (SIC), the optimal number of lags turns out to be 0.

Panel A of Table 3 shows that, for the entire sample, the L + NY market dominates the price discovery for EUR/USD, consistent with the conclusion of Wang and Yang (2011). We further use the Wald test to test the differences in information shares across markets. The results indicate that the information share of the L + NY market is significantly greater than those of the Asian, European, and U.S. markets.

For the USD/JPY market, Panel A of Table 4 also shows that the L + NY market dominates price discovery. Furthermore, the Asian market contributes less to price discovery than the L + NY market and even less than the European market in the USD/JPY market. Overall, our results for the entire sample period are consistent with Covrig and Melvin (2002) and Sapp (2002) which concur that Tokyo banks dominate price discovery in the USD/JPY market.

Considering macroeconomic news effects, we study the information shares in four markets on days with and without announcements (see Panels B–E, Tables 3 and 4). Panel B of Table 3 shows that the information share of the L + NY market is no longer the highest on days without announcements, and the information share of the European market is not significantly smaller than that of the L + NY market on days without announcements, for the EUR/USD market. Moreover, the mean information share in the European market is economically significantly larger than that in the L + NY market. Therefore, the European market appears to contribute to price discovery even more than the L + NY market on days without announcements.

Compared with days without announcements, information shares of the L + NY and U.S. periods increase on days with U.S. announcements only, but the information shares of Asian and European periods decrease only on days with U.S. announcements, as Panel C of Table 3 shows. Therefore, our results coincide with Jiang et al. (2012), suggesting that the price discovery of a certain trading period improves as announcements get released in that period. The information share of the L + NY market increases by 40% on days with U.S. announcements only, and the L + NY market dominates the price discovery of EUR/USD on days with U.S. announcements only. Panel E of Table 3 also shows that the average information share of the L + NY market on days with both U.S. and European announcements is higher than the other markets.

In contrast, on days with European announcements only, the L + NY market does not dominate the price discovery. The European market's information share does not increase on days with European announcements only. Nor does the Wald test indicate that the information share of the European period is significantly larger than that of the L + NY period. Consistent with Andersen and Bollerslev (1998), Evans and Speight (2011), and Hashimoto and Ito (2010), we find that U.S. macroeconomic announcements have relatively greater impacts on exchange rates than do the other regions' announcements, even when they represent local news.

Similarly, Table 4 shows that in the USD/JPY market, the overlapping trading of the L + NY market only dominates price discovery on days with U.S. announcements. Yet an increase in the information share of the Asian market and a decrease in the L + NY market occur on days with Japanese announcements. Moreover, the information share of Asia is not significantly smaller than that of the European and L + NY periods, so the information patterns clearly appear affected by news announcements. However, the Asian market does not dominate price discovery, with the implication that Japanese announcements are less important than U.S. announcements. We also find that the information share of the European market is economically and significantly larger than that of the L + NY market on days without any announcement.

Overall then, the L + NY market only dominates price discovery on days with U.S. announcements. The information shares of the European and Asian markets do not significantly increase on days with European and Japanese announcements, respectively. Trading in the European period plays an important role in the price discovery of FX markets. According to Cai et al. (2008), London is an important financial center for FX trading, which may be why the European market dominates price discovery in the FX market on days without U.S. announcements. However, Cai et al. (2008) also point out that major U.S. economic data releases are a key information resource in the FX market, which suggests that the L + NY market may contribute more to the price discovery process than the other markets. In contrast with Wang and Yang (2011), we find that the L + NY market only contributes more to price discovery on days with U.S. announcements. These results thereby help explain the existing findings that most information in the FX market comes from the overlapping hours of London and New York (Cai et al., 2008; Wang and Yang, 2011; Piccotti, 2016).

4.2. Robustness check

We further use the weighted price contribution (WPC) to measure the amount of new information incorporated into exchange rates during a given period. Following Wang and Yang (2015), we divide day t into 4 sequential markets or trading-hours and then calculate the WPC of market i as follows:

$$WPC_i = \sum_{t=1}^{T} \frac{r_{i,t}}{r_t} \left(\frac{|r_t|}{\sum_{s=1}^{T} |r_s|} \right), i = 1, 2, 3, 4, \tag{6}$$

where r_t is the daily return of day t, $r_{i,t}$ denotes the open-close return in the ith market, and $r_t = \sum_{i=1}^{4} r_{i,t}$. The first term of WPC_i is the weighting factor of each trading period. The second term is the relative contribution of the return on day t to the whole sample. Hence the price discovery of the ith trading-hour segment is measured by the cross-day weighted average return ratio r_{it}/r_t, with the weight for day t being $\frac{|r_t|}{\sum_{s=1}^{T} |r_s|}$.

Table 3
Information shares measured by realized variance: EUR/USD. This table reports the daily average of per-hour information shares measured by realized variances. We use the integrated variance at five-minute intervals. Each trading period has a different number of trading hours, so we report the per-hour information share for normalization. We use Wald tests of the equality of information shares between the L + NY period and Asian, European, and U.S. periods.

	Asian (%)	European (%)	L + NY (%)	U.S. (%)
Panel A. All days				
Mean	2.78%***	6.04%***	7.63%***	3.46%***
t-value	54.36	51.31	32.61	47.58
Wald test	−19.49***	−5.15***		−16.86***
Panel B. No announcement days				
Mean	2.94%***	6.42%***	6.23%***	3.36%***
t-value	22.95	24.68	13.95	20.00
Wald test	−6.86***	0.31		−5.81***
Panel C. Days with U.S. announcements only				
Mean	2.57%***	5.77%***	8.61%***	3.63%***
t-value	27.89	22.43	18.67	24.31
Wald test	−12.60***	−4.39***		−10.57***
Panel D. Days with European announcements only				
Mean	2.68%***	5.45%***	4.95%***	2.11%***
t-value	17.79	20.13	10.98	15.35
Wald test	−5.08***	1.00		−6.54***
Panel E. Days with both U.S. and European announcements				
Mean	2.73%***	5.92%***	7.73%***	3.59%***
t-value	12.86	27.90	36.47	16.94
Wald test	−16.66***	−6.06***		−13.81***

** Denote statistical significance at the 5% level.
* Denote statistical significance at the 10% level.
*** Denote statistical significance at the 1% level.

Table 4
Information shares measured by realized variance: USD/JPY. This table reports the daily average of per-hour information shares measured by realized variances. We use the integrated variance at five-minute intervals. Each trading period has a different number of trading hours, so we report the per-hour information share for normalization. We use the Wald tests of the equality of information shares between the L + NY period and Asian, European, and U.S. periods.

	Asian (%)	European (%)	L + NY (%)	U.S. (%)
Panel A. All days				
Mean	3.84***	5.10***	6.48***	3.40***
t-value	22.80	30.30	38.46	20.21
Wald test	−11.07***	−5.77***		−12.90***
Panel B. No announcement days				
Mean	3.81***	5.56***	5.46***	3.30***
t-value	7.56	11.01	10.82	6.54
Wald test	−2.30**	0.14		−3.02***
Panel C. Days with US announcements only				
Mean	3.78***	4.82***	7.63***	3.41***
t-value	10.75	13.71	21.72	9.69
Wald test	−7.76***	−5.66***		−8.50***
Panel D. Days with Japanese announcements only				
Mean	4.12***	5.44***	5.02***	3.25***
t-value	10.04	13.28	12.25	7.93
Wald test	−1.56	0.73		−3.06***
Panel E. Days with both US and Japanese announcements				
Mean	3.78***	5.01***	6.66***	3.48***
t-value	15.78	20.94	27.83	14.52
Wald test	−4.88***	−3.64***		−9.41***

* Denote statistical significance at the 10% level.
*** Denote statistical significance at the 1% level.
** Denote statistical significance at the 5% level.

The first row of Table 5 presents the WPC calculated by Eq. (6). We find that the WPC of the L + NY market is larger than the other three markets in the EUR/USD market. Similarly, Table 6 implies that the L + NY market contributes more to price discovery in the USD/JPY market in terms of WPC for the full sample. The results of Tables 5 and 6 are consistent with the findings from Tables 3 and 4 based on information shares.

To investigate effects of macroeconomic announcements on price discovery, we divide the full sample into several subsample periods and calculate corresponding WPCs for each market. The second row of Table 5 shows that the WPC of the European period is 0.88% which is larger than the WPC of the L + NY market in the EUR/USD market. However, comparing the difference between the WPCs in European and L + NY markets in the USD/JPY market, we still find that the L + NY market contributes more to price discovery, whereas the difference between European and L + NY markets in WPC sharply decreases.

Considering news effects, the third row of Table 6 shows the WPC of L + NY period is 3.55% and it is the largest among the four markets. Similar results are also found in Table 7. However, the fourth row of Table 6 tells that the European market provides more price discovery than the other three markets for the EUR/USD, similar to the finding in Table 3. The WPCs on days with European macroeconomic announcements and days without news provide evidence that the L + NY market only dominates price discovery on days with U.S. macroeconomic news. We find that, in Table 6, although the WPC in the L + NY market is still larger than those in other regions, the WPCs decrease.

We also find that the WPC of the L + NY goes back to the higher level and even higher than the other markets on days with both U.S. and European or Japanese announcements, as shown in the last row in Tables 5 and 6. The results are consistent with the finding of Tables 3 and 4.

4.3. Determinants of information share

The estimation results of Model 1 in Table 7 show that the information shares in the Asian, European and U.S. markets are significantly smaller than that in the L + NY market. The intercept term indicates the overall information share of the L + NY market. Model 2 considers the effect of market liquidity on the information share across the four sequential markets, and it suggests the average information share of the Asian, European or the U.S. trading regions are still significantly smaller than that in the L + NY region after controlling the effect of spread, trading volume, and volatility. Overall, a larger trading volume can increase information shares in the EUR/USD market; the higher volatility may enhance the price discovery efficacy of a particular market.

As the announcement of macroeconomic news may affect the information structure in the FX market, the relative contributions to price discovery of the four trading periods can vary around the announcement. Models 3 and 4 further estimate the effect of the U.S., European, and Japanese macroeconomic announcements on the FX price discovery. We find that most announcements do not have a significant effect on the information share overall, as reported in the results of Model 3 in Tables 7 and 8. Only the surprise of U.S. Business Inventory is found to positively affect information share measures. Indeed, Model 3 is not able to effectively capture the effect of announcements on price discovery because of the ignorance of identifying the information share for a specific trading period.

To identify the impact of announcement on the relative contribution of a specific trading period to the price discovery, we modify the regression model by including the interaction term of news surprises and the market dummy variables ($MKT_{j,i,t}$, $j = 1, 2, 3$) in Model 4. The higher adjusted R^2 shows that Model 4 explains the effects of announcements on information shares better than Model 3.

Model 4 allows us to examine whether news surprises affect the difference between the information share of the L + NY period and the information share of the other period. The insignificant coefficient of $\mathrm{MKT}_{2,i,t}$ indicates that overall information share in the European period is not lower than that in the L + NY period at times of no announcement, which is consistent with the finding in Table 4.

The impact of individual announcements on the information share varies with types of announcements. Among U.S. announcements, surprises of FOMC Rate Decision, GDP Price Index, New Home Sales and Business Inventory have significantly positive impacts on information shares of the L + NY period, whereas the surprise of Retail Sales Advance negatively affects the L + NY information share.

FOMC Rate Decision is released at 14:15 EST, referred as in the U.S. period. An increase in price discovery efficacy in the L + NY period ahead of the FOMC announcements in the U.S. period may be attributed to information leakage regarding the FOMC policies decisions. Our results complement the empirical findings in Bernile et al. (2016) and Cieslak et al. (2014) that address the leak of information ahead of the FOMC announcements in the S&P 500 futures market and the stock market.[17]

We find that the contribution of the L + NY period to the FX price discovery increases at the release of U.S. CPI, PPI, and New Home Sale. According to Flannery and Protopapadakis (2002), CPI and PPI have been viewed as important for equities, bonds and foreign exchange rates. Andersen et al. (2003) also find CPI, PPI and New Home Sales affect exchange rate returns and volatility. Some of the aggregate economic indicators such as Industrial Production, and Unemployment Rate do not significantly affect

Gilbert et al. (2015) study the heterogeneous response of price movements to announcements and suggest the impact of an announcement relates to its relation to fundamentals, timing, and revision noise. Gilbert et al. (2015) and Kurov et al. (2016) even suggest that earlier scheduled announcement may receive more attention and have larger impacts on asset

[17] Bernile et al. (2016) provide evidence of informed trading activities during news embargoes ahead of scheduled FOMC announcements. Cieslak et al. (2014) also address the leak of information about FOMC policies ahead of the day on which the official decisions are set.

Table 5
Weighted price contribution: EUR/USD. This table reports the weighted price contribution (WPC) across the four sequential periods. Dividing day t into 4 sequential periods or trading-hours, the WPC of market i is computed as follows, $WPC_i = \sum_{t=1}^{T} \frac{r_{i,t}}{r_t}\left(\frac{|r_t|}{\sum_{s=1}^{T}|r_s|}\right), i = 1,2,3,4$, where r_t is the daily return, $r_{i,t}$ denotes the open-close return in the ith trading period, and $r_t = \sum_{i=1}^{4} r_{i,t}$. We calculate the WPC for the full sample of all days, subsamples of no announcement days, days with U.S. announcement only, days with European announcements only and days with both U.S. and European announcements, respectively.

	Asian (%)	European (%)	L + NY (%)	U.S. (%)
All days	1.94	6.52	9.38	3.47
No announcement days	0.29	0.88	0.84	0.51
Days with U.S. announcements only	0.77	1.86	3.55	1.14
Days with European announcements only	0.29	1.25	0.97	0.32
Days with both U.S. and European announcements	0.58	2.54	4.01	1.50

Table 6
Weighted price contribution: USD/JPY. This table reports the weighted price contribution (WPC) across the four sequential periods. Dividing day t into 4 sequential trading periods or trading-hours, the WPC in period i is computed as follows, $WPC_i = \sum_{t=1}^{T} \frac{r_{i,t}}{r_t}\left(\frac{|r_t|}{\sum_{s=1}^{T}|r_s|}\right), i = 1,2,3,4$, where r_t is the daily return, $r_{i,t}$ denotes the open-close return in the ith trading period, and $r_t = \sum_{i=1}^{4} r_{i,t}$. We calculate the WPC for the full sample of all days, subsamples of no announcement days, days with U.S. announcement only, days with European announcements only and days with both U.S. and European announcements, respectively.

	Asian (%)	European (%)	L + LN (%)	U.S. (%)
All days	3.82	5.44	7.46	2.93
No announcement days	0.31	0.58	0.70	0.29
Days with US announcements only	0.85	1.29	1.78	0.83
Days with Japanese announcements only	0.62	0.67	1.15	0.41
Days with both US and Japanese announcements	2.04	2.91	3.83	1.39

prices. But we are not able to find the similar results as GDP Price Index, New Home Sales and Business Inventory are usually released after the middle of a month.

Moreover, the effect of news surprise of announcement j on the differences in information shares in the Asian, European and U.S. periods over the L + NY period can be measured through the coefficients on $MKT_{1,i,t} \times S_{j,t}$, $MKT_{2,i,t} \times S_{j,t}$ and $MKT_{3,i,t} \times S_{j,t}$, respectively. We find that news surprises of U.S. FOMC Rate Decision, GDP, House Price Index, New Home Sales, Business Inventories, and Construction Spending negatively affect the contribution to the EUR/USD price discovery of a specific trading period relative to the L + NY period. In particular, on announcement days with FOMC Rate Decision, GDP Price Index and Business Inventories, the pricing efficiency in the L + NY period becomes higher than all the other three trading periods.

On the other hand, the significant and positive coefficients on $MKT_{1,\mathrm{i,t}} \times \mathit{Retail\ Sales}_t$ and $MKT_{2,\mathrm{i,t}} \times \mathit{Personal\ Income}_t$ imply that price-discovery efficacy in the Asian and European trading-hours increase on announcement days of Retail Sales and Personal Income, respectively. Since the announcements of Retail Sales and Personal Income are scheduled at 8:30 EST that is in the L + NY period, we find evidence that a specific market reveals more information before the announcement scheduled time. The finding of possible information leakage in the period prior to the announcement time is in line with Bernile et al. (2016) and Kurov et al. (2016) that provide evidence of pre-announcement price drift before macroeconomic announcements.

The positive coefficient of $MKT_{3,\mathrm{i,t}} \times \mathit{Retail\ Sales}_{t,}$ indicates that the information share of the U.S. period increases following the U.S. Retail Sale announcement. As the announcement of Retail Sales is released in the L + NY hours, the following U.S. period shows more price discovery, implying prices continuously adjust towards the intrinsic value after the announcement. At the arrival of news, traders' heterogeneous interpretations of information may induce the information incorporation process to be detained right after the announcement; afterwards, the information disseminates over time and then it speeds up the price discovery during the following trading hours.

Among European announcements, the L + NY information share increases at the announcement of Trade Balance, and decreases at the announcements of Industrial Production and Sentix Investor Confidence. It seems that the price discovery in the L + NY overlapping trading period does not increase in response to European macroeconomic announcement all the time.

European Industrial Production is announced at 9:30 WET and Sentix Investor Confidence announcement is released at 10:00 WET; they are announced in the European trading period. The estimation results for the interactions between *MKT*s and Sentix Investor Confidence show positive pre-announcement effect in the Asian period and positive post-announcement effect in the U.S. period for this forward-looking indicator. Considering the negative announcement effect of Sentix Investor Confidence on the price discovery during the L + NY period, we find time-varying information shares before and after the announcement, although we cannot find a clear-cut rule for the change in price discovery before and after the announcement.

Table 7

Determinants of information shares: EUR/USD. This table reports the estimation results for the following regression: $\overline{IS}_{i,t} = \alpha_0 + \alpha_1 MKT_{1,i,t} + \alpha_2 MKT_{2,i,t} + \alpha_3 MKT_{3,i,t} + \sum_{j=1}^{J}\beta_j S_{j,t} + \sum_{m=1}^{3}\sum_{j=1}^{J}\lambda_{m,j} \times MKT_{m,i,t} \times S_{j,t} + \delta \times Volatility_{i,t} + \eta \times Spread_{i,t} + \theta \times Volume_{i,t} + \varepsilon_{i,t}$ where we use the per-hour information share $\overline{IS}_{i,t}$ of period i on day t in the analysis for normalization. As each trading period has a different number of trading hours, we obtain the per-hour information share by dividing the ith period's information share measured by Eq. (3) by the number of trading hours of the ith period. $MKT_{m,i,t}$ is a dummy variable for the mth market, where m = 1, 2, 3 indicates Asian, European, and U.S. periods, respectively; $MKT_{m,i,t}$ equals 1 for the mth market and 0 otherwise. $S_{j,t}$ is the standardized news surprise for announcement j (j = 1, ..., 75) on day t. $Volume_{it}$ is per-hour trading volume in period i on day t; $Volatility_{i,t}$ is calculated by the squared root of the squared 5-min returns during period i on day t; and $Spread_{i,t}$ is the relative effective spread in period i on day t. Model 2 includes variables related to market quality only. Model 3 considers news effects, by including news surprises, and Model 4 further incorporates the interaction term of news surprises and market dummy variables. The t-values denote the Newey–West robust t-values adjusted for heteroskedasticity and autocorrelation (Newey and West, 1987).

Variables	Model 1	Model 2	Model 3	Model 4
C	0.0763***	0.0447***	0.0442***	0.0434***
$MKT_{1,i,t}$	−0.0486***	−0.0249***	−0.0248***	−0.0215***
$MKT_{2,i,t}$	−0.0159***	−0.0071**	−0.0071**	0.0006
$MKT_{3,i,t}$	−0.0418***	−0.0215***	−0.0215***	−0.0201***
$Spread_{i,t}$		17.8688	18.1722	9.3686
$Volatility_{i,t}$		17.8767***	18.3834***	17.7519***
$Volume_{i,t}$ (/1000)		0.0132***	0.0132***	0.0118***
US announcements				
$FOMC\ Rate\ Decision_t$			0.0057	0.0314**
$GDP\ Price\ Index_t$			0.0040	0.0269**
$New\ Home\ Sales_t$			0.0007	0.0107**
$Retail\ Sales\ Advance_t$			−0.0035	−0.0178**
$Business\ Inventories_t$			0.0046***	0.0264*
European announcements				
$Industrial\ Production_t$			−0.0021	−0.0125**
$Sentix\ Investor\ Confidence_t$			−0.0027	−0.0128**
$Trade\ Balance_t$			0.0024	0.0162*
US announcements				
$MKT_{1,i,t} \times FOMC\ Rate\ Decision_t$				−0.0324**
$MKT_{2,i,t} \times FOMC\ Rate\ Decision_t$				−0.0375***
$MKT_{3,i,t} \times FOMC\ Rate\ Decision_t$				−0.0330***
$MKT_{1,i,t} \times GDP\ Price\ Index_t$				−0.0272**
$MKT_{2,i,t} \times GDP\ Price\ Index_t$				−0.0338**
$MKT_{3,i,t} \times GDP\ Price\ Index_t$				−0.0300**
$MKT_{2,i,t} \times House\ Price\ Index_t$				−0.0228*
$MKT_{1,i,t} \times New\ Home\ Sales_t$				−0.0149**
$MKT_{3,i,t} \times New\ Home\ Sales_t$				−0.0126**
$MKT_{2,i,t} \times Personal\ Income_t$				0.0125*
$MKT_{1,i,t} \times Retail\ Sales_t$				0.0222**
$MKT_{3,i,t} \times Retail\ Sales_t$				0.0211**
$MKT_{1,i,t} \times Business\ Inventories_t$				−0.0279**
$MKT_{2,i,t} \times Business\ Inventories_t$				−0.0311**
$MKT_{3,i,t} \times Business\ Inventories_t$				−0.0288**
$MKT_{3,i,t} \times Construction\ Spending_t$				−0.0218*
European announcements				
$MKT_{3,i,t} \times Economic\ Confidence_t$				−0.0037*
$MKT_{1,i,t} \times Industrial\ Production_t$				0.0104**
$MKT_{2,i,t} \times Industrial\ Production_t$				0.0201***
$MKT_{1,i,t} \times Sentix\ Investor\ Confidence_t$				0.0170*
$MKT_{3,i,t} \times Sentix\ Investor\ Confidence_t$				0.0145*
$MKT_{3,i,t} \times Services\ Confidence_t$				0.0255*
$MKT_{2,i,t} \times Trade\ Balance_t$				−0.0190*
$MKT_{3,i,t} \times Trade\ Balance_t$				−0.0228**
Adjusted R^2 (%)	15.82	18.19	18.62	22.63

*** Denote statistical significance at the 1% level.
** Denote statistical significance at the 5% level.
* Denote statistical significance at the 10% level.

We also find the price discovery is affected by the announcements of Economic Confidence, Industrial Production, Services Confidence, and Trade Balance in Euro area, but the direction of announcement effects is inconclusive. The heterogeneous per-announcement and post-announcement effects of these European announcements may depend on the association between the indicator and fundamentals, timing, as well as revision noise, as addressed in Gilbert et al. (2015).

Looking at the list of announcements with significant effects on the price discovery in the EUR/USD market, we find four out of five U.S. announcements and one out of two European announcements have negative impacts on the information share in the European period, that is, the trading period with $MKT_{2,i,t}$ = 1. Overall, U.S macroeconomic news seems to have

Table 8
Determinants of information shares: USD/JPY. This table reports the estimation results for the following regression: $\overline{IS}_{i,t} = \alpha_0 + \alpha_1 MKT_{1,i,t} + \alpha_2 MKT_{2,i,t} + \alpha_3 MKT_{3,i,t} + \sum_{j=1}^{J} \beta_j S_{j,t} + \sum_{m=1}^{3}\sum_{j=1}^{J} \lambda_{m,j} \times MKT_{m,i,t} \times S_{j,t} + \delta \times Volatility_{i,t} + \eta \times Spread_{i,t} + \theta \times Volume_{i,t} + \varepsilon_{i,t}$ where we use the per-hour information share $\overline{IS}_{i,t}$ of market i on day t in the analysis for normalization. As each trading period has a different number of trading hours, we obtain the per-hour information share by dividing the ith period's information share measured by Eq. (3) by the number of trading hours of the ith period. $MKT_{m,i,t}$ is a dummy variable for the mth period, where m = 1, 2, 3 indicates Asian, European, and U.S. periods, respectively; $MKT_{m,i,t}$ equals 1 for the mth period and 0 otherwise. $S_{j,t}$ is the standardized news surprise for indicator j (j = 1, ..., 75) on day t. $Volume_{it}$ is per-hour trading volume in period i on day t; $Volatility_{i,t}$ is calculated by the squared root of the squared 5-min returns during period i on day t; and $Spread_{i,t}$ is the relative effective spread in period i on day t. The t-values denote the Newey–West robust t-values adjusted for heteroskedasticity and autocorrelation (Newey and West, 1987).

Variables	Model 1	Model 2	Model 3	Model 4
C	0.0648***	0.0374***	0.0378***	0.0366***
$MKT_{1,i,t}$	−0.0264***	−0.0060	−0.0044	−0.0028
$MKT_{2,i,t}$	−0.0138***	0.0003	0.0014	0.0054*
$MKT_{3,i,t}$	−0.0307***	−0.0033	−0.0011	−0.0024
$Spread_{i,t}$		−180.42***	−214.86***	−186.19***
$Volatility_{i,t}$		0.2492***	0.2666**	0.2337***
$Volume_{i,t}$ (/1000)		0.0329***	0.0354***	0.0328***
US announcements				
$Construction\ Spending_t$			0.0041*	0.0315***
Japanese announcements				
$Capital\ Spending_t$			0.0041	0.0242**
US announcements				
$MKT_{2,i,t} \times GDP\ Price\ Index_t$				0.0328**
$MKT_{2,i,t} \times House\ Price\ Index_t$				−0.0169*
$MKT_{1,i,t} \times Leading\ Index_t$				−0.0162*
$MKT_{2,i,t} \times Personal\ Income_t$				0.0157*
$MKT_{3,i,t} \times Personal\ Income_t$				0.0165*
$MKT_{2,i,t} \times Retail\ Sales_t$				−0.0266**
$MKT_{1,i,t} \times Construction\ Spending_t$				−0.0364***
$MKT_{2,i,t} \times Construction\ Spending_t$				−0.0348***
$MKT_{3,i,t} \times Construction\ Spending_t$				−0.0374***
$MKT_{2,i,t} \times Consumer\ Confidence\ Index_t$				−0.0245**
$MKT_{3,i,t} \times Consumer\ Confidence\ Index_t$				−0.0230**
$MKT_{3,i,t} \times Trade\ Balance_t$				0.0120*
Japanese announcements				
$MKT_{1,i,t} \times Capital\ Spending_t$				−0.0287**
$MKT_{2,i,t} \times Capital\ Spending_t$				−0.0336**
$MKT_{1,i,t} \times Large\ Retailers'\ Sales_t$				0.0283**
$MKT_{2,i,t} \times Large\ Retailers'\ Sales_t$				0.0234**
$MKT_{3,i,t} \times Large\ Retailers'\ Sales_t$				0.0194*
$MKT_{3,i,t} \times Money\ Supply\ M2_t$				0.7046*
Adjusted R^2 (%)	4.20	10.92	12.91	21.10

*** Denote statistical significance at the 1% level.
** Denote statistical significance at the 5% level.
* Denote statistical significance at the 10% level.

a stronger dampened impact on the price discovery during the European period, compared with the European announcements.

In the USD/JPY market, Model 1 in Table 8 also shows that the L + NY market dominates the price discovery. Model 2 indicates that liquidity is significantly related with information shares in the L + NY market on days without announcements. The insignificant coefficients on $MKT_{1,i,t}$, $MKT_{2,i,t}$ and $MKT_{3,i,t}$ show the information shares in the Asian, European and U.S periods are not significantly different from that in the *L + NY* period, when we just control the effect of market quality and omit the announcement effects.

In the USD/JPY market, Model 4 in Table 8 shows the European trading period has a significantly higher information share than that in the L + NY market during no-announcement days. Among the U.S. announcements, the price discovery of the L + NY period improves only on days with the Construction Spending announcement released at 10:00 EST. The negative coefficients on interaction terms between $MKT_{m,i,t}$ (for m = 1, 2, 3) and Construction Spending imply that the price discovery contributions of the Asian, European, and U.S. periods are weaken on announcement days of Construction Spending. Observing the shift in information shares around the announcement of Construction Spending that is released in the L + NY period, we find the relevant information related to Construction Spending is well incorporated into the USD/JPY exchange rates during the L + NY period. There is no evidence of information leakage during the pre-announcement period, nor the opinion divergence occurring at the release time. Similarly, before Consumer Confidence is released at 10:00 EST (in the L + NY period), negative coefficients on $MKT_{2,i,t}$×Consumer Confidence $Index_t$ and $MKT_{3,i,t}$ × Consumer Confidence $Index_t$ indicate that

Table 9

Crisis and determinants of information shares: EUR/USD. $\overline{IS}_{i,t} = \gamma_0' X + CRISIS_{1,t}(\gamma_1' X) + CRISIS_{2,t}(\gamma_2'' X) + \varepsilon_{i,t}$ where $\overline{IS}_{i,t}$ is the per-hour information share of market i on day t. $X = (1, MKT_{1,i,t}, MKT_{2,i,t}, MKT_{3,i,t}, S_{1,t}, \cdots, S_{75,t}, MKT_{1,i,t} \times S_{1,t}, \cdots, MKT_{1,i,t} \times S_{75,t}, MKT_{2,i,t} \times S_{1,t}, \cdots, MKT_{2,i,t} \times S_{75,t}, MKT_{3,i,t} \times S_{1,t}, \cdots, MKT_{3,i,t} \times S_{75,t}, Volume_{i,t}, Spread_{i,t}, Volatility_{i,t})\prime$, $CRISIS_{1,t}$ and $CRISIS_{2,t}$ are crisis dummy variables, where $CRISIS_{1,t} = 1$ if t is in the period of August 1–December 31, 2008, 0 otherwise; $CRISIS_{2,t} = 1$ for t is in the period of September 16, 2009–March 14, 2012, 0 otherwise. $CRISIS_{1t}$ and $CRISIS_{2t}$ denote the subprime mortgage crisis and the Euro area sovereign debt crisis periods, respectively. For the definition of the other variables, refer to Table 7. The t-values denote the Newey–West robust t-values adjusted for heteroskedasticity and autocorrelation (Newey and West, 1987).

Variables	Tranquil Period	$CRISIS_1 = 1$	$CRISIS_2 = 1$
C	0.0891***	−0.0703***	−0.0703***
$MKT_{1,i,t}$	−0.0446***	0.0601***	0.0406***
$MKT_{2,i,t}$	−0.0083	0.0158*	0.0081
$MKT_{3,i,t}$	−0.0407***	0.0538***	0.0390***
$Spread_{\ i,t,}$	−459.0493	329.2833***	457.6044***
$Volatility_{i,t}$	806.6967	575.3623*	−789.9640***
$Volume_{\ i,t}$ (/1000)	0.0005	0.0287***	0.0208***
US announcements			
$\textit{Consumer Price Index}_t$	−0.1492**	0.1327*	0.1595**
$\textit{Factory Orders}_t$	0.0350***	−0.0112	−0.0300
$\textit{FOMC Rate Decision}_t$	−0.1282***	0.2050***	0.1087
$\textit{House Price Index}_t$	0.0387	0.0071***	−0.0410
$\textit{Industrial Production}_t$	−0.0167	0.0997**	0.0442
$\textit{Personal Spending}_t$	−0.0514***	0.0825***	0.0446***
$\textit{Retail Sales Advance}_t$	0.0026	−0.0290**	0.0189
$\textit{Manufacture Payrolls}_t$	−0.0503***	0.0576**	0.0820**
$\textit{Nonfarm Payrolls}_t$	−0.0481***	0.0407*	−0.0007
$\textit{Construction Spending}_t$	−0.0437***	0.0335	0.0486**
$\textit{Trade Balance}_t$	0.0196	−0.0383*	−0.0133
$MKT_{1,i,t}$ * $\textit{Consumer Price Index}_t$	0.1623**	−0.1332	−0.1764**
$MKT_{2,i,t} \times \textit{Consumer Price Index}_t$	0.1657**	−0.1191	−0.1766**
$MKT_{3,i,t} \times \textit{Consumer Price Index}_t$	0.1689**	−0.1634***	−0.1778**
$MKT_{1,i,t} \times \textit{Factory Orders}_t$	−0.0371**	−0.0151	0.0334
$MKT_{2,i,t} \times \textit{Factory Orders}_t$	−0.0314	0.0203	0.0217
$MKT_{3,i,t} \times \textit{Factory Orders}_t$	−0.0406**	0.0267	0.0346
$MKT_{1,i,t} \times \textit{FOMC Rate Decision}_t$	0.1689***	−0.2139***	−0.0097
$MKT_{2,i,t} \times \textit{FOMC Rate Decision}_t$	0.0774*	−0.1012	−0.1329
$MKT_{3,i,t} \times \textit{FOMC Rate Decision}_t$	0.1251**	−0.2079***	−0.1012
$MKT_{1,i,t} \times \textit{Import Price Index}_t$	0.0162	−0.0711***	−0.0351
$MKT_{2,i,t} \times \textit{Import Price Index}_t$	0.0176	−0.0694**	−0.0375
$MKT_{3,i,t} \times \textit{Import Price Index}_t$	0.0111	−0.0736**	−0.0332
$MKT_{1,i,t} \times \textit{Industrial Production}_t$	0.0173	−0.1071**	−0.0477
$MKT_{2,i,t} \times \textit{Industrial Production}_t$	0.0106	−0.0961**	−0.0433
$MKT_{3,i,t} \times \textit{Industrial Production}_t$	0.0173	−0.0975**	−0.0483
$MKT_{1,i,t} \times \textit{Monthly Budget Statement}_t$	−0.0192	0.0363*	0.0223
$MKT_{2,i,t} \times \textit{Monthly Budget Statement}_t$	−0.0211	0.0476*	0.0216
$MKT_{2,i,t} \times \textit{PCE}_t$	0.0416*	−0.0225	−0.0585*
$MKT_{2,i,t} \times \textit{Personal Consumption}_t$	0.0038	0.0729**	−0.0309
$MKT_{1,i,t} \times \textit{Personal Income}_t$	0.0358**	0.0041	−0.0007
$MKT_{3,i,t} \times \textit{Personal Income}_t$	0.0273*	−0.0179	0.0039
$MKT_{1,i,t} \times \textit{Personal Spending}_t$	0.0610***	−0.0858***	−0.0520***
$MKT_{2,i,t} \times \textit{Personal Spending}_t$	0.0558***	−0.0723***	−0.0568***
$MKT_{3,i,t} \times \textit{Personal Spending}_t$	0.0504***	−0.0517**	−0.0413**
$MKT_{2,i,t} \times \textit{Retail Sales}_t$	−0.0120	0.0391**	−0.0143
$MKT_{3,i,t} \times \textit{Retail Sales}_t$	−0.0119	0.0305*	−0.0107
$MKT_{2,i,t} \times \textit{Capacity Utilization}_t$	0.0951*	−0.0742	−0.0762
$MKT_{3,i,t} \times \textit{Capacity Utilization}_t$	0.0805*	−0.0596	−0.0593
$MKT_{1,i,t} \times \textit{Manufacture Payrolls}_t$	0.0465*	−0.0486*	−0.0741**
$MKT_{2,i,t} \times \textit{Manufacture Payrolls}_t$	0.0387	−0.0669	−0.0961*
$MKT_{3,i,t} \times \textit{Manufacture Payrolls}_t$	0.0682***	−0.0607**	−0.0948***
$MKT_{1,i,t} \times \textit{Nonfarm Payrolls}_t$	0.0506**	−0.0399	−0.0049
$MKT_{2,i,t} \times \textit{Nonfarm Payrolls}_t$	0.0758**	−0.0690*	−0.0003
$MKT_{3,i,t} \times \textit{Nonfarm Payrolls}_t$	0.0340*	−0.0365	0.0079
$MKT_{1,i,t} \times \textit{Construction Spending}_t$	0.0455**	−0.0286	−0.0492**
$MKT_{2,i,t} \times \textit{Construction Spending}_t$	0.0402	−0.0661*	−0.0480
$MKT_{3,i,t} \times \textit{Construction Spending}_t$	0.0477**	−0.0360	−0.0548**
$MKT_{1,i,t} \times \textit{Trade Balance}_t$	−0.0250	0.0433**	0.0156
$MKT_{2,i,t} \times \textit{Trade Balance}_t$	−0.0198	0.0375*	0.0125
$MKT_{3,i,t} \times \textit{Unemployment Rate}_4$	−0.0296	−0.0200	0.0819**
European announcements			
$\textit{Business Climate Indicator}_t$	−0.0265	0.0585*	0.0081
$\textit{Consumer Confidence}_t$	−0.0196***	1.0712	0.0351***

(*continued on next page*)

Table 9 (*continued*)

Variables	Tranquil Period	$CRISIS_1 = 1$	$CRISIS_2 = 1$
CPI_t	0.0100	−0.0457*	−0.0148
EU27 New Car Registrations$_t$	0.0290	−0.1635***	−0.0474
Govt Expend$_t$	0.0975***	−0.0720	−0.0789*
Gross Fix Cap$_t$	0.0311***	−0.8998	−0.0273
Sentix Investor Confidence$_t$	−0.0192*	0.0629	0.0012
Services Confidence$_t$	0.0045	0.0169	−0.0494**
Trade Balance$_t$	0.0275*	0.0003	−0.0197
Unemployment Rate$_t$	0.0600**	−0.0573	−0.0601**
$MKT_{2,i,t}$ × *Business Climate Indicator*$_t$	0.0021	0.0970**	0.0265
$MKT_{1,i,t}$ × *Consumer Confidence*$_t$	0.0225**	0.0566*	−0.0395***
$MKT_{2,i,t}$ × *Consumer Confidence*$_t$	0.0260***	0.0129	−0.0393***
$MKT_{3,i,t}$ × *Consumer Confidence*$_t$	0.0200**	−0.0147	−0.0398
$MKT_{1,i,t}$ × *CPI Core*$_t$	−0.0153	0.0482**	0.0244
$MKT_{3,i,t}$ × *CPI Core*$_t$	−0.0073	0.0469*	0.0137
$MKT_{1,i,t}$ × *Economic Confidence*$_t$	−0.0005	−0.0086*	−0.0019
$MKT_{2,i,t}$ × *Economic Confidence*$_t$	0.0005	−0.0150***	−0.0026
$MKT_{1,i,t}$ × *Gross Fixed Capital Formation*$_t$	−0.1132***	0.1281*	0.0963**
$MKT_{2,i,t}$ × *Gross Fixed Capital Formation*$_t$	−0.1090***	0.0667	0.0768
$MKT_{3,i,t}$ × *Gross Fixed Capital Formation*$_t$	−0.0941**	0.2476***	0.0824**
$MKT_{1,i,t}$ × *Household Consumption*$_t$	0.0132	0.1106**	0.0095
$MKT_{2,i,t}$ × *Household Consmption*$_t$	−0.0035	0.0937**	0.0288
$MKT_{2,i,t}$ × *Retail Sales*$_t$	−0.0090	0.0523**	−0.0170
$MKT_{1,i,t}$ × *Sentix Investor Confidence*$_t$	0.0237*	−0.0695**	0.0006
$MKT_{3,i,t}$ × *Sentix Investor Confidence*$_t$	0.0298***	−0.0730**	−0.0164
$MKT_{2,i,t}$ × *Trade Balance*$_t$	−0.0300*	−0.0138	0.0186
$MKT_{3,i,t}$ × *Trade Balance*$_t$	−0.0314*	0.0096	0.0184
$MKT_{1,i,t}$ × *Unemployment Rate*$_t$	−0.0628*	0.0507*	0.0618**
$MKT_{2,i,t}$ × *Unemployment Rate*$_t$	−0.0733**	0.1085***	0.0758**
$MKT_{3,i,t}$ × *Unemployment Rate*$_t$	−0.0625**	0.0543*	0.0597*
Adjusted R^2 (%)	26.23		

*** Denote statistical significance at the 1% level.
** Denote statistical significance at the 5% level.
* Denote statistical significance at the 10% level.

relevant information is not better incorporated into prices during the pre-announcement period (European period) nor the post-announcement period (U.S period).

The announcement of Personal Income instead enhances the price discovery in the European period and the U.S. period. Although Personal Income is announced at 8:30 EST, in the L + NY period, the L + NY period does not have better price discovery in this case. Positive coefficients on $MKT_{2,i,t}$ × *Personal Income*$_t$ and $MKT_{3,i,t}$ × *Personal Income*$_t$ show that the European period and the U.S. period have more price discovery on announcement days of Personal Income than the L + NY period. Such pattern suggests the possibility of information leakage in the European period and the emergence of opinion divergence at the release of Personal Income.

Among the Japanese announcements, the L + NY price discovery is enhanced during days with the announcement of Capital Spending which is released at 8:50 JST (in the Asian period). Negative coefficients on $MKT_{1,i,t}$ × *Capital Spending*$_t$ and $MKT_{2,i,t}$ × *Capital Spending*$_t$ show that the Asian period and the European period have worse price discovery than the L + NY period. The lower price discovery during the Asian period may reflect heterogeneous interpretations among traders for the figures of Capital Spending as the announcement is released during the Asian period. The opinion divergence continues to blur the information incorporation process during the European period, but finally price-relevant information gets absorbed into the USD/JPY exchange rate and improves the price discovery during the L + NY period.

Positive coefficients on $MKT_{,m,i,t}$ × *Large Retailers' Sales* (m = 1, 2, 3) show that the Asian period, European period, and U.S. period have more price discovery on announcement days of Large Retailers' Sales than the L + NY period. According to the variation in information shares in the announcement period and post-announcement periods, we find that, during the Asian period, relevant pricing information from the announcement of Large Retailers' Sales is partly incorporated into USD/JPY exchange rates, the remaining information disseminates over following European period and U.S. period, although the information share in the L + NY period strangely does not increase significantly. We notice the incremental in information shares of the Asian, European, and US periods relative to that in the L + NY period decays with time.

4.4. Crisis effect on price discovery

The data period in this study covers the subprime mortgage crisis and the Euro area sovereign debt crisis. We follow Ivashina and Scharfstein (2010) and Santis (2014) to identify August 1–December 31, 2008 as the subprime mortgage crisis period, and September 16, 2009–March 14, 2012 to be the Euro area sovereign debt crisis period.

Table 10

Crisis and determinants of information shares: USD/JPY. $\overline{IS}_{i,t} = \gamma_0' X + CRISIS_{1,t}(\gamma_1' X) + CRISIS_{2,t}(\gamma_2'' X) + \varepsilon_{i,t}$ where $\overline{IS}_{i,t}$ is the per-hour information share of period i on day t. $X = (1, MKT_{1,i,t}, MKT_{2,i,t}, MKT_{3,i,t}, S_{1,t}, \cdots, S_{75,t}, MKT_{1,i,t} \times S_{1,t}, \cdots, MKT_{1,i,t} \times S_{75,t}, MKT_{2,i,t} \times S_{1,t}, \cdots, MKT_{2,i,t} \times S_{75,t}, MKT_{3,i,t} \times S_{1,t}, \cdots, MKT_{3,i,t} \times S_{75,t}, Volume_{i,t}, Spread_{i,t}, Volatility_{i,t})'$, $CRISIS_{1,t}$ and $CRISIS_{2,t}$ are crisis dummy variables, where $CRISIS_{1,t} = 1$ if t is in the period of August 1 – December 31, 2008, 0 otherwise; $CRISIS_{2,t} = 1$ for t is in the period of September 16, 2009 – March 14, 2012, 0 otherwise. $CRISIS_{1t}$ and $CRISIS_{2t}$ denote the subprime mortgage crisis and the Euro area sovereign debt crisis periods, respectively. For the definition of the other variables, refer to Table 7. The t-values denote the Newey–West robust t-values adjusted for heteroskedasticity and autocorrelation (Newey and West, 1987).

Variables	Tranquil period	$CRISIS_1 = 1$	$CRISIS_2 = 1$
C	0.0579***	−0.0110	−0.0317**
$MKT_{1,i,t}$	−0.0181***	0.0097	0.0157**
$MKT_{2,i,t}$	−0.0042	0.0067	0.0061
$MKT_{3,i,t}$	−0.0213***	0.0195**	0.0224**
$Spread_{\ i,t,}$	−152.7682	48.0614	15.5203
$Volatility_{i,t}$	0.5420***	−0.3444***	−0.3468**
$Volume_{\ i,t}$ (/1000)	0.0063	−0.0023	0.0354***
US announcements			
$Consumer\ Price\ Index_t$	−0.0188	0.0378*	0.0811**
$Current\ Account\ Balance_t$	−0.0063	−0.0049	0.0425*
$Existing\ Home\ Sales_t$	0.0055	−0.0560***	0.0027
$GDP\ Price\ Index_t$	−0.0175	0.0684***	0.0343
$House\ Price\ Index_t$	−0.0020	0.0997**	0.0067
$Import\ Price\ Index_t$	0.0232**	−0.0795***	−0.0244
$Industrial\ Production_t$	0.0237**	−0.0158	0.0370
$Initial\ Jobless\ Claims_t$	0.0041	−0.0206**	−0.0058
PCE_t	0.0321	−0.2804***	−0.0278
$Personal\ Consumption_t$	−0.0274*	0.0409*	0.0502*
$Personal\ Income_t$	0.0238	0.1226***	−0.0080
$Personal\ Spending_t$	−0.0285*	0.1600***	0.0420
$Business\ Inventories_t$	0.0075	0.0251*	0.0060
$Capacity\ Utilization_t$	−0.0159*	0.0183	−0.0385
$Manufacture\ Payrolls_t$	−0.0124	0.0436**	0.0088
$Chicago\ Purchasing\ Manager_t$	−0.0350**	0.2335***	−0.0262
$Consumer\ Confidence\ Index_t$	−0.0004	0.0526**	−0.0181
$Consumer\ Credit_t$	0.0102	0.0474***	−0.0381
$Unemployment\ Rate_t$	0.0310*	0.0410*	−0.0172
$MKT_{1,i,t} \times Consumer\ Price\ Index_t$	0.0220	−0.0254	−0.0907***
$MKT_{2,i,t} \times Consumer\ Price\ Index_t$	0.0295	−0.0355	−0.1156**
$MKT_{3,i,t} \times Consumer\ Price\ Index_t$	0.0173	−0.0730***	−0.0709**
$MKT_{2,i,t} \times Current\ Account\ Balance_t$	−0.0088	0.0392**	−0.0458
$MKT_{1,i,t} \times Existing\ Home\ Sales_t$	−0.0047	0.0460**	0.0024
$MKT_{2,i,t} \times Existing\ Home\ Sales_t$	−0.0039	0.0448**	−0.0115
$MKT_{3,i,t} \times Existing\ Home\ Sales_t$	−0.0044	0.0593***	−0.0093
$MKT_{1,i,t} \times GDP\ Price\ Index_t$	0.0158	−0.0539**	−0.0402
$MKT_{2,i,t} \times GDP\ Price\ Index_t$	0.0179	−0.0708**	−0.0386
$MKT_{3,i,t} \times GDP\ Price\ Index_t$	0.0197	−0.0758***	−0.0274
$MKT_{1,i,t} \times House\ Price\ Index_t$	0.0060	−0.0909**	−0.0167
$MKT_{2,i,t} \times House\ Price\ Index_t$	0.0080	−0.1435***	−0.0110
$MKT_{3,i,t} \times House\ Price\ Index_t$	0.0006	−0.1169**	−0.0028
$MKT_{3,i,t} \times Housing\ Starts_t$	−0.0134	−0.0039	0.0270*
$MKT_{1,i,t} \times Import\ Price\ Index_t$	−0.0352***	0.0955***	0.0345*
$MKT_{2,i,t} \times Import\ Price\ Index_t$	−0.0135	0.0676***	0.0171
$MKT_{3,i,t} \times Import\ Price\ Index_t$	−0.0265**	0.0958***	0.0230
$MKT_{1,i,t} \times Industrial\ Production_t$	−0.0218**	0.0162	−0.0285
$MKT_{2,i,t} \times Industrial\ Production_t$	−0.0277*	0.0211	−0.0986
$MKT_{3,i,t} \times Industrial\ Production_t$	−0.0237**	0.0234	−0.0295
$MKT_{3,i,t} \times Initial\ Jobless\ Claims_t$	−0.0016	0.0281**	0.0042
$MKT_{2,i,t} \times Monthly\ Budget\ Statement_t$	0.0048	0.0450**	−0.0117
$MKT_{1,i,t} \times PCE_t$	−0.0337	0.4215***	0.0345
$MKT_{2,i,t} \times PCE_t$	−0.0493*	0.3181***	0.0496
$MKT_{3,i,t} \times PCE_t$	−0.0245	0.2579***	0.0074
$MKT_{1,i,t} \times Personal\ Consumption_t$	0.0222	−0.0617***	−0.0504*
$MKT_{2,i,t} \times Personal\ Consumption_t$	0.0348**	−0.0317	−0.0593*
$MKT_{3,i,t} \times Personal\ Consumption_t$	0.0336*	−0.0422	−0.0611**
$MKT_{1,i,t} \times Personal\ Income_t$	−0.0223	−0.2173***	−0.0051
$MKT_{2,i,t} \times Personal\ Income_t$	−0.0351	−0.1165*	0.0190
$MKT_{3,i,t} \times Personal\ Income_t$	−0.0229	−0.1257**	0.0086
$MKT_{1,i,t} \times Personal\ Spending_t$	0.0299*	−0.1886***	−0.0516
$MKT_{2,i,t} \times Personal\ Spending_t$	0.0325*	−0.1802***	−0.0442
$MKT_{3,i,t} \times Personal\ Spending_t$	0.0265	−0.1622***	−0.0396
$MKT_{1,i,t} \times PPI_t$	−0.0141	0.0383**	−0.0054
$MKT_{1,i,t} \times Retail\ Sales_t$	0.0010	0.0329**	0.0142

(*continued on next page*)

Table 10 (*continued*)

Variables	Tranquil period	$CRISIS_1 = 1$	$CRISIS_2 = 1$
$MKT_{1,i,t} \times$ *Business Inventories*$_t$	−0.0062	−0.0329**	−0.0059
$MKT_{1,i,t} \times$ *Capacity Utilization*$_t$	0.0178*	−0.0178	0.0267
$MKT_{3,i,t} \times$ *Capacity Utilization*$_t$	0.0197**	−0.0299*	0.0285
$MKT_{1,i,t} \times$ *Manufacture Payrolls*$_t$	0.0198	−0.0578***	−0.0192
$MKT_{1,i,t} \times$ *Chicago PMI*$_t$	0.0317**	−0.3220	0.0478
$MKT_{2,i,t} \times$ *Chicago PMI*$_t$	0.0504***	−0.2303***	0.0235
$MKT_{3,i,t} \times$ *Chicago PMI*$_t$	0.0301**	−0.2565***	0.0386
$MKT_{1,i,t} \times$ *Consumer Confidence Index*$_t$	−0.0088	−0.0810***	0.0258
$MKT_{3,i,t} \times$ *Consumer Confidence Index*$_t$	0.0001	−0.0547*	0.0153
$MKT_{1,i,t} \times$ *Consumer Credit*$_t$	−0.0040	−0.0480*	0.0282
$MKT_{3,i,t} \times$ *Consumer Credit*$_t$	−0.0084	−0.0577**	0.0329
$MKT_{3,i,t} \times$ *Trade Balance*$_t$	0.0139	−0.0580**	−0.0041
$MKT_{2,i,t} \times$ *Unemployment Rate*$_t$	−0.0410*	−0.0571**	−0.0011
$MKT_{3,i,t} \times$ *Unemployment Rate*$_4$	−0.0252	−0.0583**	0.0184
Japanese announcements			
Capital Spending$_t$	0.0970***	−0.1227***	−0.0736***
Housing Starts$_t$	−0.0165	−0.9878***	−0.1810
Industrial Production$_t$	0.0259**	−0.0130	0.0215
Jobless Rate$_t$	0.0134	0.5704***	0.0102
Large Retailers' Sales$_t$	−0.0227*	−0.0616	−0.0212
Trade Balance$_t$	−0.0008	0.0391*	0.0070
Tokyo CPI$_t$	−0.0114	0.2312***	0.0307
Tankan Large Non-Mfg Index$_t$	0.1000**	−0.0539	−0.0887*
$MKT_{1,i,t} \times$ *Capital Spending*$_t$	−0.1191***	0.1311***	0.0890***
$MKT_{2,i,t} \times$ *Capital Spending*$_t$	−0.0981***	0.1336***	0.0657**
$MKT_{3,i,t} \times$ *Capital Spending*$_t$	−0.1034***	0.1357***	0.0875***
$MKT_{1,i,t} \times$ *Housing Starts*$_t$	0.0311	1.4757***	0.1577
$MKT_{2,i,t} \times$ *Housing Starts*$_t$	0.0056	1.0777***	0.2011
$MKT_{3,i,t} \times$ *Housing Starts*$_t$	0.0121	1.0919***	0.1894
$MKT_{1,i,t} \times$ *Industrial Production*$_t$	−0.0303*	0.0077	−0.0162
$MKT_{2,i,t} \times$ *Industrial Production*$_t$	−0.0340**	−0.0482	−0.0200
$MKT_{1,i,t} \times$ *Jobless Rate*$_t$	−0.0206	−0.8321***	−0.0088
$MKT_{2,i,t} \times$ *Jobless Rate*$_t$	−0.0182	−0.6048***	−0.0111
$MKT_{3,i,t} \times$ *Jobless Rate*$_t$	−0.0097	−0.6294***	−0.0069
$MKT_{1,i,t} \times$ *Large Retailers' Sales*$_t$	0.0379**	−0.1697**	0.0113
$MKT_{2,i,t} \times$ *Money Stock M2*$_t$	1.0700**	−1.0326	−0.1479
$MKT_{2,i,t} \times$ *Trade Balance*$_t$	−0.0103	−0.0472**	0.0047
$MKT_{3,i,t} \times$ *Trade Balance*$_t$	0.0141	−0.0673**	−0.0136
$MKT_{1,i,t} \times$ *Tokyo CPI*$_t$	0.0125	−0.2541***	−0.0304
$MKT_{2,i,t} \times$ *Tokyo CPI*$_t$	0.0195	−0.2166***	−0.0436
$MKT_{3,i,t} \times$ *Tokyo CPI*$_t$	0.0056	−0.2373***	−0.0322
$MKT_{1,i,t} \times$ *Tankan Large Non-Mfg Index*$_t$	−0.1101**	0.0572	0.1059**
$MKT_{2,i,t} \times$ *Tankan Large Non-Mfg Index*$_t$	−0.0986**	0.0343	0.0817*
$MKT_{3,i,t} \times$ *Tankan Large Non-Mfg Index*$_t$	−0.0929*	0.0537	0.0794
$MKT_{3,i,t} \times$ *Retail Sales*$_t$	0.0082	−0.0566	−0.0470**
Adjusted R^2 (%)	18.88		

*** Denote statistical significance at the 1% level.
** Denote statistical significance at the 5% level.
* Denote statistical significance at the 10% level.

We define dummy variables $CRISIS_{1,t}$ and $CRISIS_{2,t,}$ to refer to the above two crisis periods. $CRISIS_{1,t}$=1 if t is in the period of August 1–December 31, 2008, 0 otherwise; $CRISIS_{2,t}$=1 if t is in the period of September 16, 2009–March 14, 2012, 0 otherwise. The estimation results for the regression model that considers the crisis effect are reported in Tables 9 and 10 for the EUR/USD and USD/JPY markets, respectively.

In the EUR/USD market, during the subprime mortgage crisis, the information shares of the Asian, European and U.S. trading hours increase. However, during the European debt crisis, information shares in the Asian and U.S. periods increase. In the USD/JPY market, Table 10 also reveals similar results that information shares decrease in the L + NY period and increase in Asian and U.S. periods during both crisis periods.

In the EUR/USD market, during the tranquil period, the spread negatively relates to information share in the L + NY period, while volatility is positively associated with the information share in the L + NY period. It suggests that lower transaction cost and higher price volatility enhance the information share in the L + NY hours in the tranquil period.

During the financial subprime crisis period, the impact of spread and volatility on the L + NY information share increases. During the European sovereign debt crisis, a positive association between spread and the L + NY information share is observed. In the USD/JPY market, we find a negative relationship between the volatility and the L + NY information share during both crisis periods. A market with many noise traders may feature a higher volatility, thus it may explain the information share decreases with volatility.

Among announcements we consider, Table 9 shows that only the surprise of Factory Orders negatively affects the information share in the L + NY period. Seven U.S. announcements positively affect the information share in the L + NY trading hours during the subprime crisis period, and four U.S. announcements positively relate to the information share in the L + NY period during the European debt crisis. Compared with the influence of European announcements on the L + NY information share, we infer that the U.S. announcements strongly affect the price discovery in the L + NY trading hours during the crisis periods.

Moreover, observing changes in information shares in the other three trading periods relative to the L + NY period, we find that announcements of Consumer Price Index, FOMC Rate Decision, PCE, Personal Income, Personal Spending, Capacity Utilization, Manufacture Payrolls, Nonfarm Payrolls and Construction Spending positively affect the information share in the Asian, European and U.S. hours, during the tranquil period. The number of announcements with significant effects on information shares during the tranquil period is even larger than that in both crisis periods.

In the EUR/USD market, we observe in Table 9 that the information share in the L + NY overlapping trading hours increases with European announcements of Govt Expend, Gross Fix Cap, Trade Balance and Unemployment Rate during the tranquil period. During the subprime crisis period, we find the L + NY price discovery is improved on announcement days of European Business Climate Indicator, whilst on days with Consumer Confidence announcements the L + NY price discovery is dampened during the European sovereign crisis.

Overall, more U.S. announcements have a significant impact on the L + NY information share in the financial subprime crisis period, compared to the European debt crisis period. Additionally, Japanese macroeconomic announcements are also more influential on the price discovery in the financial subprime crisis period than in the European sovereign debt crisis.

5. Conclusions

Studying the overall variation in information shares across four sequential trading sessions, including Asian, European, the overlapping London and New York (L + NY) and U.S. trading hours, we show that L + NY trading hours dominate the price discovery in FX markets, consistent with Cai et al. (2008) and Wang and Yang (2011). With the consideration of macroeconomic announcements, we explore the pervasiveness of the dominance of the L + NY trading hours in FX price discovery.

We find that the L + NY trading hours lead the price discovery only during days with U.S. announcements, while European trading period turns out to contribute more than the L + NY trading period to the price discovery during days without U.S. announcements. Information shares in European and Asian trading hours significantly increase during days with European and Japanese macroeconomic announcements, respectively. The results support the local information hypothesis that information may be asymmetrically distributed between different regions and suggest local traders may be better informed at the release of local announcements.

We study the informational efficiency in the 24-h foreign exchange trading platform around scheduled macroeconomic announcements. Higher information shares before the announcement suggest the possibility of information leakage prior to the announcement, while the rise in information share after the announcement reflects heterogeneous traders' interpretations of news emerge at the announcement and following information transmission after the announcement induces price-relevant information to be incorporated into prices.

Our analysis complements earlier studies by analyzing the determinants of FX price discovery efficacy on the basis of information shares. Higher liquidity improves information shares. We also find that the influence of U.S. macroeconomic announcements than those of European and Japanese announcements, consistent with Andersen et al. (2003), Ehrmann and Fratzscher (2004) and Hashimoto and Ito (2010).

References

Admati, A., Pfleiderer, P., 1988. A theory of intraday patterns: volume and price variability. Rev. Financ. Stud. 1, 3–40.

Almeida, A., Goodhart, C., Payne, R., 1998. The effects of macroeconomic news on high frequency exchange rate behavior. J. Financ. Quantitat. Anal. 33, 383–408.

Andersen, T.G., Bollerslev, T., 1998. Deutsche mark–dollar volatility: intraday activity patterns, macroeconomic announcements, and longer run dependencies. J. Finance 53, 219–265.

Andersen, T.G., Bollerslev, T., Diebold, F.X., Vega, C., 2003. Micro effects of macro announcements: real-time price discovery in foreign exchange. Am. Econ. Rev. 93, 38–62.

Andersen, T.G., Benzoni, L., 2008. Realized volatility, Working Paper Series WP-08-14, Federal Reserve Bank of Chicago.

Baik, B., Kang, J.K., Kim, J.M., 2010. Local institutional investors, information asymmetries, and equity returns. J. Financ. Econ. 97, 81–106.

Balduzzi, P., Elton, E.J., Green, T.C., 2001. Economic news and bond prices: evidence from the U.S. Treasury market. J. Financ. Quantitat. Anal. 36, 523–543.

Barclay, M.J., Hendershott, T., 2003. Price discovery and trading after hours. Rev. Financ. Stud. 16, 1041–1073.

Barclay, M.J., Hendershott, T., 2008. A comparison of trading and non-trading mechanisms for price discovery. J. Empir. Finance 15, 839–849.

Barclay, M.J., Litzenberger, R.H., Warner, J.B., 1990. Private information, trading volume, and stock-return variances. Rev. Financ. Stud. 3, 233–254.

Bauwens, L., Omrane, W.B., Giot, P., 2005. News announcements, market activity and volatility in the Euro/Dollar foreign exchange market. J. Int. Money Finance 24, 1108–1125.

Bernile, G., Hu, J., Tang, Y., 2016. Can information be locked-up? Informed volume and price variability trading ahead of macro-news announcements. J. Financ. Econ. 121, 492–520.

Bhattacharya, U., Daouk, H., Jorgenson, B., Kehr, C., 2000. When an event is not an event: the curious case of an emerging market. J. Financ. Econ. 55, 69–101.

BIS (Bank for International Settlements), 2013. Triennial Central Bank Survey of Foreign Exchange and Derivatives Market Activity in April 2013. Bank for International Settlements.
Brunnermeier, M., Pedersen, L., 2009. Market liquidity and funding liquidity. Rev. Financ. Stud. 22, 2201–2238.
Cai, F., Howorka, E., Wongswan, J., 2008. Informational linkages across trading regions: evidence from foreign exchange markets. J. Int. Money Finance 27, 1215–1243.
Chae, J., 2005. Trading volume, information asymmetry, and timing information. J. Finance 60, 413–442.
Chen, Y.L., Gau, Y.F., 2010. News announcements and price discovery in foreign exchange spot and futures markets. J. Bank. Finance 34, 1628–1636.
Cieslak, A., Morse, A., Vissing-Jorgensen, A., 2014. Stock returns over the FOMC cycle, Working Paper, National Bureau of Economic Research.
Coval, J.D., Moskowitz, T.J., 2001. The geography of investment: informed trading and asset prices. J. Polit. Econ. 109, 811–841.
Covrig, V., Melvin, M., 2002. Asymmetric information and price discovery in the FX market: Does Tokyo know more about the Yen? J. Empir. Finance 9, 271–285.
D'Souza, C., 2007. Where does price discovery occur in FX markets? Working Paper 2007–52, Bank of Canada.
Ederington, L.H., Lee, J.H., 1993. How markets process information: news releases and volatility. J. Finance 48, 1161–1191.
Ehrmann, M., Fratzscher, M., 2004. Exchange rates and fundamentals: new evidence from real-time data. J. Int. Money Finance 24, 317–341.
Evans, K.P., Speight, A.E.H., 2011. Intraday euro exchange rates and international macroeconomic announcements. Europ. J. Finance 17, 83–110.
Faust, J., Rogers, J.H., Wang, S.Y.B., Wright, J.H., 2007. The high-frequency response of exchange rates and interest rates to macroeconomic announcements. J. Monet. Econ. 54, 1051–1068.
Flannery, M.J., Protopapadakis, A.A., 2002. Macroeconomic factors do influence aggregate stock returns. Rev. Financ. Stud. 15, 751–782.
Galati, G., Heath, A., McGuire, P., 2007. Evidence of carry trade activity – BIS Quarter Review, September 2007, 27–41.
Gilbert, T., Scotti, C., Strasser, G., Vega, C., 2015. Is the intrinsic value of macroeconomic news announcements related to their asset price impact? Working Paper, Department of Economics, Boston College.
Gonzalo, J., Granger, C.W.J., 1995. Estimation of common long-memory components in co-integrated systems. J. Bus. Econ. Stat. 13, 27–36.
Hasbrouck, J., 1995. One security, many markets: determining the contributions to price discovery. J. Finance 50, 1175–1199.
Hashimoto, Y., Ito, T., 2010. Effects of Japanese macroeconomic statistic announcements on the Dollar/Yen exchange rate: high resolution picture. J. Japanese Int. Econ. 24, 334–354.
Hau, H., 2001. Location matters: an examination of trading profits. J. Finance 56, 1959–1983.
Hayo, B., Neuenkirch, M., 2010. Do Federal Reserve communications help predict federal funds target rate decisions? J. Macroecon. 32, 1014–1024.
He, Y., Lin, H., Wang, J., Wu, C., 2009. Price discovery in the round-the-clock U.S. Treasury market. J. Financ. Intermed. 18, 464–490.
Huberman, G., Schwert, G.W., 1985. Information aggregation, inflation, and the pricing of indexed bonds. J. Polit. Econ. 93, 92–114.
Ito, T., Hashimoto, Y., 2006. Intraday seasonality in activities of the foreign exchange markets: evidence from the electronic broking system. J. Japanese Int. Econ. 20, 637–664.
Ivashina, V., Scharfstein, D., 2010. Bank lending during the financial crisis of 2008. J. Financ. Econ. 97, 319–338.
Ivković, Z., Weisbenner, S., 2005. Local does as local is: information content of the geography of individual investors' common stock investments. J. Finance 60, 267–306.
Jiang, C.X., Likitapiwat, T., McInish, T., 2012. Information content of earnings announcements: evidence from after hours trading. J. Financ. Quantitat. Anal. 47, 1303–1330.
Kaul, A., Sapp, S., 2009. Trading activity, dealer concentration and foreign exchange market quality. J. Bank. Finance 33, 2122–2131.
Kim, O., Verrecchia, R.E., 1994. Market reaction to anticipated announcements. J. Financ. Econ. 30, 273–309.
Kurov, A., Sancetta, A., Strasser, G., Wolfe, M. H., 2016. Price drift before U.S. macroeconomic news: private information about public announcements? Working Paper, European Central Bank.
Kyle, A.S., 1985. Continuous auctions and insider trading. Econometrica 53, 1315–1336.
Longstaff, F.A., 2010. The subprime credit crisis and contagion in financial market. J. Financ. Econ. 97, 436–450.
Love, R., Payne, R., 2008. Macroeconomic news, order flow and exchange rates. J. Financ. Quantitat. Anal. 43, 467–488.
Marshall, A., Musayev, T., Pinto, H., Tang, L., 2012. Impact of news announcements on the foreign exchange implied volatility. J. Int. Financ. Mark. Inst. Money 22, 719–737.
Menkhoff, L., Sarno, L., Schmeling, M., Schrimpf, A., 2016. Information flows in foreign exchange markets: dissecting customer currency trades. J. Finance 71, 601–634.
Menkhoff, L., Schmeling, M., 2008. Local information in foreign exchange markets. J. Int. Money Finance 27, 1383–1406.
Melvin, M., Taylor, M.P., 2009. The crisis in the foreign exchange market. J. Int. Money Finance 28, 1317–1330.
Mizrach, B., Neely, C.J., 2008. Information shares in the U.S. Treasury market. J. Bank. Finance 32, 1221–1233.
Narayan, P.K., Sharma, S.S., Thuraisamy, K.S., 2014. An analysis of price discovery from panel data models of CDS and equity returns. J. Bank. Finance 41, 167–177.
Newey, W.K., West, K.D., 1987. A simple, positive semi-definite, heteroskedasticity and autocorrelation consistent covariance matrix. Econometrica 55, 703–708.
Newey, W.K., West, K.D., 1994. Automatic lag selection in covariance matrix estimation. Rev. Econ. Stud. 61, 631–653.
Piccotti, L.R., 2016. Pricing errors and the geography of trade in the foreign exchange market. J. Financ. Markets 28, 46–69.
Riordan, R., Storkenmaier, A., Wagener, M., Zhang, S., 2013. Public information arrival: price discovery and liquidity in electronic limit order markets. J. Bank. Finance 37, 1148–1159.
Sapp, S.G., 2002. Price leadership in the spot foreign exchange market. J. Financ. Quantitat. Anal. 37, 425–448.
Tetlock, P., 2010. Does public financial news resolve asymmetric information? Rev. Financ. Stud. 23, 3520–3557.
Wang, J., Yang, M., 2011. Housewives of Tokyo versus the gnomes of Zurich: measuring price discovery in sequential markets. J. Financ. Market 14, 82–108.
Wang, J., Yang, M., 2015. How well does the weighted price contribution measure price discovery? J. Econ. Dyn. Control 55, 113–129.
Xiong, W., Yan, H., 2010. Heterogeneous expectations and bond markets. Rev. Financ. Stud. 23, 1433–1466.
Zhang, L., Mykland, P., Ait-Sahalia, Y., 2005. A tale of two times scales: determining integrated volatility with noisy high frequency data. J. Am. Stat. Assoc. 100, 1394–1411.